Compensation of Mutual Coupling in Small Phased Array Antennas

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Abstract

A new technique to compensate for mutual coupling effect in small phased array antennas is presented. This method is a modification to classical approach for correcting the array output vector by multiplication a decoupling matrix to achieve a less unperturbed array response. Two different calculation methods of coupling coefficients between the array elements are presented. The performance is demonstrated by a simulation based on a numerical analysis with the Finite Element Method (FEM) and a practical application to digital beamforming (DBF) array.

Keywords: Phased Array, Mutual Coupling, Active Element Pattern,

1. Introduction

Phased array antennas are used with the intention to increase the efficiency and performance of communication systems. Even in mobile communications, phased arrays enable Space Division Multiple Access (SDMA) and increase the system capacity [1]. Besides fixed beam forming, adaptive or steered beam forming is applied to control the array radiation pattern [2]. In order to achieve high gain, low side lobe level, deep nulls or beam scanning in desired direction we should know the behavior of each element radiation in array, because there are mutual coupling effects among the elements. In other word, the radiation patterns of the elements of an array are different from their pattern when they are isolated. For many antennas, the Method of Moments (MOM) represents a suitable technique to compute the coupling between elements [3]. Due to resultant memory usage and computation time the analysis of a large array using a conventional MOM, is often impossible. For a large array where the total number of elements is much greater than the number of edge elements, it is reasonable to assume an infinite array to determine an array element factor that accounts for the effect of mutual coupling which is identical for all elements. In an infinite array, each element sees an identical environment, therefore the array element-factor which is called Embedded Element Pattern is defined as the radiated pattern obtained when one element is fed and all other elements terminated in match loads [4]. In small phased arrays, the mutual coupling between elements will be introduced by [5]: (i) distortion of active element pattern because each element sees a different environment (ii) active impedance variation and mismatch between elements and feed circuits. These variations will produce two major effects: (i) amplitude and phase of field radiated by array element will not be directly proportional to amplitude and phase of excitation of that element (ii) array pattern (Far Field) will not be calculated by product of array factor and element factor. Distortion of the radiation pattern usually exposes itself by increasing beamwidth, filling of nulls, raising side lobe level and changing direction of the main beam in beam scanning. However it is possible to remove mutual coupling effects by modifying excitation coefficient of each element. This compensation is performed by calculating of decoupling matrix and its multiplication to excitation
coefficients [6], [7]. In this paper a new method is introduced to obtain the pattern of the phased arrays, based on the method of Styskal [6] and use of active element pattern is efficient and successful the method. In order to validate the method, simulation results of a phased microstrip array is presented and discussed.

2. A linear phased array antenna in the presence of Mutual Coupling

We consider a linear phased array with single mode, meaning that the element aperture currents may change in amplitude but not in shape, as a function of radiation direction. In the presence of mutual coupling almost all array elements will have different radiation pattern [4]. Let \( g_n(u) \) is the radiation pattern of the \( n \)th element of the array when other array elements are not excited (where \( u = \sin \theta \)), thus each element sees different electromagnetic environment, mainly as a consequence of different position on the array antenna and mutual coupling between adjacent elements, so \( g_n(u) \) is called active element pattern [8]. Fig. 1. shows the geometry of active element pattern for a uniform N-element array. In receive mode, the incident field \( E_n \) at the element \( n \) impresses a current distribution \( a_n \) which is proportional to isolated element pattern \( f_n(u) \), so the active element pattern of element \( n \) can be modeled by the desired element pattern times a sum of direction from all other elements:

\[
g_n(u) = f_n(u) \sum_{m=1}^{N} c_{nm} e^{jkd_n u}
\]

Where \( d \) is element spacing, \( k = \frac{2\pi}{\lambda} \) is the wave number, \( u = \sin \theta \) and \( \theta \) denotes the angle from broadside. The \( C_{nm} \) represents the coefficients of coupling matrix \( C \) describing the magnitude of coupling between element \( n \) and \( m \). Thus compensation for the mutual coupling can be accomplished by simply multiplying the received array pattern \( G(u) = [g_1(u), g_2(u), ... , g_N(u)] \), by the inverse coupling matrix \( C^{-1} \), thus we can write the compensated (desired) array pattern as:

\[
F(u) = C^{-1} G(u)
\]

where \( F(u) = [f_1(u), f_2(u), ... , f_N(u)] \). Thus for compensation, we need first to obtain the coupling matrix \( C \), and then multiplying its inverse by active element pattern vector. The technique is applicable to linear array as well as planar array.

The matrix \( C^{-1} \) may be difficult or impractical to realize by an analog network, but it can be readily realized in digital beamforming antenna systems.

The active element pattern of edge elements is different from other elements, so if we terminate the edge elements with match loads (parasitic elements), it seems that the mutual coupling effect reduces considerably.

3. Determination of the Mutual Coupling Matrix

There are two methods to determine the coupling coefficients.

3.1 Fourier Transform Technique: The most popular technique to solve for the coefficients of the coupling matrix has been provided by [6]. In this method the \( C_{nm} \) are derived as Fourier decomposition of the measured active element pattern \( g_n(u) \), thus from (1):

\[
c_{nm} = \frac{d}{\lambda} \int_{-\frac{\lambda}{2d}}^{\frac{\lambda}{2d}} g_n(u) e^{-jkd_n u} du
\]
In order to do this, \( f_n(u) \) must not have a null in the integration interval, and other restriction on \( (3) \) is that the element spacing should be larger than \( \lambda/2 \), for closer spacing the domain of integration exceeds the visible region.

### 3.2 Scattering Matrix

Defining scattering matrix of array \( S \), an active element pattern \( g_n(u) \) of the \( n \)th element which is excited by a wave of amplitude 1 can be represented by the following equation:

\[
g_n(u) = f_n(u) \sum_{m=1}^{q} (\delta_{nm} + S_{nm}) e^{inudu}
\]  

(4)

where:

\[
\delta_{nm} = \begin{cases} 
1 & m = n \\
0 & m \neq n 
\end{cases}
\]

Comparing (4) with (1) shows that:

\[
C_{nm} = \delta_{nm} + S_{nm}
\]  

(5)

or equivalent matrix,

\[
C = I + S
\]  

(6)

Where \( I \) is the identity matrix. It is obvious that when feed lines between the element apertures and output terminals are not matched, this method should be modified, thus although the measurement of network parameters is easier than the pattern measurement, but the scattering method is less practical than the Fourier decomposition technique.

### 4. Simulation results

In this paper, the simulation results come from the a uniform linear phased array using High Frequency Structure Simulator (HFSS) software which is used for Finite Element Method (FEM) calculations. Figure 2 shows a 10-element coax-fed patch array with \( L_p = 17.1 \ mm \) and \( W_p = 20 \ mm \) operating at 5.03GHZ with a periodic spacing 0.475\( \lambda_0 \). For both the array and isolated element, the 0.125-inch thick RT/duriod substrate \( (\varepsilon_r = 2.33) \) extended 0.5\( \lambda_0 \) from patch edges. A ground plane are also considered. The feed position on patch element has been adjusted to exhibit a good impedance matching \( (Z = 49.1 + j0.4) \).

The coupling coefficients \( C_{nm} \) were then numerically evaluated according to \( (3) \) and the inverse matrix \( C^{-1} \) was computed. Fig. 3 shows the active element pattern of the edge and central elements.

![Figure 2. Top view of the array with periodic spacing of 0.475\( \lambda_0 \) used in this paper](image)

![Figure 3. Active element pattern of the edge (-) and the center element (--) of the 10-element array.](image)

In figure 4 and 5 synthesized 26-dB Chebyshev patterns obtained without and with the mutual coupling compensation in H and E planes are shown. For easier comparison, the ideal theoretical calculated radiation patterns are also shown. Comparison between figures 4 and 5 shows that the mutual coupling in the H-plane is smaller than the E-plane, hence to reduce the mutual coupling, it is better to locate the elements in arrange of the H-plane. As seen, the compensation corrects sidelobe level, and main beam direction corresponding to theoretical one. Figures 6 and 7 show the same 26-dB Chebyshev patterns scanned to 25°. By applying the same decoupling matrix, the compensation reduces sidelobe level to 10-dB and cause the pattern to get close to the ideal one and the compensation is scan independent. Figures 8 and 9...
shows the radiation pattern of array with terminated edge elements (parasitic elements), the results show that choosing parasitic elements at the edge of array reduces the mutual coupling considerably.

5. Conclusion

A technique to compensate for mutual coupling effect in small phased array was developed and verified by simulation. This technique is based on calculation of the coupling coefficients which are obtained by the Isolated and Active element pattern measurements. The technique is applicable to linear array as well as to planar array. The importance of this method is that the coupling matrix is scan independent and it can be readily implemented in a digital beamforming antenna system.
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References


Figure 9. Comparison of theoretical and simulated (without and with compensation) radiation patterns of 10-element array in H-plane with parasitic elements