TACHKLING MUTUAL COUPLING IN ANTENNA ARRAYS FOR WIRELESS COMMUNICATIONS

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Keywords: Wireless communication, mutual coupling, antenna array, receiving mutual impedance, DOA estimation.

Abstract

A new model for tackling mutual coupling in wireless communications is introduced. A new concept of receiving mutual impedance is introduced and explained theoretically. Receiving mutual impedances for typical antenna arrays are obtained. Application of the new method is demonstrated in several arrays for direction finding, adaptive nulling, and MIMO communications.

1 Introduction

Antenna arrays are becoming more and more frequently used in communication systems. They are used for adaptive beamforming in smart antenna systems, for adaptive nulling in interference suppression arrays, for direction finding in positioning systems, or for multiantenna communications in MIMO systems, etc. Modern electron devices for communications tend to be smaller and smaller in size in order to be portable and mobile. Operating in a limited space, antenna arrays experience strong electromagnetic coupling which distorts the array manifold and degrades array functions. In terms of signal analysis, strong electromagnetic coupling gives rise to increased signal correlation which in general leads to a decrease in system capacity, lower signal-to-noise ratio, inaccurate beamforming and direction finding, or ineffective nulling of interferences.

In this paper, a new way of looking at the antenna mutual coupling phenomenon and a better method for its analysis and solution are introduced and discussed. A new parameter—the receiving mutual impedance—is introduced to characterize the mutual coupling effect in the antenna arrays. The importance of this parameter will be explained. The theoretical calculation method and the experimental determination method of this parameter are exemplified through simple dipole and monopole antenna arrays. The use of the receiving mutual impedance for the analysis of mutual coupling effect in typical wireless communication antenna arrays will be explained with realistic examples. The superior performance of the new method over conventional mutual coupling analysis methods will be fully demonstrated in these examples.

2 The concept of receiving mutual impedance

A The Receiving Mutual Impedance (RMI)

The concept of receiving mutual impedance was suggested in [1] as an alternative to the concept of conventional mutual impedance [2] for use in receiving antenna arrays. In fact, the need to handle mutual coupling problems differently in transmitting and receiving arrays has been noted before in [3] and [4]. More recently, some theoretical studies (for example [5], [6]) also indicated a more accurate characterization of mutual coupling in DOA estimation arrays by using a “receiving-mode” defined mutual impedances rather than the conventional mutual impedances. The basic difference between the receiving mutual impedance and the conventional mutual impedance lies in the fundamental causes of the coupling defining in these two mutual impedances. In the conventional mutual impedance, the coupling is caused by the transmitting current distribution on an antenna while in the receiving mutual impedance, the coupling is caused by the receiving current distribution on an antenna.

Definition: The receiving mutual impedance $Z_{12}^{\text{rmi}}$ between two antennas is the ratio of the coupled voltage across antenna 1’s terminal load $Z_L^1$ (due to the receiving current distribution on antenna 2) to the terminal current through antenna 2’s terminal load $Z_L^2$ when the array is excited by an external plane wave source. That is,

$$Z_{12}^{\text{rmi}} = \frac{V_1 - V_1'}{I_2}$$

The definition of the receiving mutual impedance requires specifying a plane wave to excite the two antennas as shown in Fig. 1. The coming direction of the plane wave is to be the same as the direction of the signal that the array is designed to receive. In Fig. 1, $V_1$ and $I_2$ are the received voltages across the terminal loads of antennas 1 and 2, respectively, when the array is excited by the coming plane wave source. The corresponding currents through the two antennas are $I_1$ and $I_2$. 
In (1), $U_1$ is the received voltage across the terminal load of antennas 1 when antenna 1 is excited by the external plane wave source alone (with antenna 2 removed from the array). $U_1$ is also called the isolation voltage on antenna 1. The definition of $Z_{12}^{21}$ is similar and is not to be repeated here.

**B The Mutual Coupling Analysis**

When an antenna array with $N$ elements for receiving an incoming signal, which is assumed to be a plane wave source, the received terminal voltage at the $k$th antenna element $V_k$ can be expressed as two parts: the received voltage due to the excitation of the $k$th antenna element by the plane wave source alone $U_k$ and the coupled voltage due to the scattered fields from the other antenna elements in the array $W_k$. That is,

$$V_k = U_k + W_k.$$  

(2)

The coupled voltage $W_k$ in (2) can be written as [1], [7], [8]:

$$W_k = Z_{12}^{21}I_1 + Z_{12}^{21}I_2 + \cdots + Z_{12}^{21}I_{k-1} + Z_{12}^{21}I_{k+1} + \cdots + Z_{12}^{21}I_N$$  

(3)

where $Z_{12}^{21}$ is the receiving mutual impedance between the $k$th and the $i$th antenna elements and $I_i$ is the terminal current at the $i$th antenna element given by:

$$I_i = V_i/Z_L, \quad i = 1, 2, \cdots, N$$  

(4)

with $Z_L$ being the terminal load impedance of the antenna elements. Putting (3) and (4) into (2), we have:

$$V_k = U_k + Z_{12}^{21}V_1/Z_L + Z_{12}^{21}V_2/Z_L + \cdots + Z_{12}^{21}V_{k-1}/Z_L + Z_{12}^{21}V_{k+1}/Z_L + \cdots + Z_{12}^{21}V_N/Z_L.$$  

(5)

Applying (5) to all antenna elements in the array ($k = 1, 2, \cdots, N$), the relationship between the uncoupled voltages $U_k$ and the received voltages (i.e., coupled voltages) $V_k$ can be written in a matrix equation as:

$$\begin{bmatrix} V_1 \\ V_2 \\ \vdots \\ V_N \end{bmatrix} = \begin{bmatrix} 1 + Z_{21}^{12}/Z_L & Z_{21}^{12}/Z_L & \cdots & Z_{21}^{12}/Z_L \\ Z_{21}^{21}/Z_L & 1 + Z_{21}^{22}/Z_L & \cdots & Z_{21}^{22}/Z_L \\ \vdots & \vdots & \ddots & \vdots \\ Z_{21}^{N1}/Z_L & Z_{21}^{N2}/Z_L & \cdots & 1 + Z_{21}^{NN}/Z_L \end{bmatrix} \begin{bmatrix} U_1 \\ U_2 \\ \vdots \\ U_N \end{bmatrix}. $$  

(6)

Note that (6) is different from the equation derived by using the conventional mutual impedance method (CMIM) (see for example [11]) which results in the following typical equation relating the open-circuit voltages $V_{ok}$ to the received terminal voltages $V_k$ (this is same as the $V_k$ in our formulation (6) above).

$$\begin{bmatrix} V_{ok} \\ V_{o2} \\ \vdots \\ V_{oN} \end{bmatrix} = \begin{bmatrix} 1 + Z_{21}^{12}/Z_L & Z_{21}^{12}/Z_L & \cdots & Z_{21}^{12}/Z_L \\ Z_{21}^{21}/Z_L & 1 + Z_{21}^{22}/Z_L & \cdots & Z_{21}^{22}/Z_L \\ \vdots & \vdots & \ddots & \vdots \\ Z_{21}^{N1}/Z_L & Z_{21}^{N2}/Z_L & \cdots & 1 + Z_{21}^{NN}/Z_L \end{bmatrix} \begin{bmatrix} V_1 \\ V_2 \\ \vdots \\ V_N \end{bmatrix}. $$  

(7)

In (7), $Z_{ij}$ are the conventional mutual impedances whose definition and calculation can be found, for example, in [2]. Instead of obtaining the uncoupled voltages $U_k$ on the antenna terminal load, the CMIM obtains the open-circuit voltages $V_{ok}$ which are assumed to be independent of mutual coupling.

In Fig. 2, we show the calculated receiving mutual impedance $Z_{ij}^{12}$ between two monopole antennas against their separation at a frequency of 2.4 GHz. The dimensions of the monopole antennas are: monopole length = 3 cm (0.24 λ at 2.4 GHz), radius of the monopole wires = 0.3 mm. Each monopole antenna is connected to a terminal load of $Z_L = 50$ Ω. The external plane wave source used to excite the array comes from the horizontal direction with $\theta = 90^\circ$ and $\phi = 0^\circ$. The conventional mutual impedances of these two antennas are shown in Fig. 3. Comparing Figs. 2 and 3, it can be seen that they are very different, though their variation trends are almost the same.
3 Examples of applications

A Direction-of-Arrival (DOA) Estimation

In Fig. 4, we use computer simulation to study a DOA estimation example of using a seven-element dipole antenna array for detecting two coherent signals coming from \( \phi_1 = 90^\circ \) and \( \phi_2 = 105^\circ \) using the conventional mutual impedance method (CMIM) and the receiving mutual impedance method (RMIM). It can be seen that using our new method (RMIM) produces a much better performance than the conventional method (CMIM).

In Fig. 5, we use an experimental method to study a DOA estimation example of using a seven-element monopole antenna array to detect two coherent signals at \( \phi_1 = 81.4^\circ \) and \( \phi_2 = 111.7^\circ \). The experiment was carried out inside an anechoic chamber and the received antenna voltages were measured by a vector network analyzer (VNA). Fig. 5 shows the results of the MUSIC spectra which were obtained with the mutual coupling in the received voltages \( V \) being compensated by different methods: (i) by using the receiving mutual impedance method (RMIM), (ii) by using the
conventional mutual mutual impedance method (CMIM), and (iii) no compensation at all (NC). It can be seen from the Fig. 5 that our new method (RMIM) performed more accurately than the CMIM and the NC cases.

B Adaptive Nulling

The signal environment for this example is shown in Table I. The SOI and interferences are plane waves linearly polarized in the $\hat{z}$ direction. This example has been studied before in [10]. From our study, the result of this example is shown in Fig. 6. Adaptive radiation patterns obtained by using four types of voltages have been shown in Fig. 6. The dash-line radiation pattern is the result obtained by using the measured voltages across the antenna terminal loads which have not been compensated for the mutual coupling effect. The dotted-line radiation pattern is the result obtained by using the open-circuit voltages derived by the method in [11]. The solid-line radiation pattern is the result obtained by using voltages corrected from the measured voltages by using the new method. The small graph inside Fig. 6 shows the radiation pattern obtained by using ideal voltages across the terminal loads which are completely free from any mutual coupling effect. Both the ideal voltages and the measured voltages are calculated by the moment method [12] with the current distribution on each antenna being expanded by 20 sinusoidal basis functions and using the Galerkin matching procedure. From Fig. 6, we see that the (un-compensated) measured voltages can hardly be used to suppress the interferences. The open-circuit voltages can be used to locate the three interferences but the dips are not deep enough. However, by using the compensated (corrected) voltages obtained by the new method, the dips generated at the interference directions are substantially deeper. For the ideal case, the dips are much deeper than all the other cases because this is a theoretically ideal situation in which the antenna elements are completely isolated from each other.

<table>
<thead>
<tr>
<th>TABLE I THE SIGNAL ENVIRONMENT FOR FIG. 6</th>
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<tbody>
<tr>
<td>Amplitude (V/m)</td>
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<tr>
<td>-----------------</td>
</tr>
<tr>
<td>Signal of interest</td>
</tr>
<tr>
<td>Interference #1</td>
</tr>
<tr>
<td>Interference #2</td>
</tr>
<tr>
<td>Interference #3</td>
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</tbody>
</table>

C MIMO Communications

We study the effect of change of monopole terminal loads on the MIMO channel capacity. Fig. 7 shows the variations of the average channel capacities and channel correlation coefficients $\rho_{11,12}$ with the monopole terminal load (resistive load) of a 2×2 MIMO system. The antennas are the prototype monopoles and connected to different terminal loads. Two cases of element separations are shown in Fig. 7, $d = 0.15\lambda$ and $0.5\lambda$, for both the transmitting and receiving arrays. The average SNR per receiving antenna is 20 dB in the capacity calculation.

It can be seen that the terminal load has a significant effect on the average channel capacity for the case $d = 0.15\lambda$. In this case, the maximum average channel capacity of about 5.3 bit/s/Hz is achieved when the terminal loads are about 14 $\Omega$, but not 50 $\Omega$. The reason is that in an array, the input impedances of the antenna elements are changed due to mutual coupling. It is found that in the transmitting array, the input impedance of the monopole is 31.5 +j16.0 $\Omega$ with a 50-$\Omega$ terminal load while the input impedance of an isolated same monopole is 42.5+j8.6 $\Omega$. There is a big difference between these two. When the terminal load is changed from 50 $\Omega$ to 14 $\Omega$, the input impedance becomes 26.8 +j24.0 $\Omega$. It shows that the matching condition is somewhat improved with a terminal load of 14 $\Omega$ and hence a greater average channel capacity is obtained. (The more exact reason is the change in the channel correlation as discussed further below.) For the case with element separation $d = 0.5\lambda$, the result shows that the average channel capacity changes very little.
with the terminal load, less than 1% from the value of 5.5 bit/s/Hz. It shows that the average channel capacity is rather sensitive to the change in the antenna terminal load for MIMO systems with compact antenna arrays, especially when the terminal loads are large. When looking further at the channel correlation coefficients $|\rho_{11,22}|$, the variation for the smaller element separation at $d = 0.15\lambda$ is again in the reverse direction as the average channel capacity. It reaches a minimum of 0.01 when the terminal load is about 14 Ω and increases to 0.54 when the terminal load is changed to 1000 Ω. Thus the change in the terminal load has a significant effect on the channel correlation coefficient for the compact array case. The reason is that terminal loads of the monopole elements affect the mutual coupling effect through changing the relative phases between the monopole elements which result in different element patterns and hence channel correlation is changed.

4 Conclusions

A new model for tackling mutual coupling in wireless communications is introduced. A new concept of receiving mutual impedance is introduced and explained. Application of the new method has been demonstrated in several arrays for direction finding, adaptive nulling, and MIMO communications.

Acknowledgements

This research was supported by the US ONR research fund under the project no. of “PR no. 09PR03332-01”.

References


