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Discrete Phase-Only Synthesis of A Dual-Beam Collinear Dipole Antenna Array using Genetic Algorithms

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Abstract

In this paper, the authors propose a technique based on real-coded Genetic Algorithm (GA) for optimal design of reconfigurable dual-beam collinear half-wavelength dipole antenna arrays with phase-only control of discrete phase shifters. The problem is to find a common amplitude distribution that will generate a pencil beam with zero phases and a flat-top beam with discrete phases of a six-bit discrete phase shifter.

Key words: Dual-beam, reconfigurable arrays, genetic algorithms, phased array, dipole antennas, array synthesis.

1. Introduction

Reconfigurable array antennas capable of radiating multiple radiation patterns with fixed amplitudes and discrete phases are desirable in many applications. In general, the design and implementation of the feed network is much simpler if the element excitations corresponding to different patterns differ only in phase. Several methods of obtaining phase-only multiple pattern antenna arrays have been described [1-8].
Phase-only synthesis with pre-fixed amplitude distributions is presented [1] using modified Woodward-Lawson technique. Bucci et al. [2] proposed the method of projection to synthesize reconfigurable array antennas using common amplitude with continuously controllable phase shifters. The design of a phase-differentiated

reconfigurable array has been reported [3] using particle swarm optimization. Baskar et. al. [4] synthesized reconfigurable array antennas with phase-only control of 6-bit discrete as well as continuous phase shifter using generalized generation gap model genetic algorithm. Phase-only beam shaping with pre-fixed amplitude distribution is reported [5] using analytical technique.

Dobias et al. [6] synthesized reconfigurable array antennas with phase-only control of quantized phase shifters using a conventional alternating-projection method and better synthesis results were obtained, as compared to continuous phase excitations with subsequent quantization [2, 3]. F. Ares et al. [7] described two-pattern linear array antennas using 8-bit phase shifter, and the tolerance of the radiation patterns to errors in different antenna parameters was also investigated. Design of phase-differentiated multiple pattern antenna arrays [8] has been reported based on simulated annealing optimization technique.
All these methods [1-8] are meant for isotropic antennas and element pattern has not been included.

On the other hand, an evolutionary algorithm such as genetic algorithm (GA) is a global iterative optimizer that performs population-based probabilistic searches with an ability to escape from local optima.

In this paper, optimization formulation using real-coded GA is employed for the design of a reconfigurable dual-beam collinear half-wavelength dipole antenna array with a 6-bit discrete phase shifter. Patterns are optimized in cosine space (cosine of far-field angle) instead of angle space [3,4]. The optimized phase excitations obtained by this method can be directly implemented without further quantization.

2. Problem Formulation

The design of reconfigurable dual-beam array antennas involves finding a common amplitude distribution that can generate either a pencil or a flat-top beam power pattern, when the phase distribution of the array is modified appropriately. All the excitation phases are set at 0^o to generate a pencil beam and are varied in the range $-180^o \le \phi \le 180^o$ in step of $\frac{360^o}{2^6}$ or 5.625^o of a 6-bit discrete phase shifter to form a flat-top beam.

We consider a collinear array of 2N number of identical half-wavelength dipole antennas, which are assumed uncoupled, symmetrically and equally spaced a distance d apart (center to center) along the Z-axis with its center at the origin. Assuming sinusoidal current distribution of a very thin half-wavelength dipole antenna directed along Z-axis, the element pattern in cosine space (u) is given by eqn. (1):

$$\mathrm{Elepat}(u) = \frac{\cos(0.5\pi u)}{\sqrt{1-u^2}} \tag{1}$$

The free space far-field pattern F (u) in the principal plane (YZ plane) after considering the element pattern with symmetric amplitude and phase distributions is given by eqn. (2):

$$F(u) = 2\sum_{n=1}^{N} I_n \cos[(n-0.5)kdu]e^{j\phi_n} \times \mathrm{Elepat}(u) \tag{2}$$

$$\text{Normalized absolute far-field, } F_n(u) = \frac{|F(u)|}{|F(u)|_{max.}} \tag{3}$$

Where I_n=excitation amplitude, ϕ_n=excitation phase, n=element number, $k=2\pi/\lambda$, being wave number, λ=wavelength, $u=\cos\theta$, θ being polar angle of the far-field point measured from end fire (0^o to 180^o).

For the dual-beam array optimization, the fitness function must quantify the entire array radiation pattern. The fitness function to be minimized for dual-beam array optimization problem can be expressed as follows:

$$\text{Fitness} = \sum_{i=1}^{3}(Q_{i,d}^{(p)} - Q_i^{(p)})^2 + \sum_{i=1}^{4}(Q_{i,d}^{(s)} - Q_i^{(s)})^2 \tag{4}$$

Where the superscript p indicates the design specification for the pencil beam and the superscript s indicates the design specification for the flat-top beam as given in Table1. The subscript d represents the desired value of each design specification. Q_i represents the calculated value of each design specifications. The lower the fitness, the more fit the array to the desired specifications. Acceptable side lobe level (SLL) and ripple should be equal to or less than the desired value. These two terms in eqn. (4) vanish if they are less than their respective desired value by multiplying appropriate Heaviside step function with these terms. The desired maximum ripple level (RL) of flat-top beam in the entire coverage region near zero dB ($|u| \leq 0.2$) is not allowed to exceed 0.5 dB from the peak value of 0 dB.

3. Real-Coded Ga Optimization Overview

Genetic Algorithm is an iterative global optimizer that mimics the theories of evolution motivated by Darwin and works on the concept of survival of the fittest using methods analogous to genetic recombination and mutation to promote the evolution of a population 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. Hence, it is faster than binary GA. 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 [9] 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 arithmetic crossover and uniform mutation [9] 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: Score all individuals again. The best-scoring M numbers of individuals survive to the next generation.

Step 6: Repeat steps 2-5 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.

3.1 Tournament Selection

Tournament Selection combines the idea of ranking in a very interesting and efficient way. This method in a single generation selects some k no. of individuals and selects the best one from this set of ‘k’ individuals into the next generation.

This process is repeated population-size number of times. It is clear, that large values of k increase selective pressure of this procedure; typical value accepted by many applications is k = 2, so called tournament size.

3.2. Arithmetic Crossover

It produces two complimentary linear combinations of the parents (I^A and I^B) chosen at random, and it is given below:

$$I^{A(new)} = r\, I^A + (1-r)\, I^B \tag{5}$$

$$I^{B(new)} = (1-r)\, I^A + r\, I^B \tag{6}$$

Where r is a uniform random number U (0,1)

3.3 Uniform Mutation

Mutation operator is responsible for the fine-tuning capabilities of the system so that it can jump out of local optima. It randomly selects one variable of a parent and sets it equal to a uniform random number U (a_k, b_k). In a similar way, mutation is applied to all the parents.

It is defined as follows: For a parent I^A, if any variable I_k^A is mutated, the result is:

$$\bar{I}^A = \left(I_1^A, \ldots\ldots\ldots, \bar{I}_k^A, \ldots\ldots\ldots\ldots\, I_N^A\right), \tag{7}$$

Where $\bar{I}_k^A = U(a_k, b_k)$; a_k, b_k are lower and upper bounds of I_k^A respectively.

4. Results

We consider a collinear array of 20 half-wavelength Z-directed identical dipole antennas laid down on Z-axis spaced 0.6λ apart in order to generate a pencil beam and a flat-top beam with optimized common amplitude distribution and discrete phases of a 6-bit discrete phase shifter.

Because of symmetry, only ten amplitudes and ten phases are to be optimized. For convenience, the genetic algorithm is designed to provide vectors of 20 real values between zero and one. Each 20-element vector is mapped to 10 amplitude and 10 phase weights, where the first 10 values from the vector are scaled to desired amplitude weight range and the second 10 values are scaled to desired phase weight range.

For design specifications as given in Table1, GA is run independently ten times, each time with different random number but fixed 850 generations with an initial population of 200.Best run having the lowest fitness value is taken as final. At each generation, 100 pairs of parents are chosen by tournament, where each parent is selected as the better of two randomly chosen individuals. Crossover and mutation operators are called fourth and sixth times every generation respectively in order to ensure that only four pairs of parents take part in crossover and six numbers of parents take part in mutation in stead of all. This will reduce the overall computational time in optimization considerably. Of the total individuals, the best-scoring 200 numbers of individuals survive to the next generation. All phases are restricted to lie between -180 and 180 degree and amplitudes between 0 and 1. Dynamic range ratio ($|I_{max}/I_{min}|$) of amplitude distribution is found to be 7.36.Final fitness value is found to be 0.0002. Simulated results using GA are also shown in Table1.There is a very good agreement between desired and obtained results using GA**.**

In our design, phases are not required to generate pencil beam compared to [1,2] where it is required. Moreover, [2] results in all asymmetrical pattern, amplitude and phase distributions that complicate the feed network further. Coverage region near zero dB for calculating ripple of flat-top beam as well as how ripple is measured, are not mentioned in [3,4]. In our synthesis, they are all clearly mentioned. Moreover, in our methods, element pattern has been taken into consideration in the optimization.

Table 1: Desired and obtained results for dual-beam collinear dipole antenna arrays

Design parameters	Pencil beam		Flat-top beam	
	Desired	Obtained	Desired	Obtained
Side lobe level (SLL)	-25dB	-26.54dB	-25dB	-25.13dB
Half-power beamwidth (HPBW)	0.10	0.102	0.48	0.472
Beamwidth at SLL	0.24	0.246	0.66	0.67
Ripple ($-0.2 \leq u \leq 0.2$)	N/A	N/A	0.5dB	0.5dB

Figure1 shows the normalized absolute power patterns in dB for dual-beam collinear dipole antenna arrays. Corresponding common amplitude and 6-bit discrete phase distributions in degree are shown in Figure2.

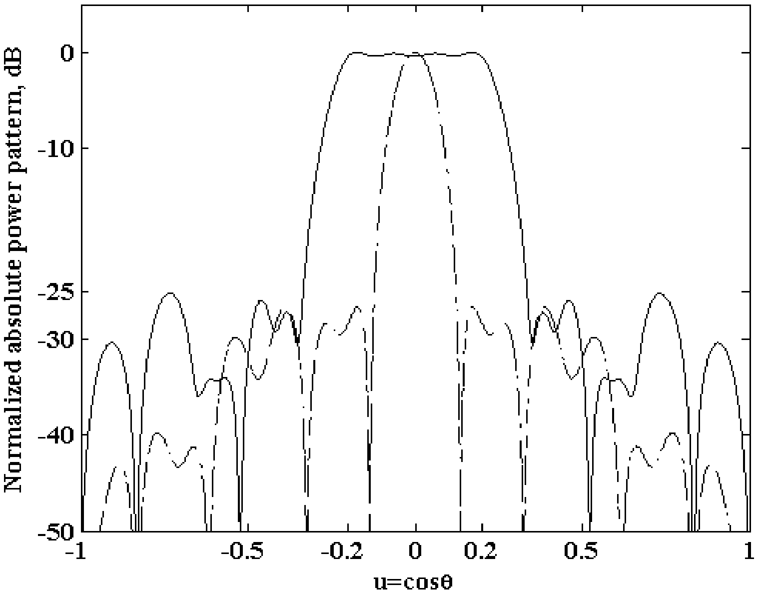

Figure 1: Normalized absolute power patterns in dB for reconfigurable collinear dipole antenna arrays

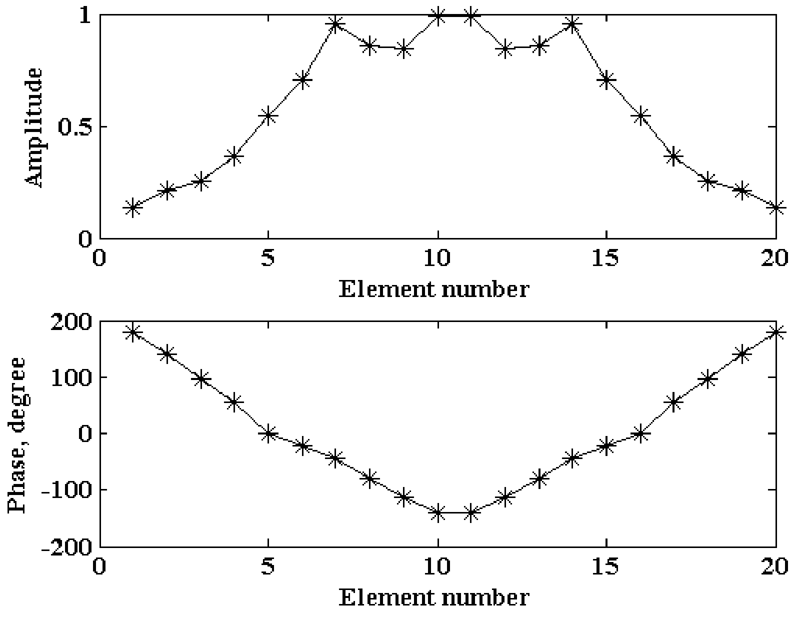

Figure 2: Excitation amplitude and 6-bit discrete phase distributions in degree

5. Conclusions

The method presented here takes element pattern and discrete phases directly into account during synthesis. This leads to better synthesis results, compared to conventional methods where phases are subsequently quantized [3,4].

Moreover, in a reconfigurable antenna array [3,4], if element pattern is multiplied after optimizing it for isotropic antennas, it is bound to change the radiation pattern, specially the side lobe level and ripple of flat-top beam, even in the absence of mutual coupling. Equally spacing pattern points in cosine space provide a more uniform sampling and less number of sampling points than angle space [3,4], which in turn reduces the complexity of optimization.

Results clearly show a very good agreement between desired and GA synthesized pattern even with a 6-bit discrete phase shifter instead of a continuous phase shifter [3]. The patterns, amplitude and phase distributions are all symmetric in nature that greatly simplifies the feed network. Moreover, for practical applications, the design of reconfigurable antenna arrays with fixed amplitude and quantized phases is preferred in order to keep costs low, make control simple and maintain accuracy. This design method can be used directly in practice to synthesize reconfigurable collinear dipole antenna arrays with phase-only control of discrete phase shifters. Results for a collinear dipole antenna array have illustrated the performance of this proposed technique.

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