EFFICIENT PRINTED ANTENNA ARRAY SYNTHESIS INCLUDING COUPLING EFFECTS USING EVOLUTIONARY GENETIC ALGORITHMS

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Abstract. This paper presents a novel technique for pattern synthesis of printed antenna arrays, which takes into account the effect of coupling among the radiating elements of the array. To this end, macromodels of the coupling among neighboring elements are generated using full-wave simulation data. The array analysis is then based on such coupling macromodels combined with full-wave radiation models of the individual radiating elements. The array synthesis is performed using a newly developed efficient optimization scheme based on an accelerated hybrid evolutionary genetic algorithm (GA). Numerical results are presented to illustrate the advantages of the proposed technique over conventional pattern synthesis methods.

I. INTRODUCTION

The design and optimization of large antenna arrays is a very challenging task due to the complexity of underlying electromagnetic effects. Conventional pattern synthesis techniques use prescribed element weighting such as Binominal, Chebyscheff, Taylor and Hansen distributions [1]-[2]. They are very easy to use due to the availability of a host of analytical formulas or algorithms. However, they are very limited in terms of the variety of patterns that can be synthesized or the range of radiation characteristics than can be achieved. Most importantly, even if the desired pattern can be synthesized, the performance of the fabricated array is likely to deviate from the specifications simply because the design process does not account for mutual coupling, which is crucial in achieving the prescribed side lobe or null levels.

For a realistic modeling of an array structure and to account for the coupling effects among the radiating elements, it is essential to perform a full-wave simulation of the entire structure. This is of course the ideal solution, but it is unfortunately also the least practical. Even using an integral formulation based on the method of moments (MoM), which is the most efficient for treatment of open boundary structures, the size of the numerical problem can easily turn formidable. A moment method solution of a 64-element array of simple patch antennas leads to more than ten thousand unknowns. Even if sufficient computer memory is available, the computation time of such problems are exhaustive and certainly not suitable for optimization purposes. This is especially true for pattern synthesis, where the solution space of the element excitations is usually colossal.

In this paper, we propose the use of full-wave simulation for the modeling of the coupling effects among the neighboring elements of an array. To this end, radiation macromodels are generated based on full-wave simulation data [3]. The macromodels correspond to the radiation patterns of individual radiating elements as primary radiators as well as the patterns of secondary radiating currents induced on the elements due to the coupling. For pattern synthesis using these full-wave macromodels, an efficient optimization scheme has recently been developed based on an accelerated hybrid evolutionary genetic algorithm. Using this novel technique, printed arrays as large as 10,000 elements have been optimized within less than half an hour on a personal computer. A detailed description of GA-based optimization scheme is presented in [4].

II. BACKGROUND ON ARRAY FACTOR APPROACH

In conventional synthesis techniques, the array factor is determined by the excitation and location of each element without accounting for mutual coupling between elements in the array. To incorporate the effect of coupling into the array factor, several approaches have been proposed in the past [1]-[2]. In effect, these techniques treat an N-element array as an N-port network. Due to coupling, each element in the array has a slightly different pattern, called the active element pattern, which is given by

$$f_{active,i} = f_{element} \times \left(1 + \sum_{\substack{j=1 \\ j \neq i}}^{N} S_{ji} \frac{g_j}{g_i} \right) \tag{1}$$

where $f_{active,i}$ is the active element pattern of the i^{th} element of the array. g_i is the phase difference between the center of element i and the center of an element located at the origin of the coordinate system assuming the usual far-field assumptions. S_{ji} are the scattering parameters of the N-port network. This technique can be implemented successfully if the active element patterns can be characterized experimentally using measured data. But it lacks versatility for modeling purposes. In an experimental context, one can excite each element individually and measure its coupling to other neighboring elements. However, computing the S parameters of the N-port array network using a full-wave simulator is not usually an easy task. Oftentimes the elements are interconnected through the feed network, and the S parameters of the N-port are directly influenced by this feed network.

III. FULL-WAVE COUPLING MACROMODELS

The generation of radiation macromodels based on full-wave simulation data is important for two reasons: (a) to obtain an accurate element pattern, and (b) to accurately account for the inter-element coupling. Here, we confine the coupling to neighboring elements even though the domain of coupling can easily be extended. In an array topology, each element is surrounded by a certain number of neighboring elements. Practical arrays usually have a structured and symmetric topology. A limited number of coupling mechanisms can easily be discerned. For example, in a uniformly spaced 2-D rectangular patch array, these include coupling along the radiating and non-radiating edges.

To the first-order approximation, the coupling from element i to element j can be attributed to a secondary perturbed current distribution induced on element j due to the presence of a primary current distribution on element i. The secondary perturbed current distribution in turn radiates a perturbed field $\mathbf{E}^{s}{}_{ji}(\theta, \phi)$ in the far radiation zone. The total field radiated by an individual element j is then given by

$$\mathbf{E}^{tot}{}_{j}(\theta,\phi) = \mathbf{E}^{p}{}_{jj}(\theta,\phi) + \sum_{\substack{i=1 \\ i \neq j}}^{N} \mathbf{E}^{s}{}_{jj}(\theta,\phi), \tag{2}$$

where $\mathbf{E}^{p}{}_{jj}(\theta, \phi)$ is the primary field radiated by element j. It is not difficult to generate full-wave macromodels for all the relevant secondary perturbed fields in an array. This can be done by considering unique pairs of neighboring elements and performing a full-wave simulation of the coupled structure using a numerical technique such as the method of moments (MoM). The total radiation pattern of the whole array is then the sum of all primary fields of the individual elements and all secondary fields radiated by each element due to coupling from the neighboring elements.

To illustrate the advantage of this approach for incorporating the coupling effects, let us consider a rectangular 2-D array of 4×4 square patches as shown in Figure 1. The substrate parameters are ε_r=2.57 and d=1.59mm and the size of the patch is 40.2mm with a resonant frequency of 2.28GHz. Just for the purpose of studying the coupling, we illuminate the array with a normally incident plane wave. Figure 2 shows the radiation pattern of the array for the θ–polarized field component at ϕ=90. This figure compares the results obtained by (a) a full-wave simulation of the entire array (FW) using MoM, (b) using the array factor approach ignoring the coupling (AF), and (c) using the radiation coupling macromodels as proposed in this paper. Note that the coupling macromodels are constructed from full-wave data but with only two coupled patches. As is seen, the macromodel approach is able to accurately predict the side lobe levels as well as the finite null levels, while the array factor approach predicts an actually zero null at a slightly different angle.

IV. PATTERN SYNTHSIS USING GA-BASED OPTIMIZERS

In recent years, genetic algorithms have attracted a great deal of attention due to their surprisingly superior performance [1]-[3]. In particular, when treating "stiff" problems with large parameter spaces like antenna arrays, these algorithms may provide the only possible solution to the optimization problem [5]-[7]. Genetic algorithms maintain a set of possible solutions called the population. Each generation of new solutions called children are created from the old solutions via genetic operators. These new solutions can either replace or coexist with the prior generation. The population evolves in this way until it finds an optimal solution.

The rate of convergence of a genetic algorithm depends on the quality of the genetic operators involved. Due to the continuous nature of the pattern synthesis problem, it would be logical to use continuous genes (evolutionary GA) rather than binary genes for encoding the solution. Therefore, instead of bit string operations, one can introduce evolutionary genetic operators based on a variety of mathematical operations. In addition, to further accelerate the rate of convergence of the GA, a novel genetic operator has been introduced in [4] based on Powell's method of conjugate directions. In this hybrid scheme, while the genetic algorithm provides the opportunity to converge toward a global minimum without getting trapped in local minima, the Powell operator accelerates the rate of convergence of the process through local minimization of the solution.

As an example, the hybrid evolutionary genetic algorithm was utilized to design a planar (two-dimensional) array of 256 (16x16) patch elements with the goal of achieving a maximum side lobe level of –50dB. The radiating elements are square patches of dimension 40.2cm printed on a grounded substrate of thickness 1.59mm and permittivity $\varepsilon_r = 2.57$. The spacing among the radiating elements is uniform along the x- and y-axes and equal to half free space wavelength. The optimization is performed at the resonant frequency of the patches, which is 2.28GHz. Figures 3 shows the synthesized pattern of the optimized 256-element array. As is seen, a maximum side lobe level of –50dB has been achieved. The entire optimization process takes 6 seconds on a 266MHz Pentium II personal computer.

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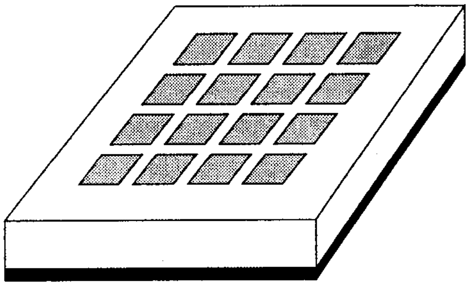

Figure 1: A planar 16-element patch array.

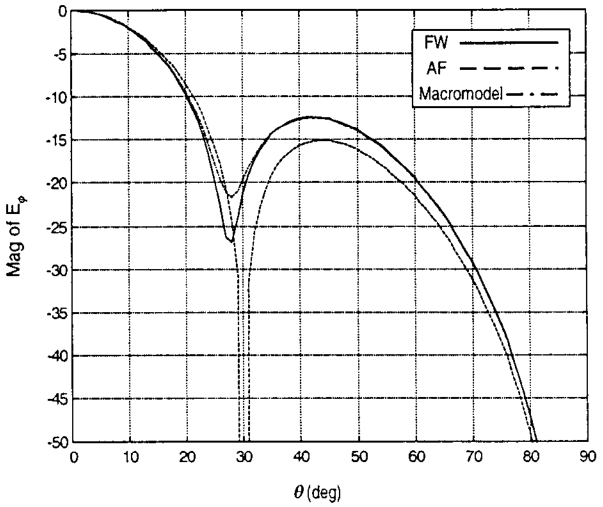

Figure 2: Radiation pattern of the patch array of Figure 1 (θ–polarized) at ϕ=90.

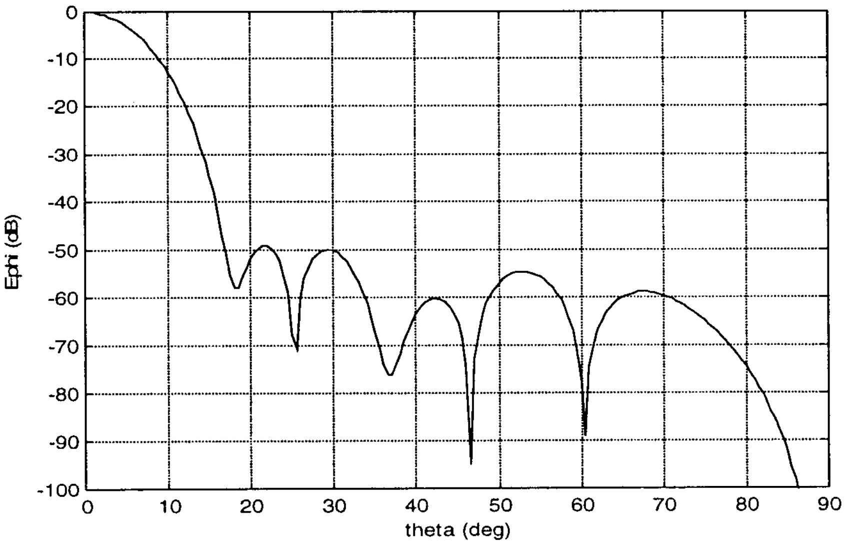

Figure 2: Radiation pattern of an optimized 256-element array (ϕ–polarized) at ϕ=0.