Design of Reconfigurable Array Antennas with Minimum Variation of Active Impedances

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ABSTRACT: In this letter, the authors propose an optimization method based on Genetic Algorithm (GA) to reconfigure a linear array of vertical half-wavelength dipole antennas to generate two patterns with minimum active impedance variation when the antenna switches from one pattern to other in the presence or absence of a ground plane behind the array. The problem is to find a fixed voltage amplitude distribution that will generate two broadsided symmetrical beams in the horizontal plane: a pencil beam with zero phases and a flat-top beam with phases in the range –180 to +180 degrees. Mutual coupling effect is taken into account via open circuit mutual impedance matrix.

Key words: Reconfigurable array, genetic algorithms, mutual coupling, dipole antennas.

1. INTRODUCTION

Reconfigurability of a single array antenna in radiating multiple radiation patterns with a fixed amplitude distribution and a variable phase distribution is desired in many applications. In general, the design of the circuitry feeding the array is simpler when the array is reconfigured from one pattern to other by only phase variation. Several methods of generating phase-only multiple pattern antenna arrays have been described in previous works [1-6].

F. Ares et al. [1], for example, reported the synthesis of phase-only multiple radiation patterns with pre-fixed amplitude distributions using modified Woodward-Lawson technique. Bucci et al. [2] proposed the method of projection to synthesize reconfigurable array antennas by phase-only control. The design of a phase differentiated reconfigurable array has been described using particle swarm optimization in theta domain [3]. Continuously controllable phase-only beam shaping with pre-fixed amplitude distributions was reported [4] using an analytical technique. F. Ares et al. [5] described phase differentiated multiple pattern antenna arrays based on simulated annealing optimization technique. Beam reconfiguration of linear arrays of parallel dipoles has been discussed [6] with the help of mechanical displacement of a parasitic array in front of an active one. Mutual coupling effect has been ignored in [1-5] and as a result, it leads to pattern error when such an effect is finally considered in a physical implementation of the antenna.

In this letter, we synthesize phase-only reconfigurable arrays –setting a common voltage amplitude distribution for obtaining two different power patterns– using real-coded genetic algorithms [7], including mutual coupling effect via self and mutual impedances of the elements [8]. In addition, minimization of the maximum variation of the active impedances of antennas in the presence or absence of a ground plane, when the antenna switches between patterns, is implemented using optimized voltage excitations without changing both the geometry of the elements and their spatial locations. Patterns are optimized in cosine space (cosine of far-field azimuthal angle) instead of angle space [3,5].

2. THEORETICAL FORMULATION

We consider a uniformly spaced linear array of N half-wavelength center-fed dipole antennas parallel to z-axis and laid down on positive x-axis as shown in fig.1, with inter-element distance of d.

All excitation voltage phases are kept fixed at 0^o to generate a pencil beam, and are varied in the range -180^o to 180^o to form a flat-top beam pattern [3]. Excitation voltage amplitudes are also varied in the range 0 to 1. Both excitation voltage amplitudes and phases are assumed symmetric with respect to the center of the array.

The far-field pattern $F(u)$ in the horizontal (xy) plane in the absence of any ground plane is given by eqn. (1). Element pattern has been assumed omnidirectional in the horizontal plane in the absence of ground plane.

$$F(u) = \sum_{n=1}^{N} I_n e^{j(n-1)kdu} \quad , \qquad (1)$$

Where n= the element number, $k = 2\pi/\lambda$=free-space wave number, λ= wavelength at the design frequency, I_n = complex excitation current of n-th element, obtained from $[I]_{N\times 1} = [Z]^{-1}_{N\times N}\,[V]_{N\times 1}$, being $[Z]$ the mutual impedance matrix (size NxN) and $[V]$ the voltage matrix (size Nx1) of the elements, j the imaginary unit, d is the inter-element spacing, and u=cosϕ, ϕ being the azimuthal angle of far-field measured from x-axis (0^o to 180^o).

The expressions related to self-impedances Z_{nn} and mutual impedances Z_{mn} in the mutual impedance matrix are taken from [8] and applied, the former being calculated specifically with C. T. Tai's formula.

When a ground plane is placed at $\lambda/4$ behind the array, and parallel to xz plane, to concentrate the radiation in only one hemisphere of the space, then the image principles [8] are to be applied to evaluate the self and mutual impedances of the elements so as to obtain the modified mutual impedance matrix of the array. The modified expression of the element factor is also obtained from [8].

The far-field pattern in the horizontal plane in this case is given by eqn. (2):

$$F(u)=\sum_{n=1}^{N}\left[2\sin\left(kh\sqrt{1-u^2}\right)\right]I_n e^{j(n-1)kdu} \quad (2)$$

Where $h=\lambda/4$=distance between ground plane and array and the bracketed term is the element factor.

The fitness function to be minimized for dual-beam array optimization problem is expressed as follows:

$$Fitness=\left(SLL_o-SLL_d\right)^2 H(S)+\left(RL_o-RL_d\right)^2 H(R)+\left|\Delta\,\mathrm{Re}[Z^A]\right|_{\max}+\left|\Delta\,\mathrm{Im}[Z^A]\right|_{\max} \quad (3)$$

Where SLL_o and SLL_d are obtained and desired values of side lobe level, RL_o and RL_d are obtained and desired values of ripple level of flat-top beam pattern, third and fourth terms in eqn. (3) are maximum variation of real and imaginary part of active impedances respectively, *H(S)* and *H(R)* are Heaviside step functions defined as follows:

$$\left[H(S),H(R)\right]=\begin{cases}1 \text{ when } \left(\mathrm{S,R}\right)\geq 0\\ 0 \text{ when } \left(\mathrm{S,R}\right)<0\end{cases} \quad (4)$$

$$S = SLL_o-SLL_d\ ,\ R = RL_o-RL_d \quad (5)$$

The active impedance of *n*-th element is defined as: $Z_n^A = V_n/I_n$, leading this to a corresponding $[Z^A]_{N\text{x}1}$ matrix (one column).

Maximum active impedance variation parameters are defined as the maximum variation of whether the real or imaginary part of the active impedance of any of the elements of the array when passing from one diagram to the other:

$$|\Delta\mathrm{Re}\ [Z^A]\ |_{\max} = \mathrm{Max}\ |\ \mathrm{Re}\ (Z_n^A)_{\text{flat-top}} - \mathrm{Re}(Z_n^A)_{\text{pencil}}\ | \quad (6)$$

$$|\Delta\mathrm{Im}\ [Z^A]\ |_{\max} = \mathrm{Max}\ |\ \mathrm{Im}(Z_n^A)_{\text{flat-top}} - \mathrm{Im}(Z_n^A)_{\text{pencil}}\ | \quad (7)$$

with n going from 1 to N. The lower the fitness, the more fit the array to the desired specifications. The desired maximum ripple level (RL) in the entire coverage region near zero dB ($-0.19 \leq u \leq 0.19$) is not to exceed 0.5 dB from the peak value of 0 dB. The difference terms in connection to side lobe level and ripple level in fitness function eqn. (3) are made zero when their respective calculated values are less than their desired values by multiplying appropriate Heaviside step function with these terms.

3. REAL-CODED GA OPTIMIZATION OVERVIEW

Genetic Algorithm is an iterative stochastic optimizer that works on the concept of survival of the fittest, motivated by Darwin, and using methods based on the mechanics of natural genetics and natural selection to construct search and optimization procedures that best satisfies a predefined goal. Real-coded GA uses floating-point number representation for the real variables and thus is free from binary encoding and decoding. The real-coded GA is summarized as follows:

Step 1: Randomly generate an initial population of M individuals within the variable constraint range.

Step 2: Evaluate the fitness of the population from the fitness function.

Step 3: Select the superior individuals using tournament selection [7] and place them in the mating pool. Number of individuals in the mating pool are same as M.

Step 4: Individuals so called parents placed in the mating pool are now allowed to breed followed by mutate using heuristic crossover and uniform mutation [7] respectively. In the crossover process, two parents produce two children. Subsequent mutations of the parents add diversity to the population and explore new areas of parameter search space.

Step 5: Repeat steps 2-4 until a stopping criterion, such as a sufficiently good solution being discovered or a maximum number of generations being completed, is satisfied. The best scoring individual in the population is taken as the final answer.

4. NUMERICAL RESULTS

We consider a linear array of 20 parallel center-fed dipole antennas of length $\lambda/2$ and radius 0.005λ, all parallel to *z*-axis and uniformly spaced $\lambda/2$ apart along *x* axis. Because of symmetry, only ten amplitudes and ten phases are to be optimized. All voltage phases are restricted to lie between -180 and 180 degrees, as mentioned before, and voltage amplitudes between 0 and 1.

For design specifications as given in Table 1 and Table 2, GA is run with an initial population of 80 and tournament selection of size two [7]. Crossover and mutation operators are called sixth times each in every generation in order to ensure that only six pairs of parents each participate in crossover and mutation instead of all. This will reduce the overall computational time in optimization considerably. Number of attempts in heuristic crossover is taken to be three.

In case of dual-beam pattern in absence of ground plane, results are shown in Table 1. There is a very good agreement between desired and obtained results using GA. It is interesting to note that the maximum variation of real and imaginary parts of active impedances of the antenna, when it switches between patterns, is found out to be very low i.e. 6.89 Ω and 8.80 Ω respectively. Corresponding voltage amplitude and phase distributions in degree are shown in Table 3. Fig. 2 shows normalized amplitude power patterns in dB for dual-beam array in absence of ground plane.

In case of dual-beam pattern in presence of a ground plane $\lambda/4$ behind the array, results are shown in Table 2. We understand that placing a ground plane behind the array increases the active impedances of the elements considerably but with our optimized voltage excitations values, the maximum variation of active impedances is reduced largely. Voltage amplitude distributions and phase distributions in degree are shown in Table 3. Fig. 3 shows normalized amplitude power patterns in dB for dual-beam array in presence of ground plane.

Coverage region for calculating ripple of flat-top beam is not mentioned in [3]. In our case, they are all clearly mentioned. Equally spacing pattern points in cosine space provide a more uniform sampling and less number of sampling points than angle space [3], which in turn reduces the complexity of optimization. This proposed design method is different from others [1-5] in the sense that the optimized voltage excitations not only take care of correct radiation patterns in presence of mutual coupling but also minimizes the maximum variation of active impedances of the elements.

5. CONCLUSIONS

We present a method based on real-coded genetic algorithm that optimizes voltage excitations of the elements for the design of a reconfigurable array antenna with or without the presence of a ground plane behind the array. This design method also minimizes the maximum variation of active impedances of the elements when the antenna switches between patterns without changing the geometry of the elements, and this minimization is more difficult to obtain when a ground plane is placed behind the array. Mutual coupling effect has also been taken into consideration. Results for a linear dipole antenna array have illustrated the performance of this proposed technique. The method in general can be applied to reconfigurable array antennas switching between some other types of patterns.

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Table1

Desired and obtained results in absence of ground plane

Design parameters	**Pencil beam**		**Flat-top beam**	
	Desired	**Obtained**	**Desired**	**Obtained**
Side lobe level (SLL, in dB)	-20.00	-21.49	-20.00	-21.06
Ripple (in dB, $-0.19 \leq u \leq 0.19$)	N/A	N/A	0.500	0.439
$\lvert\Delta \mathrm{Re}[Z^A]\rvert_{max}$= 6.89 Ω	$\lvert\Delta \mathrm{Im}[Z^A]\rvert_{max}$= 8.80 Ω			

Table2

Desired and obtained results in presence of ground plane $\lambda/4$ behind

Design parameters	**Pencil beam**		**Flat-top beam**	
	Desired	**Obtained**	**Desired**	**Obtained**
Side lobe level (SLL, in dB)	-20.00	-22.82	-20.00	-21.85
Ripple (in dB, $-0.19 \leq u \leq 0.19$)	N/A	N/A	0.500	0.610
$\lvert\Delta \mathrm{Re}[Z^A]\rvert_{max}$= 16.37 Ω	$\lvert\Delta \mathrm{Im}[Z^A]\rvert_{max}$= 18.82 Ω			

Table3

Amplitude and phase distributions in degree.
(*) For both pencil and flat top beams.
(**) For flat top beam. For pencil beam, they are equal to zero.

Element number	**Without ground plane**		**With ground plane**	
	Voltage amplitude (*)	**Voltage phase, in degree (**)**	**Voltage amplitude (*)**	**Voltage phase, in degree (**)**
1&20	0.1426	72.72	0.2162	-104.80
2&19	0.3113	98.78	0.1636	-125.78
3&18	0.2814	115.31	0.2448	-153.36
4&17	0.4316	173.74	0.4915	151.49
5&16	0.6876	-153.50	0.6316	126.94
6&15	0.8266	-143.50	0.8076	114.19
7&14	0.9185	-129.17	0.7573	91.69
8&13	0.7363	-87.48	0.6924	59.25
9&12	0.8739	-50.47	0.9472	29.08
10&11	0.9568	-38.26	0.9889	03.78

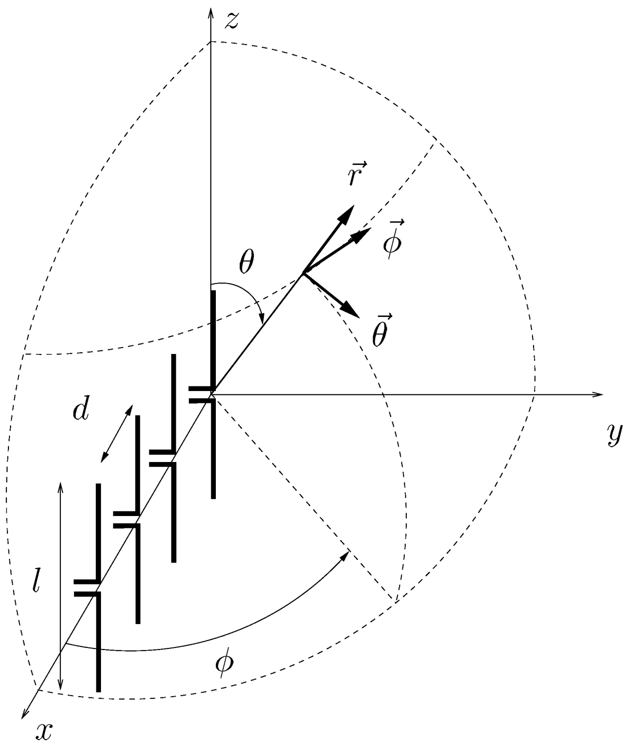

Figure 1. Geometry of a linear array of parallel dipoles along *x*-axis

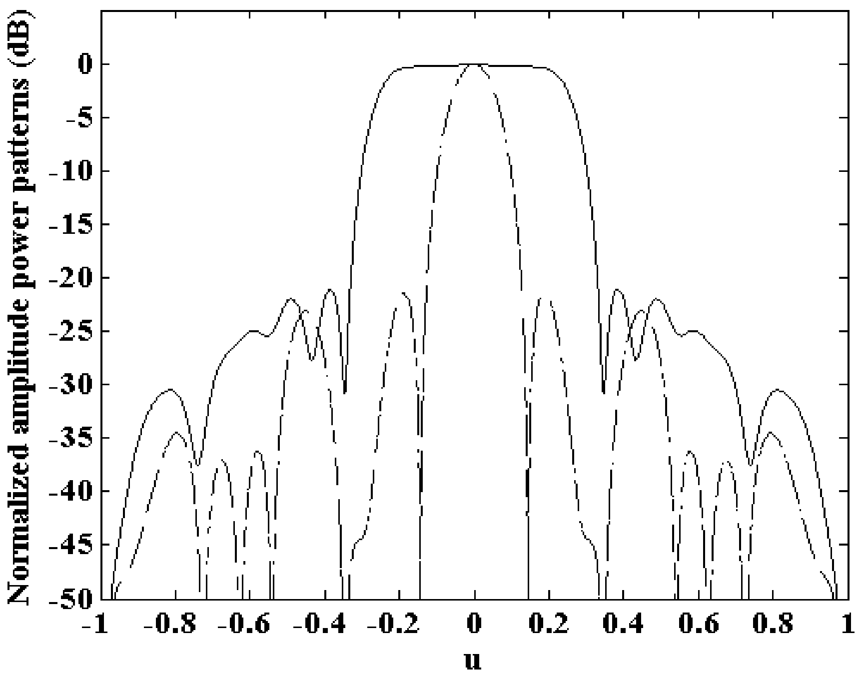

Figure 2. Normalized amplitude power patterns in dB for dual-beam array without ground plane. Dashed line, pencil beam pattern; solid line, flat-top beam pattern.

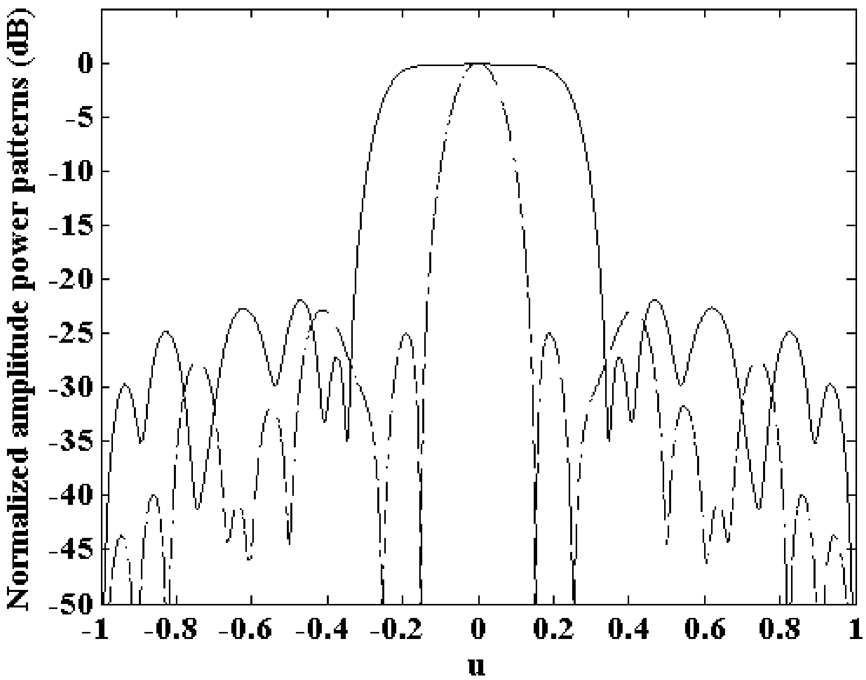

Figure 3. Normalized amplitude power patterns in dB for dual-beam array with ground plane placed $\lambda/4$ behind. Dashed line, pencil beam pattern; solid line, flat-top beam pattern.