A NEW COMPENSATING METHOD FOR THE MUTUAL COUPLING EFFECT IN ADAPTIVE ANTENNA ARRAYS COMPOSED OF WIRE ELEMENTS

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Abstract—A new compensation method for the mutual coupling of adaptive antenna arrays composed of wire elements is introduced. For the antenna array composed of wire elements, the new compensation method can decouple the terminal voltages with high accuracy for both the 1-D incident signals and 2-D incident signals. The new compensation method is based on the mutual coupling grid and the transient mutual coupling coefficient proposed in this paper. By contrast with the CMIM and RMIM, the new compensation method can provide better compensation for the DOA estimations. Even for the ultra compact antenna array and the incident signals inclined with respect to the azimuth the new compensation method can work well. The numerical results verify the validity and the effectiveness of the new compensation method.

1. INTRODUCTION

The mutual coupling between antenna elements has a strong effect on the performance of adaptive antenna arrays, especially for the compact arrays and wideband arrays [1–5]. Compensating for the mutual coupling in adaptive arrays has attracted much attention for the last few decades [1–9]. Gupta studied the effect of mutual coupling on the performance of adaptive arrays and adopted the conventional mutual impedance method (CMIM) to reduce the effect of mutual coupling [1]. This method was later used to compensate for the mutual coupling by operating the decoupling matrix on the adaptive algorithms in [2] and [3]. In the definition of the conventional mutual coupling, a voltage or current source should be imposed on one element so that

it can affect the other element by the mutual coupling effect, which is different from the adaptive receiving antenna arrays since all antenna elements operate in the receiving mode. Hui, therefore, proposed a new mutual impedance definition for receiving antenna arrays, named receiving mutual impedance [6–9]. The receiving mutual impedance method (RMIM) has shown a better performance than the CMIM in the compensating for the mutual coupling of adaptive antenna arrays. However, it has been shown very recently that the only difference between the RMI and the CMI is whether there are the open circuit voltages in the equivalent circuit models [10]. At the same time, both the CMIM and the proposed RMIM is expected to be improved to become applicable for the 2-D array signal processing such as 2-D DOA estimations and 2-D adaptive nulling.

In this paper, we propose a new compensation method for the mutual coupling effect of the adaptive antenna arrays. A mutual coupling grid is established to describe the course of the mutual coupling of an adaptive antenna array and to explain the validity of the new compensation method. A transient mutual coupling coefficient is defined and its calculation formula is derived. And then, the decoupling matrix is provided to compensate for the mutual coupling effect of the antenna arrays. Additionally, the fast calculation and measurement method for the transient mutual coupling coefficients are introduced. The new method, with a simple processing to obtain the decoupling matrix, can compensate for the mutual coupling with high accuracy even for the ultra compact antenna arrays. It is crucial that the new compensation method is applicable for the 2-D signal processing. Even for the incident wave inclined to the azimuth plane, the new compensation method can decouple the terminal voltages and provide direction estimations with high accuracy. The comparison
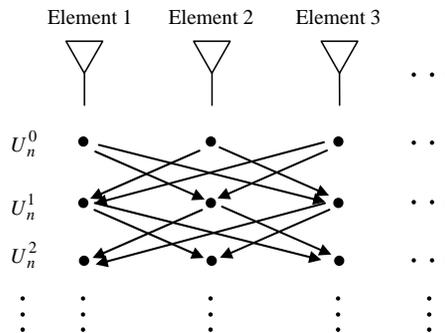
Figure 1. Mutual coupling grid of the antenna array.

results involving the CMIM, the RMIM and the new compensation method verify the advantages of the new compensation method.

The new compensation method is employed in the DOA estimation to testify its performance, where the original MUSIC algorithm is utilized for 1-D and 2-D DOA estimation [11]. It is shown from the numerical examples that the new method performs excellently with high accuracy of compensating for the mutual coupling effect.

2. COMPENSATION METHOD FOR THE MUTUAL COUPLING

2.1. Calculation of the Transient Mutual Coupling Coefficient

Consider an antenna array with N elements with each of them terminated with the same load. As a receiving array, the voltages will be induced across all the terminals of the antenna elements when a plane wave incidents on the antenna array. The terminal voltage on each antenna element is composed of the terminal voltage due to the incident wave only in addition to that due to the mutual coupling effect by the other antenna elements. A mutual coupling grid is designed to describe the course of the mutual coupling on the antenna array, as is shown in Figure 1. Actually, the course of the mutual coupling includes the structure-mode scattering and the antenna-mode scattering of the elements. Whereas the structure-mode scattering can be neglected in the course of the mutual coupling for the antenna array composed of the wire elements which is referred to as the minimally scattering antennas [12]. Therefore, in the antenna array with the wire elements, only the antenna-mode scattering is considered. The antenna-mode scattering is produced by the secondary radiation of elements. In this case, the secondary radiation is mainly dominated by the radiation characters of the element and the reflection characters of the element port. When two elements are isolated from each other and operate in the receiving status, the steady state of the electromagnetic distributions exists on them. However, the steady state of the isolated elements will be disturbed if two elements are arranged to form an antenna array since the boundary condition is changed. And thus the electromagnetic wave will be partly reflected on each element. The reflected wave from one element is then received by another element and reflected partly at the element port. This course will be repeated at the next rounds until a new steady state of the electromagnetic field on the elements is established.

Assume U_n^0 ($n = 1, 2, \ldots, N$) is the induced terminal voltage on each element due to the incident plane wave only. If the antenna is

matched, an amount of power equal to that absorbed by the matched load is scattered from the antenna and affects the objects near it. In case of mismatched antenna the amount of power scattered is different from that power absorbed by the load and is depend on the degree of mismatch. With the primary reflection of the electromagnetic wave, a voltage U_n^1 ($n = 1, 2, \ldots, N$) on each element terminal is induced. It follows the second, the third, and the infinite reflections and inductions. In practice, this course will not stop until the reflected wave is attenuated to zero.

In the mutual coupling grid, the ratio of U_m^1 to U_n^0 calculated when only element m and element n are considered is defined as the transient mutual coupling coefficient that can be written as

$$\bar{\alpha}_{mn} = \frac{U_m^1}{U_n^0}. \tag{1}$$

According to the reciprocity of antenna arrays, $\bar{\alpha}_{mn} = \bar{\alpha}_{nm}$. Obviously, the same parameter exists in the course of the second, the third, and all the other reflections and inductions. Corresponding with the transient mutual coupling coefficient, the transient mutual coupling matrix T_α is defined as following

$$T_\alpha = \begin{bmatrix} 0 & \bar{\alpha}_{12} & \ldots & \overline{\alpha}_{1N} \\ \bar{\alpha}_{21} & 0 & \ldots & \overline{\alpha}_{2N} \\ \vdots & \vdots & \ddots & \vdots \\ \bar{\alpha}_{N1} & \bar{\alpha}_{N2} & \ldots & 0 \end{bmatrix}. \tag{2}$$

The calculation of $\bar{\alpha}_{mn}$ can be carried out with all the other antenna elements removed. In this case, the measured terminal voltages on element m and element n can be written as

$$V_m = U_m^0 + U_m^1 + U_m^2 + \ldots U_m^i + \ldots, \tag{3a}$$
$$V_n = U_n^0 + U_n^1 + U_n^2 + \ldots + U_n^i + \ldots, \tag{3b}$$

where V_m and V_n denote the measured terminal voltage on element m and element n, respectively, and the superscripts of each voltage represent the times of the reflection and induction. According to the reciprocity, Eq. (3) can be further written as

$$V_m = \left[1 + (\bar{\alpha}_{mn})^2 + (\bar{\alpha}_{mn})^4 + \ldots + (\bar{\alpha}_{mn})^{2i} + \ldots\right] U_m^0$$
$$+ \left[\bar{\alpha}_{mn} + (\bar{\alpha}_{mn})^3 + \ldots + (\bar{\alpha}_{mn})^{2i+1} + \ldots\right] U_n^0, \tag{4a}$$
$$V_n = \left[\bar{\alpha}_{mn} + (\overline{\alpha}_{mn})^3 + \ldots + (\bar{\alpha}_{mn})^{2i+1} + \ldots\right] U_m^0$$
$$+ \left[1 + (\bar{\alpha}_{mn})^2 + (\bar{\alpha}_{mn})^4 + \ldots + (\bar{\alpha}_{mn})^{2i} + \ldots\right] U_n^0. \tag{4b}$$

Merge Eqs. (4a) and (4b), one obtains

$$V_m + V_n = \left[1 + (\bar{\alpha}_{mn}) + (\bar{\alpha}_{mn})^2 + \ldots + (\bar{\alpha}_{mn})^i + \ldots\right] \left(U_m^0 + U_n^0\right). \quad (5)$$

Since $|\bar{\alpha}_{mn}| < 1$, $\bar{\alpha}_{mn}$ can be obtained from Eq. (5), that is

$$\bar{\alpha}_{mn} = 1 - \frac{U_m^0 + U_n^0}{V_m + V_n}, \quad (6)$$

In Eq (6), V_m, V_n, U_m^0 and U_n^0 can be calculated by the method of moments.

2.2. Compensation Method for the Mutual Coupling Effect

In order to apply the transient mutual coupling matrix to compensate for the mutual coupling effect, the relationship of the measured terminal voltages and the induced voltages due to the incident wave only should be derived. Assume that $V = [V_1 \ V_2 \ \ldots \ V_N]^T$ denotes the measured terminal voltage vector on the antenna array and that $U^0 = [U_1^0 \ U_2^0 \ \ldots \ U_N^0]^T$ denotes the induced voltages due to the incident wave only or the decoupled voltage vector. According to the mutual coupling grid, one obtains

$$V = \left(I + T_\alpha + T_\alpha^2 + \ldots + T_\alpha^n + \ldots\right) U^0. \quad (7)$$

The Neumann series of matrix in Eq. (7) converges to $(I - T_\alpha)^{-1}$ since $|\bar{\alpha}_{mn}| < 1$. And thus, the decoupled voltage vector can be expressed as

$$U^0 = (I - T_\alpha) V. \quad (8)$$

The matrix $I - T_\alpha$ is the decoupling matrix that can be employed in the adaptive antenna arrays to compensate for the mutual coupling effect. The power series of matrix T_α in Eq. (7) involves all the reflection and induction relationships in the mutual coupling grid. Consequently, Eq. (8) can well perform the decoupling, which is verified by the following numerical examples.

The proposed method in this paper has the same premise as the RMIM. It is assumed that the antenna array operates in the receiving mode and the effect of the antenna load on the mutual coupling is taken into account. Different with the CMIM and the RMIM, a mutual coupling grid is proposed to describe the mutual coupling effect of the antenna array. Based on this, the relation between the decoupled voltages and the actual measured voltages is built. When neglecting the structure-mode scattering, Eq. (7) and Eq. (8) provide the complete relationship between the decoupled voltages and the actual measured voltages. Additionally, the calculation of $\bar{\alpha}_{mn}$ and T_α

does not involve other approximations. Hence, the decoupled voltages obtained from Eq. (7) and Eq. (8) are the most close to the ideal voltages. Reference [9] provides a better calculation method of the RMI than the previous work. However, the compensation accuracy of the new method depends on the selection of the incident angles for solving the matrix equation, which will bring about the bias of the decoupled voltages. In this paper, an accurate fast calculation and measurement method of the decoupling matrix are introduced as following. It is simpler than the previous calculation methods of the RMI.

3. FAST MEASUREMENT AND CALCULATION OF THE TRANSIENT MUTUAL COUPLING COEFFICIENT

The transient mutual coupling coefficient cannot be measured according to the calculation formula. In order to make the new compensation method to be more practical, it is necessary to look for the measurement method for the transient mutual coupling coefficient. A measurement method was proposed for the RMI in [8]. This method can provide accurate measurement for the antenna array with two elements as well as the antenna array with multiple elements in most practical situations. In this paper, the fast measurement and calculation of the transient mutual coupling coefficient is introduced. In the measurement, an auxiliary element is added to the original antenna array and thus the new antenna array is measured by the vector network analyzer in the anechoic chamber. The calculated and the measured results for the transient mutual coupling coefficient are given for comparison and it can be seen that the fast measurement and calculation method is very effective.

In the calculation of the transient mutual coupling coefficient, only two elements are considered and both elements act as the receiving antennas. In order to measure the transient mutual coupling coefficient, two elements are extracted from the antenna array and an auxiliary element is used. Thus, the antenna array composed of the original two elements and the auxiliary element is the object of the measurement. The platform of the measurement is shown in Figure 2. In calculating the transient mutual coupling coefficient using Eq. (6), a plane wave from a certain direction is chosen to incident on the antenna array. In the measurement platform, the function of the plane wave is replaced by the auxiliary element. When the spacing between the auxiliary element and the original two elements is far larger than the wavelength, the induced voltage on the original element would be nearly the same with that due to the plane wave. The relationship
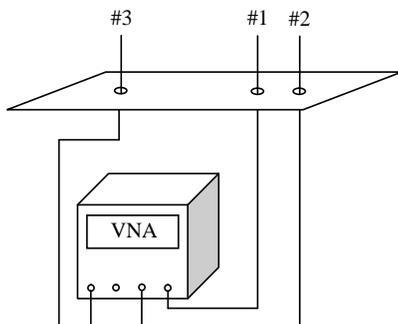
Figure 2. Measurement of the transient mutual coupling coefficient using the auxiliary element.

between the scattering parameter S_{pq} and the induced voltage V_p across the terminal of the element p can be represented as [13],

$$V_p = S_{pq}\xi\sqrt{Z_0}, \tag{9}$$

where ξ is the square root of the power emitted by the element q and Z_0 the system impedance. Therefore, the terminal voltages involved in Eq. (6) can be expressed by the scattering parameters. One obtains

$$V_1 = S_{13}\xi\sqrt{Z_0}, \tag{10a}$$

$$V_2 = S_{23}\xi\sqrt{Z_0}, \tag{10b}$$

$$U_1^0 = S_{13}^0\xi\sqrt{Z_0}, \tag{10c}$$

$$U_2^0 = S_{23}^0\xi\sqrt{Z_0}, \tag{10d}$$

where S_{13}^0 is measured with element 2 removed and S_{23}^0 measured with element 1 removed. And then the transient mutual coupling coefficient in terms of the measured scattering parameters is obtained by substituting Eq. (10) into Eq. (6). It gives

$$\bar{\alpha}_{12} = 1 - \frac{S_{13}^0 + S_{23}^0}{S_{13} + S_{23}}. \tag{11}$$

From the measurement method, a fast calculation method for the transient mutual coupling coefficient can be developed. In the original method, both elements act as the receiving antennas with the terminal loads and a plane wave is needed to incident on the elements. The current distribution on each element should be calculated, and thus only the transient mutual coupling coefficient at one frequency point is obtained though one process. In the fast method, the auxiliary element is employed to compose a new antenna array with three

elements. The plane wave and the terminal loads are not needed any more. By calculating the scattering parameters involved in Eq. (11), the transient mutual coupling coefficient can be obtained. It is convenient to calculate the transient mutual coupling coefficient in a certain frequency range with the fast method. It is verified by the EM simulations that the calculated transient mutual coupling coefficient via the fast method gets accurate when the spacing between the auxiliary element and the original elements is larger than about 1 wavelength.

To testify the effectiveness of the fast measurement and calculation method, the transient mutual coupling coefficient of two monopoles are calculated and measured. The monopoles operate in the vicinity of 3 GHz. The length of each element is $l = 25\,\text{mm}$, the radius of the wire is $r = 0.3\,\text{mm}$ and the spacing of two elements is $d = 30\,\text{mm}$. Each element is terminated with the same load impedance of $Z_L = 50\,\Omega$ which is matched with the system impedance. In the measurement, the port of each element is directly connected with the test cable. An auxiliary element that is the same as the original elements is arranged on the straight line determined by the two original elements. The distance between the auxiliary element and the closer element is $d' = 300\,\text{mm}$. The transient mutual coupling coefficient in the frequency range of 2.5 GHz~3.5 GHz are calculated via Eq. (6) and Eq. (11), respectively. The EM tool FEKO is used to calculate the distributions of the currents and the scattering parameters that are needed in above calculations. The calculated and the measurement results are given in Figure 3.

It can be seen that the transient mutual coupling coefficient
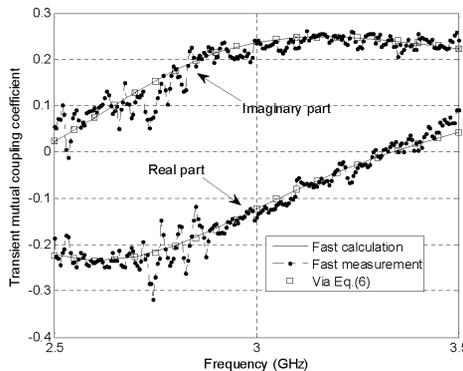
Figure 3. Calculated and measured transient mutual coupling coefficient.

calculated by the fast calculation method is nearly the same with those calculated by Eq. (6) and the measurement results are well coincident with the calculated results, which verifies the effectiveness of the auxiliary element method.

4. NUMERICAL EXAMPLES

In order to verify the compensation performance for the mutual coupling effect by the new method, the uniform linear arrays (ULAs) with 4 elements and the uniform circular arrays (UCAs) with 6 elements are used. The original MUSIC algorithm [11] is employed to find the signal direction for the 1-D and 2-D DOA estimations. And the electromagnetic simulation tool FEKO is used to calculate the current distributions and terminal voltages on the antennas.

4.1. The Decoupling for the Terminal Voltages

In this subsection, a ULA with 4 monopole elements ($N = 4$) is considered as is shown in Figure 4. The array is designed at the frequency of 2.5 GHz. The length of each element is $l = 0.24\lambda$ with $l/r = 100$ where λ is the wavelength and r the radius of the wire. Each element is terminated with the same load impedance of $Z_L = 50\,\Omega$. In the below numerical examples, different element separations are given, that is $d = 0.5\lambda$, 0.25λ, and 0.05λ.

An incident plane wave from $\phi = 45°$ in azimuth is chosen to calculate the decoupling matrix. Actually, almost identical decoupling matrices can be obtained by choosing other directions. The transient mutual coupling coefficients are calculated via Eq. (6) and then the transient mutual coupling matrix is obtained via Eq. (2). Finally, the decoupling matrix is calculated via Eq. (8). The transient mutual coupling coefficients in the case of different element separations are listed in Table 1.
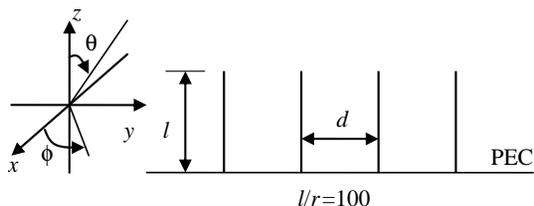
Figure 4. ULA with 4 elements and the coordinate system.

Above decoupling matrices are then used to compensate for the mutual coupling effect of the ULA with 4 elements for an incident wave from $\phi = 90°$ in azimuth. The measured voltages, theoretical non-coupling voltages and the decoupled voltages obtained by the new compensation method at different element separations are listed in Table 2, Table 3 and Table 4. It is shown form these tables that the measured terminal voltages under $d = 0.25\lambda$ and $d = 0.05\lambda$ are disturbed so seriously that they cannot be used in the DOA estimations and however can be compensated well via the new compensation method.

The same decoupling matrix is also used to compensate for the

Table 1. The transient mutual coupling coefficients at different element separations.

	$d = 0.5\lambda$	$d = 0.25\lambda$	$d = 0.05\lambda$
$\alpha_{12}, \alpha_{21}, \alpha_{23}$ $\alpha_{32}, \alpha_{34}, \alpha_{43}$	$0.0842 + 0.1702i$	$-0.2279 + 0.1803i$	$-0.4303 - 0.1098i$
α_{13}, α_{31} α_{24}, α_{42}	$-0.0297 - 0.1020i$	$0.0842 + 0.1702i$	$-0.3971 - 0.0192i$
α_{14}, α_{41}	$0.0156 + 0.0712i$	$0.1288 - 0.0472i$	$-0.3507 + 0.0631i$

Table 2. Compensation results for the terminal voltages of the ULA at $d = 0.5\lambda$ with the incident wave from $\phi = 90°$ in azimuth.

	Element 1	Element 2	Element 3	Element 4
Measured voltage	$3.848\angle-25.16°$	$3.643\angle148.28°$	$3.643\angle-31.72°$	$3.848\angle154.84°$
Theoretical	$4.594\angle-9.91°$	$4.594\angle170.09°$	$4.594\angle-9.91°$	$4.594\angle170.09°$
Decoupled voltage	$4.5961\angle-9.8741°$	$4.5957\angle170.1333°$	$4.5957\angle-9.8667°$	$4.5961\angle170.1259°$

Table 3. Compensation results for the terminal voltages of the ULA at $d = 0.25\lambda$ with the incident wave from $\phi = 90°$ in azimuth.

	Element 1	Element 2	Element 3	Element 4
Measured voltage	$3.464\angle-46.1°$	$4.469\angle60.73°$	$4.346\angle157.96°$	$5.374\angle-94.86°$
Theoretical	$4.594\angle-9.91°$	$4.594\angle80.09°$	$4.594\angle170.09°$	$4.594\angle-99.91°$
Decoupled voltage	$4.599\angle-9.8273°$	$4.5909\angle80.1512°$	$4.5923\angle170.113°$	$4.5906\angle-99.9253°$

mutual coupling effect when the plane wave incidents from non-horizontal directions (θ, ϕ), such as $(45°, 45°)$ and $(20°, 45°)$. Here, only the compensation results for the antenna array with the element separation of $d = 0.25\lambda$ are given in Table 5 and Table 6. It is shown that the mutual coupling effect can be compensated with high accuracy even for the incident wave far from the horizontal direction, which means that the new compensation method can be employed in the 2-D DOA estimations and can provide accurate angle estimations.

Table 4. Compensation results for the terminal voltages of the ULA at $d = 0.05\lambda$ with the incident wave from $\phi = 90°$ in azimuth.

	Element 1	Element 2	Element 3	Element 4
Measured voltage	$3.189\angle-51.16°$	$2.414\angle-19.78°$	$2.543\angle32.91°$	$3.782\angle74.06°$
Theoretical	$4.594\angle-9.91°$	$4.594\angle8.09°$	$4.594\angle26.09°$	$4.594\angle44.09°$
Decoupled voltage	$4.5506\angle-9.9544°$	$4.558\angle7.9007°$	$4.5589\angle26.169°$	$4.5651\angle44.2836°$

Table 5. Compensation results for the terminal voltages of the ULA at $d = 0.25\lambda$ with the incident wave from $(45°, 45°)$.

	Element 1	Element 2	Element 3	Element 4
Measured voltage	$1.865\angle-0.77°$	$1.7\angle55.99°$	$2.182\angle83.39°$	$2.926\angle134.25°$
Theoretical	$2.883\angle-9.62°$	$2.883\angle35.38°$	$2.883\angle80.38°$	$2.883\angle125.38°$
Decoupled voltage	$2.8854\angle-9.3135°$	$2.8912\angle35.6955°$	$2.8868\angle80.5637°$	$2.889\angle125.3842°$

Table 6. Compensation results for the terminal voltages of the ULA at $d = 0.25\lambda$ with the incident wave from $(20°, 45°)$.

	Element 1	Element 2	Element 3	Element 4
Measured voltage	$1.065\angle2.48°$	$0.8373\angle44.84°$	$0.9259\angle51.92°$	$1.224\angle63.8°$
Theoretical	$1.269\angle-9.38°$	$1.269\angle12.39°$	$1.269\angle34.16°$	$1.269\angle55.92°$
Decoupled voltage	$1.2762\angle-9.0573°$	$1.2802\angle12.9889°$	$1.2774\angle34.5359°$	$1.2733\angle55.9355°$

4.2. DOA Estimation for Two Signals from Horizontal Direction

In the below simulations, the decoupling matrices are employed in the DOA estimation algorithms. The measured terminal signals influenced by the mutual coupling effect are obtained by the below steps. First, a plane wave from a certain direction incidents on the antenna array and the voltage across each terminal is calculated using FEKO. If there are multiple signals coming from different directions, the terminal voltages should be calculated for all directions. Second, after being normalized, a vector composed of the voltages across all terminals induced by one signal acts as the actual steering vector owing to this signal, while the direction matrix is composed of all theses actual steering vectors owing to all signals. And then generate the ideal stochastic signal matrix. Finally, the measured terminal signals are obtained by multiplying the direction matrix and the ideal stochastic signal matrix.

In the following processing of the signals, the decoupling matrix is used to compensate for the measured terminal signals with noise. In all simulations of this subsection, it is assumed that two signals come from $\phi = -10°$ and $\phi = 30°$, respectively, the signal-to-noise ratio (SNR) is $20\,\mathrm{dB}$ and the data sample equals 1000. The DOA estimation results via MUSIC algorithm [11] are shown in Figure 5, Figure 6, and Figure 7 for $d = 0.5\lambda$, 0.25λ, and 0.05λ, respectively. In the DOA estimations, five different kinds of voltages are input to
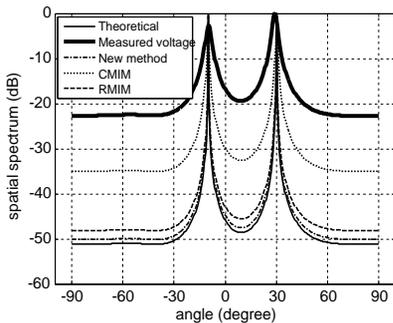
Figure 5. Spatial spectrum of the MUSIC algorithm for DOA estimation of tow signals from $\phi = -10°$ and $\phi = 30°$. The dimensions of the ULA are $l = 0.24\lambda$, $l/r = 100$, $d = 0.5\lambda$ and $Z_L = 50\,\Omega$.
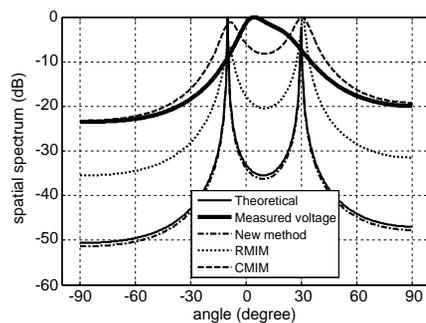
Figure 6. Spatial spectrum of the MUSIC algorithm for DOA estimation of tow signals from $\phi = -10°$ and $\phi = 30°$. The dimensions of the ULA are $l = 0.24\lambda$, $l/r = 100$, $d = 0.25\lambda$ and $Z_L = 50\,\Omega$.
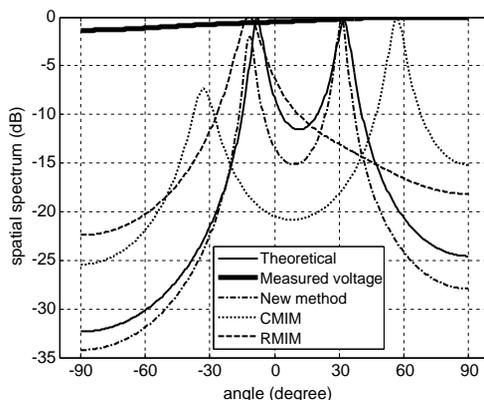
Figure 7. Spatial spectrum of the MUSIC algorithm for DOA estimation of tow signals from $\phi = -10°$ and $\phi = 30°$. The dimensions of the ULA are $l = 0.24\lambda$, $l/r = 100$, $d = 0.05\lambda$ and $Z_L = 50\,\Omega$.

the MUSIC algorithm. The first kind is the measured voltages which are the coupled voltages across the terminals. The second kind is the theoretical non-coupling voltages which are ideal voltages across the terminals when antenna elements are in isolation from all other elements. The third kind is the decoupled terminal voltages via the new method. The fourth and the fifth kinds are the decoupled voltages via the CMIM and the RMIM proposed in [9], respectively.

It is shown from Figure 5, Figure 6, and Figure 7 that the performance of the MUSIC algorithm degrades due to the mutual coupling effect, especially when the element separation becomes smaller than half wavelength. In Figure 6 and Figure 7, MUSIC algorithm cannot make a distinction between the two signals in the case of non-compensation. When the terminal voltages are compensated by the new method, the performance of the MUSIC algorithm is close to that using the theoretical non-coupling voltages. There are obvious sharp spectrum peaks in the case of $d = 0.5\lambda$ and $d = 0.25\lambda$ when the terminal voltages are decoupled by the new method, which is helpful for the DOA estimations. In Figure 7, although a small estimation bias exists for the signal from $\phi = 30°$, this estimation achieves a considerable precision for so small element separation of $d = 0.05\lambda$. By contrast with the CMIM and the RMIM, the new method can provide the most accurate compensation for the mutual coupling effect, which can be seen from the DOA estimation results.

4.3. DOA Estimation for Two Signals from Non-horizontal Direction

The new compensation method is now employed in the 2-D DOA estimation algorithm. A UCA composed of 6 monopole elements ($N = 6$) shown in Figure 8 is considered with two different radii of $R = 0.5\lambda$ and 0.25λ. The UCA use the same monopole as that of the ULAs used above. Two signals with the same SNR of 20 dB incident from the direction of $(60°, 90°)$ and $(30°, 90°)$, respectively, and the data sample equals 1000. An incident plane wave from $(90°, 90°)$ is chosen to calculate the decoupling matrices for the UCAs with different radii. And then these decoupling matrices are input to the MUSIC algorithm to compensate for the mutual coupling effect.

For comparison, the measured voltages, the theoretical non-coupling voltages, the decoupled voltages via the CMIM and RMIM
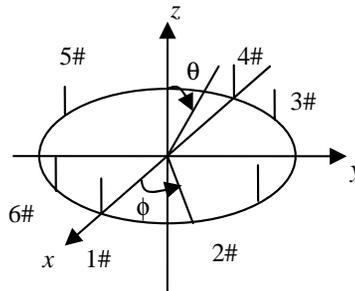
Figure 8. The UCA with 6 dipoles and the coordinate system.
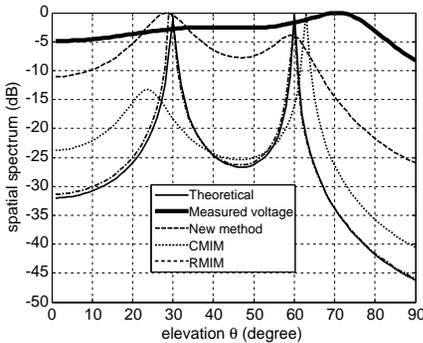
Figure 9. Spatial spectrum of the MUSIC algorithm for DOA estimation of tow signals from $(60°, 90°)$ and $(30°, 90°)$. The radius of the UCA is $R = 0.5\lambda$.
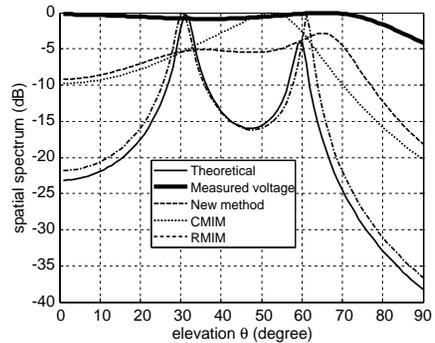
Figure 10. Spatial spectrum of the MUSIC algorithm for DOA estimation of tow signals from $(60°, 90°)$ and $(30°, 90°)$. The radius of the UCA is $R = 0.25\lambda$.

are also input to the MUSIC algorithm. The DOA estimation results in the case of $R = 0.5\lambda$ and 0.25λ are shown in Figure 9 and Figure 10, respectively. For clarity, only the spatial spectrums on the plane of $\phi = 90°$ are extracted from the 2-D spatial spectrums to be demonstrated. It is shown that the spectrum curves due to the decoupled voltages via the new method are the most close to those due to the theoretical non-coupling voltages, which indicates that the new method can compensate for the mutual coupling effect for signals from the non-horizontal direction with high accuracy. Therefore, it is proved once again that the new compensation method is applicable for the 2-D DOA estimations. At the same time, it can be seen that both the CMIM and the RMIM cannot carry out the compensation well for the 2-D DOA estimations since the MUSIC algorithm cannot estimate the incident angles of the two signals using the decoupled voltages via the two methods.

5. CONCLUSION

A new compensation method for the mutual coupling effect of adaptive antenna arrays composed of the wire elements is presented in the paper. The new compensation method is based on the mutual coupling grid and the proposed transient mutual coupling coefficient. The fast calculation and measurement methods are provided to obtain the transient mutual coupling coefficient. By contrast with the CMIM and the RMIM, the new compensation method can provide better compensation for the mutual coupling effect for both the 1-D and the 2-D DOA estimations, which is verified by the simulation results. It can be seen from the simulation results that the new compensation method can work well even for the ultra compact antenna arrays and incident signals far from the azimuth plane However, this method is only applicable to the antenna array with wire elements since the wire elements are regarded as the minimally scattering antennas.

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