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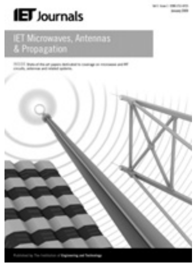

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Compensate for the coupled radiation patterns of compact transmitting antenna arrays

C.H. Niow[1] *Y.T. Yu*[1,2] *H.T. Hui*[1]

[1]*Department of Electrical and Computer Engineering, National University of Singapore, 4 Engineering Drive 3, Singapore 117576, Singapore*

[2]*College of Communication Engineering, Chongqing University, Chongqing 400044, People's Republic of China*

E-mail: hthui@itee.uq.edu.au

Abstract: An effective method is suggested to compensate for the mutual coupling in the coupled array patterns of compact antenna arrays. By using the mutual impedances of the antenna elements, the authors showed that it is possible to design compensation networks that can remove the distortion on array patterns due to the mutual coupling effect. The compensated array patterns enable us to predict the radiation characteristics of compact antenna arrays using the principle of pattern multiplication based on their ideal and isolated element patterns. Equations for the construction of such compensation networks are obtained and the realisation method is discussed. With these compensation networks, further conventional port-decoupling and matching circuits can be designed and connected to their inputs to achieve maximum power transfer from the source to the antenna array. Numerical examples on dipole and monopole arrays demonstrate the validity and accuracy of the method.

1 Introduction

Antenna mutual coupling has an adverse effect in many antenna array applications [1]. Mutual coupling effect limits the smallest separation that array elements can be placed and hence the array size. The development of the ever-decreasing size of electronic devices has attracted a lot of recent interest in the design of small-sized antenna arrays [2, 3], so-called compact antenna arrays. In compact antenna arrays, antenna mutual coupling has a significant effect on the array performance such as gain, bandwidth, impedance matching and the array beamwidth. It is well known that the beamforming function of a compact antenna array is particularly affected by the existence of strong antenna mutual coupling. Previously, decoupling methods [4–12] have been suggested to overcome the mutual coupling effect in antenna arrays. However, these methods were only considered for the decoupling of the mutual coupling effect in receiving arrays [4–9] or for decoupling the input ports of the feeding networks [10–12]. From a signal processing perspective, it is often more important to have spatially distinctive signals emanating uniquely from the individual antenna elements, that is, to have isolated element radiation patterns from an antenna array even if there is strong mutual coupling. This characteristic is crucial to many array signal-processing algorithms such as beamforming and beamsteering. Conventional port-decoupling methods cannot lead to the result of isolated element patterns but only achieve no coupling between the input ports and guarantee maximum power transfer between the source and the array. In this paper, we investigate and propose a simple method to compensate for the mutual coupling effect in transmitting compact antenna arrays so that the radiation patterns of the individual antenna element (the element patterns) effectively appear as isolated element patterns. We will show that for a transmitting compact array, it is sufficient to know the mutual impedances of the antenna elements in order to design a compensation feeding network that is able to restore the isolated element patterns from the coupled element patterns so that the total array radiation pattern can be predicted using the principle of pattern multiplication [13]. Our investigation shows that the mutual impedances (defined in the conventional method [14]) are the most critical parameters for the design of the compensation network. Once the mutual impedances are known, the compensation network is reduced to a simple circuit realisation problem that involves only a moderate modification of the original uncompensated feeding network of the array. The compensation network can further accommodate a matching or port-decoupling network and this eventually leads to a total decoupled feeding network with isolated and matched signal paths from the signal sources to the individual decoupled radiation patterns of the antenna elements. Once this method is implemented for a transmitting array, its array pattern can be easily calculated using the principle of pattern multiplication without the need to use complicated coupled element patterns. This greatly facilitates the use of antenna arrays as a signal processing tool. We will demonstrate this method with some typical numerical examples on array pattern calculations and beamforming performance of antenna arrays.

2 Compensation method

Consider a transmitting antenna array that consists of two closely spaced interacting antennas shown in Fig. 1*a*. Antenna #1 is excited by a voltage source (signal to be transmitted) V_{s1} and antenna #2 is excited by V_{s2}. The internal impedances of the two voltage sources are Z_{g1} and Z_{g2}, respectively. Accounting for the mutual coupling effect, the two antennas can be represented by their equivalent circuits shown in Fig. 1*b*, in which V_{12} and V_{21} are the coupled voltages at antenna #1 and antenna #2, respectively, and $Z_{\text{in}1}$ and $Z_{\text{in}2}$ are the input impedances looking from the antenna terminals into the antennas. The distortion of the radiation pattern of the array is caused by the coupled voltage sources V_{12} and V_{21}, which can be expressed using the mutual impedances Z_{12} and Z_{21} [14] of the array as

$$V_{12} = Z_{12}I_2 \tag{1a}$$

$$V_{21} = Z_{21}I_1 \tag{1b}$$

where I_1 and I_2 are the currents on antennas. Hence, to restore the isolated radiation patterns of the array, the coupled voltages V_{12} and V_{21} have to be offset (or compensated) from the feeding voltages to the antennas. That means the feeding circuits of the antennas have to be modified as shown in Fig. 2 with two controlled voltage sources added to the excitation voltages V_{s1} and V_{s2} in order to compensate the coupled voltages V_{12} and V_{21}. For the compensated array in Fig. 2, it is easy to obtain its radiation pattern and verify it to be same as that of an array with two completely isolated antennas. This will be demonstrated in Section 3 by numerical examples. For theoretical analysis, it is useful to obtain the net excitation voltages (the compensated voltages) to the antennas in Fig. 2. These compensated voltages are required in the design of a compensation feeding network. Let these be V'_{S1} and V'_{S2}, which can be expressed as

$$V'_{S1} = V_{S1} + V_{12} = V_{S1} + Z_{12}\frac{V_{S2}}{Z_{g2} + Z_{\text{in}\,2}} \tag{2a}$$

$$V'_{S2} = V_{S2} + V_{21} = V_{S2} + Z_{21}\frac{V_{S1}}{Z_{g1} + Z_{\text{in}\,1}} \tag{2b}$$

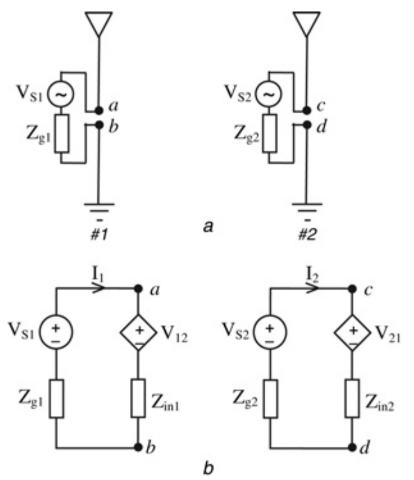

Fig. 1 *Typical transmitting antenna array*

a Transmitting antenna array consisted of two closely spaced antennas
b Equivalent circuits of the two antennas in Fig. 1*a*

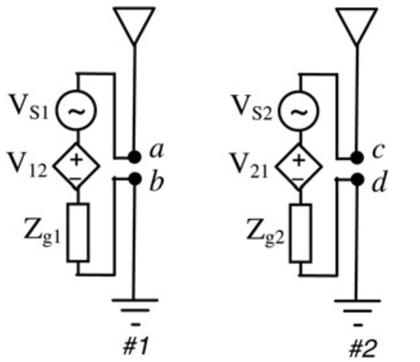

Fig. 2 *Decoupling feeding networks of the array in Fig. 1a*

and can be expressed in a matrix form as

$$\begin{bmatrix} V'_{S1} \\ V'_{S2} \end{bmatrix} = \begin{bmatrix} 1 & \dfrac{Z_{12}}{Z_{A2}} \\ \dfrac{Z_{21}}{Z_{A1}} & 1 \end{bmatrix} \begin{bmatrix} V_{S1} \\ V_{S2} \end{bmatrix} \tag{3}$$

where $Z_{A1} = Z_{g1} + Z_{\text{in}1}$ and $Z_{A2} = Z_{g2} + Z_{\text{in}2}$. Equation (3) means that if the antennas are excited with the compensated voltages V'_{S1} and V'_{S1} instead of the excitation voltages V_{S1} and V_{S2}, the two antenna elements will produce the isolated radiation patterns as if they were produced by the two excitation voltages V_{S1} and V_{S2} without the effect of mutual coupling. Such desirable results would mean that the radiation pattern of the array can now be predicted accurately by using the principle of pattern multiplication [13]. Practically, in order to feed the array using V'_{S1} and V'_{S2}, the compensation feeding network designed based on (3) can be connected between the original feeding sources V_{S1} and V_{S2} and the antenna terminals, as shown in Fig. 3. Looking from (3), the compensation feeding network designed based on Fig. 2 is independent of the excitation sources V_{S1} and V_{S2}. It only depends on the antenna array dimensions and the array configuration. The two-antenna array in (3) can be easily generalised to that of an *n*-antenna array which can be expressed as

$$\begin{bmatrix} V'_{S1} \\ V'_{S2} \\ \vdots \\ V'_{Sn} \end{bmatrix} = \begin{bmatrix} 1 & \dfrac{Z_{12}}{Z_{A2}} & \cdots & \dfrac{Z_{1n}}{Z_{An}} \\ \dfrac{Z_{21}}{Z_{A1}} & 1 & \cdots & \vdots \\ \vdots & \vdots & \ddots & \vdots \\ \dfrac{Z_{n1}}{Z_{An}} & \cdots & \cdots & 1 \end{bmatrix} \begin{bmatrix} V_{S1} \\ V_{S2} \\ \vdots \\ V_{Sn} \end{bmatrix} \tag{4}$$

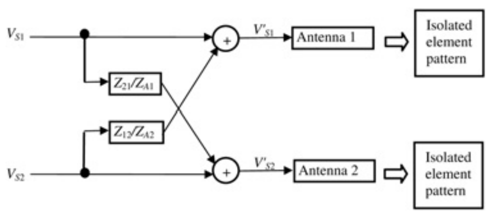

Fig. 3 *Compensation feeding network for a two-element transmitting antenna array*

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Although (4) is simple, it has not been explicitly derived before. This expression is important in the analysis of mutual coupling in transmitting antenna arrays and the design of array feeding networks. From (2), it is clear that the proposed compensation method can accommodate another matching circuit in the feeding network such as a conventional port-decoupling network. This can be accomplished by changing the impedances of $Z_{g1}, Z_{g2}, \ldots, Z_{gn}$ so as to match the antenna impedances $Z_{\text{in}1}, Z_{\text{in}2}, \ldots, Z_{\text{in}(n)}$. In the following section, we will demonstrate the validity and accuracy of this decoupling method by numerical examples based on computer simulations using FEKO [15].

3 Numerical results and discussions

3.1 Two-element dipole array

We first consider a two-element dipole array. The length of the dipoles is $\lambda/2$ (where λ is the wavelength corresponding to the operating frequency of the excitation sources) and their radius is 1/100 of their length. The antenna separation between the two dipoles is varied from 0.1λ to 0.5λ. The input impedances and the mutual impedances with the different antenna separations are calculated using FEKO [15]. The source internal impedances Z_{g1} and Z_{g2} are 50 Ω and the excitation voltage sources are set to $V_{s1} = 1$ V and $V_{s2} = 1\angle 135^\circ$ V. We first use (3) to calculate the compensation voltages V'_{s1} and V'_{s2} that will produce the isolated radiation patterns for the array. The results are shown in Table 1 with the antenna separation varying from 0.1λ to 0.5λ. It can be seen that the values of the compensation voltages are very different from the excitation voltages. Next, we obtain the array patterns excited by the compensation voltages for two cases with antenna separations at 0.2λ and 0.5λ. The results are shown in Figs. 4*a*–*e* (at a plane perpendicular to the dipole axes). The results are compared with array patterns obtained (i)

Table 1 Compensation voltages V'_{s1} and V'_{s2} of the two-element dipole array at different antenna separations

Antenna separation d (λ)	V'_{s1}, V	V'_{s2}, V
0.1	$0.723\angle 32.36^\circ$	$0.722\angle 102.85^\circ$
0.2	$0.959\angle 25.87^\circ$	$0.588\angle 121.2^\circ$
0.3	$1.121\angle 19.83^\circ$	$0.641\angle 141.75^\circ$
0.4	$1.231\angle 10.63^\circ$	$0.811\angle 150.65^\circ$
0.5	$1.272\angle 9.09^\circ$	$0.959\angle 150.25^\circ$

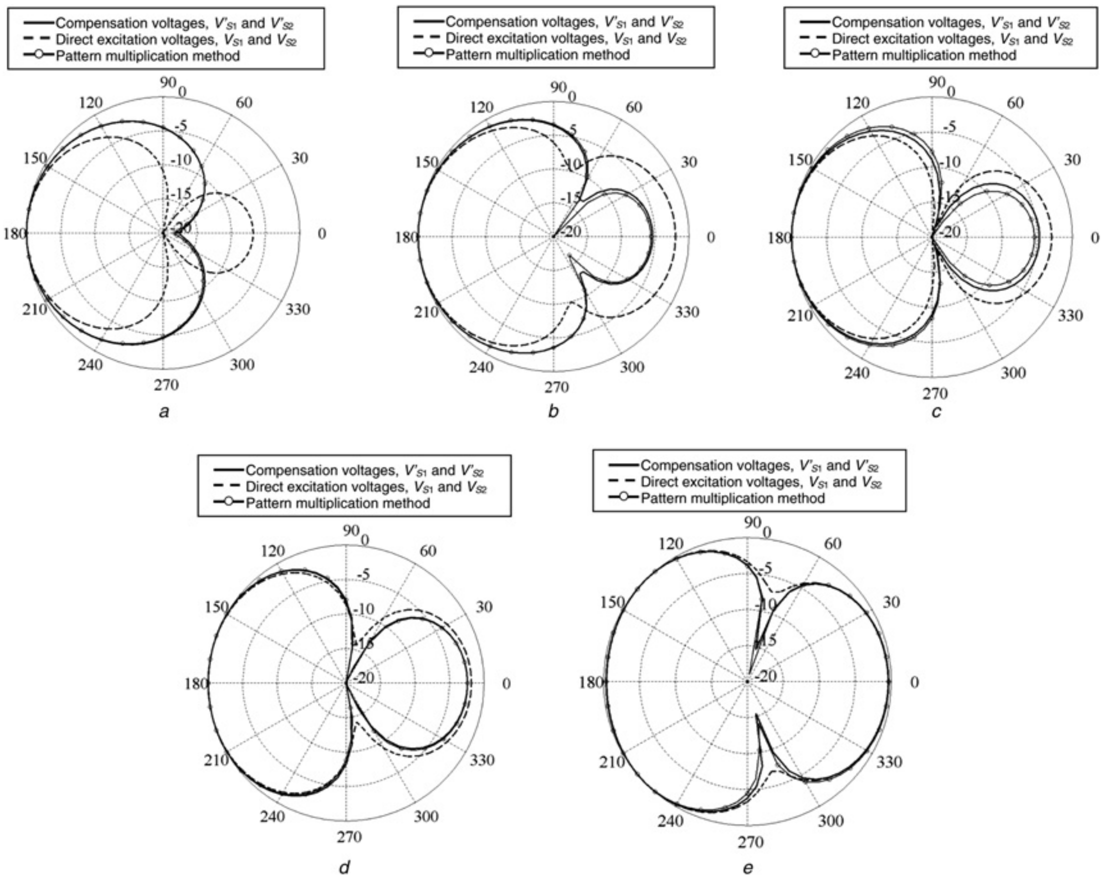

Fig. 4 *Array radiation patterns of the two-element dipole array with different element separations*

a Normalised array radiation patterns at d 0.1λ for the two-element dipole array obtained by different feeding voltages (radial scale in dB and angular scale in degree)
b Normalised array radiation patterns at $d = 0.2\lambda$ for the two-element dipole array obtained by different feeding voltages (radial scale in dB and angular scale in degree)
c Normalised array radiation patterns at $d = 0.3\lambda$ for the two-element dipole array obtained by different feeding voltages (radial scale in dB and angular scale in degree)
d Normalised array radiation patterns at $d = 0.4\lambda$ for the two-element dipole array obtained by different feeding voltages (radial scale in dB and angular scale in degree)
e Normalised array radiation patterns at $d = 0.5\lambda$ for the two-element dipole array obtained by different feeding voltages (radial scale in dB and angular scale in degree)

using the direct excitation voltages V_{s1} and V_{s2} and (ii) using the principle of pattern multiplication. From these figures, we can observe that the array patterns obtained using the compensation voltages are almost exactly the same as the array patterns obtained using the principle of pattern multiplication (the array factor). The main beam and the side lobes are also accurately restored using the compensation method. This indicates that our compensation method is valid and effective. We can also see the mutual coupling effect becomes stronger as the antenna separation is smaller. Also, the coupled array pattern in Fig. 4*e* with the antenna separation of 0.5λ is very similar to the decoupled pattern or the pattern obtained by the principle of pattern multiplication. This seems to suggest that the conventional practice of ignoring mutual coupling effect for arrays with element separations greater than or equal to half-wavelength is applicable.

3.2 Five-element dipole ULA

Next, we study a five-element dipole uniform linear array (ULA) using two different cases to demonstrate the effectiveness of our compensation method as shown in (4). Similar to the two-element dipole array, the length of the dipoles is $\lambda/2$ and their radius is 1/100 of their length. The source internal impedances Z_{g1} to Z_{g5} are 50 Ω. The antenna separation d and the beam angle φ are varied for two cases: $\varphi = 45^\circ$, $d = 0.5\lambda$ and $\varphi = 60^\circ$, $d = 0.3\lambda$. In Table 2, we calculate the compensation voltages of the dipole elements when the array main beam is formed towards two different directions at different antenna separations. The direct excitation voltages are shown in Table 3 for comparison. A comparison of Tables 2 and 3 shows that the mutual coupling effect is stronger at $d = 0.3\lambda$ as the differences between compensation and the direct excitation voltages are greater than those at $d = 0.5\lambda$. We have also calculated the compensated array patterns for the two cases as shown in Figs. 5*a* and *b*. They are compared with the array patterns obtained using the direct excitation voltages and the principle of pattern multiplication method. The uncompensated array pattern in Fig. 5*a* shows a slightly different beam direction instead of the desired direction of 45°. On the other hand, the compensated array pattern correctly restores the beam direction to 45° and is almost exactly the same as that predicted by the principle of pattern multiplication (the array factor).

Table 2 Compensation voltages of the five-element dipole array at different antenna separations and main-beam directions

	$\varphi = 45^\circ$, $d = 0.5\lambda$	$\varphi = 60^\circ$, $d = 0.3\lambda$
V'_{S1}	$0.821\angle 17.93^\circ$	$1.015\angle -17.87^\circ$
V'_{S2}	$1.105\angle -112.236^\circ$	$1.42\angle -69.66^\circ$
V'_{S3}	$1.153\angle 113.68^\circ$	$1.612\angle -125.51^\circ$
V'_{S4}	$1.14\angle -19.06^\circ$	$1.442\angle 173^\circ$
V'_{S5}	$1.189\angle -156.65^\circ$	$1.36\angle 138.27^\circ$

Table 3 Excitation voltages of the five-element dipole array at different antenna separations and main-beam directions

	$\varphi = 45^\circ$, $d = 0.5\lambda$	$\varphi = 60^\circ$, $d = 0.3\lambda$
V_{S1}	$1\angle 0^\circ$	$1\angle 0^\circ$
V_{S2}	$1\angle -127.28^\circ$	$1\angle -54^\circ$
V_{S3}	$1\angle -254.56^\circ$	$1\angle -108^\circ$
V_{S4}	$1\angle -381.84^\circ$	$1\angle -162^\circ$
V_{S5}	$1\angle -509.12^\circ$	$1\angle -216^\circ$

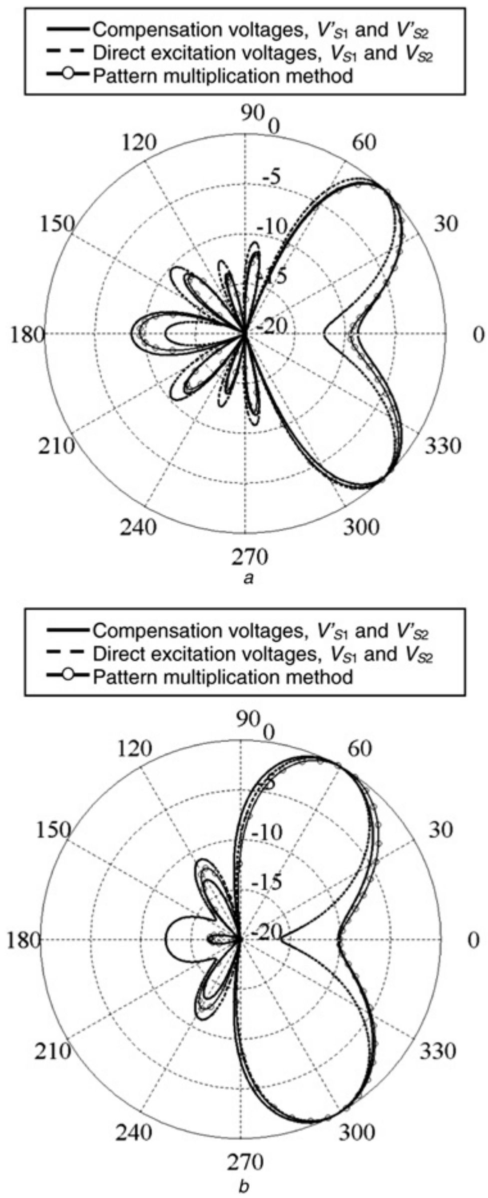

Fig. 5 *Array radiation patterns of the five-element dipole array with different element separations and main-beam directions*

a Normalised array radiation patterns for the five-element dipole array at $d = 0.5\lambda$ when the main-beam direction is excited at $\varphi = 45^\circ$ (radial scale in dB and angular scale in degree)
b Normalised array radiation patterns for the five-element dipole array at $d = 0.3\lambda$ when the main-beam direction is excited at $\varphi = 60^\circ$ (radial scale in dB and angular scale in degree)

3.3 Seven-element monopole ULA

Finally, we study an array with an even greater number of elements, a seven-element compact monopole ULA, for beamforming. The length of the monopoles is $\lambda/4$ and their radius is 1/100 of their length. The separation d between adjacent monopoles is 0.15λ. The monopoles are parallel to the z-axis and an infinite ground plane is at the xy-plane. In Table 4, we calculate the compensation voltages of the

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Table 4 Compensation voltages of the seven-element monopole array for forming different main-beam directions

	$\varphi = 0^\circ$	$\varphi = 30^\circ$	$\varphi = 60^\circ$	$\varphi = 90^\circ$
V'_{S1}	$1.088\angle-10.35^\circ$	$1.101\angle-11.29^\circ$	$1.169\angle-11.9^\circ$	$1.28\angle-6.99^\circ$
V'_{S2}	$1.332\angle-49.44^\circ$	$1.361\angle-45.48^\circ$	$1.53\angle-28.83^\circ$	$1.618\angle-4.9^\circ$
V'_{S3}	$1.421\angle-104.27^\circ$	$1.495\angle-90.87^\circ$	$1.626\angle-56.45^\circ$	$1.656\angle-11.2^\circ$
V'_{S4}	$1.551\angle-151.62^\circ$	$1.583\angle-133.99^\circ$	$1.638\angle-85.57^\circ$	$1.647\angle-12.74^\circ$
V'_{S5}	$1.487\angle154.06^\circ$	$1.587\angle176.55^\circ$	$1.702\angle-117.4^\circ$	$1.656\angle-11.2^\circ$
V'_{S6}	$1.676\angle95.42^\circ$	$1.751\angle127.84^\circ$	$1.767\angle-141.76^\circ$	$1.618\angle-4.9^\circ$
V'_{S7}	$1.606\angle48.53^\circ$	$1.654\angle85.43^\circ$	$1.419\angle-167.34^\circ$	$1.28\angle-6.99^\circ$

Table 5 Excitation voltages of the seven-element monopole array for forming different main-beaming directions

	$\varphi = 0^\circ$	$\varphi = 30^\circ$	$\varphi = 60^\circ$	$\varphi = 90^\circ$
V_{S1}	$1\angle0^\circ$	$1\angle0^\circ$	$1\angle0^\circ$	$1\angle0^\circ$
V_{S2}	$1\angle-54^\circ$	$1\angle-46.8^\circ$	$1\angle-27^\circ$	$1\angle0^\circ$
V_{S3}	$1\angle-108^\circ$	$1\angle-93.5^\circ$	$1\angle-54^\circ$	$1\angle0^\circ$
V_{S4}	$1\angle-162^\circ$	$1\angle-140.3^\circ$	$1\angle-81^\circ$	$1\angle0^\circ$
V_{S5}	$1\angle-216^\circ$	$1\angle-187.1^\circ$	$1\angle-108^\circ$	$1\angle0^\circ$
V_{S6}	$1\angle-270^\circ$	$1\angle-233.8^\circ$	$1\angle-135^\circ$	$1\angle0^\circ$
V_{S7}	$1\angle-324^\circ$	$1\angle-280.6^\circ$	$1\angle-162^\circ$	$1\angle0^\circ$

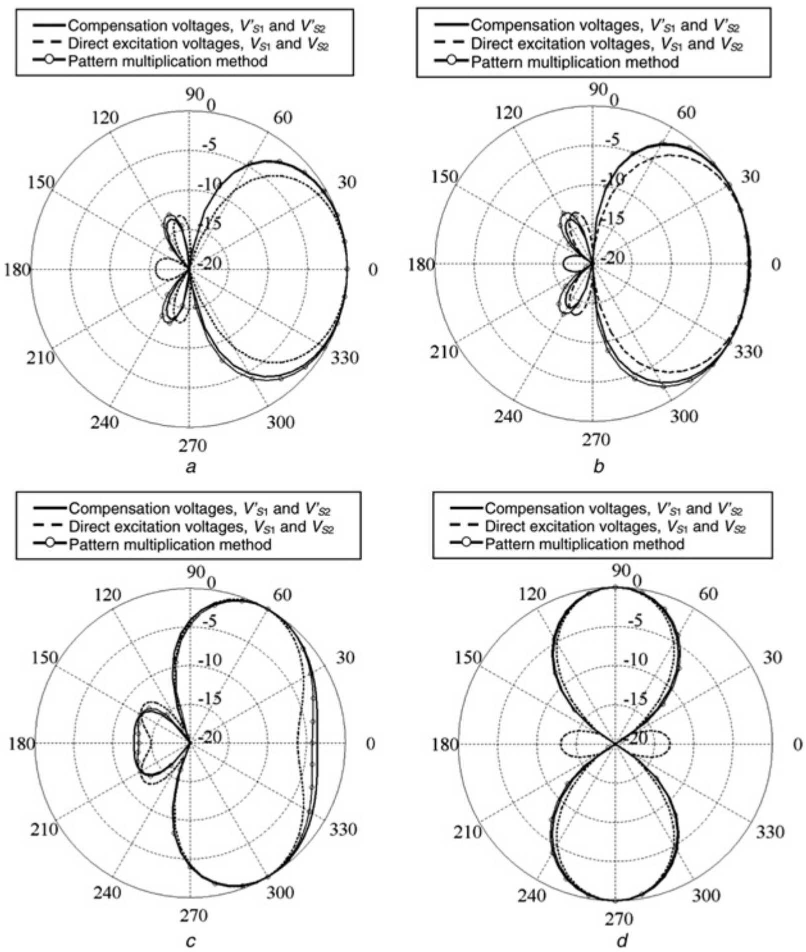

Fig. 6 *Array radiation patterns of the seven-element monopole array with different main-beam directions*

a Normalised array radiation patterns for the seven-element monopole array at $d = 0.15\lambda$ when the main-beam direction is excited at $\varphi = 0^\circ$
b Normalised array radiation patterns for the seven-element monopole array at $d = 0.15\lambda$ when the main-beam direction is excited at $\varphi = 30^\circ$
c Normalised array radiation patterns for the seven-element monopole array at $d = 0.15\lambda$ when the main-beam direction is excited at $\varphi = 60^\circ$
d Normalised array radiation patterns for the seven-element monopole array at $d = 0.15\lambda$ when the main-beam direction is excited at $\varphi = 90^\circ$

monopole elements when a single beam is formed towards four different directions. The direct excitation voltages are shown in Table 5 for comparison. A comparison of Tables 4 and 5 shows that the mutual coupling effect is very strong as the compensation and the direct excitation voltages are very different. We calculated the compensated array patterns for all the cases as shown in Figs. 6*a*–*d*. They are also compared with the array patterns obtained using the direct excitation voltages and the principle of pattern multiplication method. From these figures, it is clear that mutual coupling has a significant effect on the radiation patterns. However, comparing the array patterns for the seven-element array with those for the two-element array in Figs. 4*a* to *e*, it shows that mutual coupling seems to have a smaller effect on the array patterns for an array with a larger number of elements. Nevertheless, we observe from Figs. 6*a*–*d* that the array patterns obtained using the compensation voltages are almost exactly the same as the array patterns obtained using the principle of pattern multiplication (the array factor).

The above studies show the importance of compensation for the mutual coupling effect in array beamforming. Note that conventional port-decoupling methods cannot restore the coupled array patterns to their uncoupled or isolated array patterns which are used in the array beamforming algorithms.

4 Conclusions

We have investigated the problem of mutual coupling in transmitting compact antenna arrays and suggested an effective method to compensate for the mutual coupling in the coupled array patterns. By using the mutual impedances of the antenna elements, we showed that it is possible to design compensation networks that can remove the distortion on array patterns due to the mutual coupling effect. The compensated array patterns enable us to predict the radiation characteristics of compact antenna arrays using the principle of pattern multiplication based on their ideal and isolated element patterns. We have laid down the equations for the construction of such compensation networks. With these compensation networks, further conventional port-decoupling and matching circuits can be designed and connected to their inputs to achieve maximum power transfer from the source to the antennas. Numerical examples on the dipole and monopole arrays have demonstrated the validity and accuracy of the method.

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