Antenna Array Optimization using Evolutionary Approaches

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Antenna designers are constantly challenged with the temptation to search for optimum solutions for the design of complex electromagnetic devices. The ability of using numerical methods to accurately and efficiently characterizing the relative quality of a particular design has excited the engineers to apply stochastic global evolutionary optimizers (EO) for this objective. EO techniques have been applied with growing applications to the design of complex electromagnetic systems. Among various EO techniques, Genetic Algorithms (GA) and Particle Swarm Optimization (PSO) have attracted considerable attention and shown superior performance. These schemes are finding popularity in electromagnetics as design tools and problem solvers because of their flexibility, versatility and ability to optimize in complex multimodal search spaces. This paper discusses the design optimization of antenna arrays with special emphasis on evolutionary optimization techniques.

Keywords: Antenna Arrays, Evolutionary Approaches

1. Introduction

In many communication systems, one is interested in point to point communication and for this, a highly directive beam of radiation is required. By arranging several dipoles (or other elementary radiators) in the form of an array, a directive beam of radiation can be obtained [1]. Consider a linear array of n isotropic elements of equal amplitude and separated by distance d as shown in Fig. 1 [2]. The total field E at a far field point P in the given direction ϕ is given by,

$$E = 1 + e^{j\psi} + e^{j2\psi} + e^{j3\psi} + \ldots\ldots\ldots\ldots\ldots + e^{j(n-1)\psi} \tag{1}$$

where Ψ is the total phase difference of the fields from adjacent sources. It is given by;

$$\psi = 2\pi(d/\lambda)*\cos\phi + \alpha \tag{2}$$

where α is the phase difference between the feed currents of adjacent sources i.e. source 2 w.r.t source 1 and source 3 w.r.t. source 2… and so on. The point P is considered very far away from the sources, thus the angle ϕ that it makes with x-axis as shown in Fig. 1, will be same for all the sources. The amplitudes of fields from the sources are all equal and taken as unity. Source 1 is the phase reference. In an array of identical elements, there are five controls that can be used to shape the overall pattern of the antenna array [3]. These are:

a. the geometrical configuration of overall array (linear, circular, rectangular, spherical etc.)
b. the relative displacement between the elements
c. the excitation amplitude of individual elements
d. the excitation phase of individual elements
e. the relative pattern of individual elements

In case of linear phased arrays, elements are equally spaced at $\lambda/2$ distance; whereas in sparse array this condition is not met i.e. the sparse antenna arrays are those in which elements are not equally spaced. Sparse arrays are very economical because by reducing the number of array elements, cost & complexity is reduced considerably. Thus these arrays are of wide practical interest.

Sparse arrays are able to produce high quality images and this leads to several interesting applications. By reducing the number of array elements by a factor of four or more, the cost and complexity of commercial clinical scanner (ultrasound scanner) can be reduced. Image quality will remain the same if the transmit power is increased in order to compensate for the few transmit and receive elements [4].

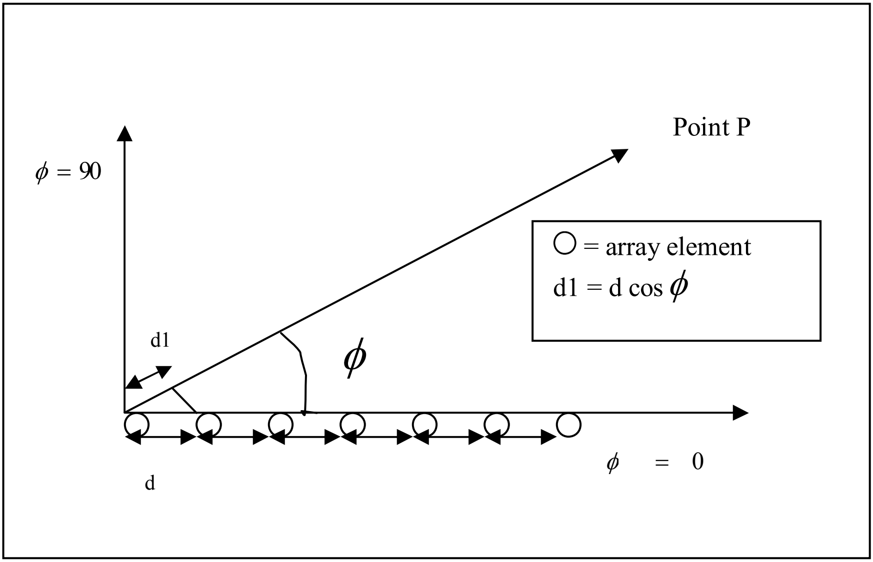

Figure 1: Geometry of a linear array of *n* isotropic elements of equal amplitude and separated by distance *d*.

Antenna array processing also finds its use in complex random environment in mobile communication [5]. The received signal is a multipath signal and for a noise limited system, it is important to absorb all the energy. If the channel power transfers from all the elements to all the elements are known, then it is possible to maximize the total transfer power by jointly adjusting the antenna weights in the arrays. Another thing is the possibility for two arrays, in a scattering environment, to create parallel channels, and thus, in effect, act as many independent antennas at the same time, carrying much more traffic over the same bandwidth. Array of antennas can be mounted on vehicles, ships, aircraft, and satellite and base stations to fulfill the increased channel requirement for these services [6].

Sparse or aperiodic arrays also find their use in radar applications. In radar, usually parabolic reflectors were employed earlier to develop directive beam antennas based on the geometrical properties of reflectors. Depending upon the requirement, various technologies have been employed, such as paraboloidal cylinders, paraboloids, offset focus paraboloids, and various types of lenses. One of the difficulties with these antennas has been their three dimensional structure, which is quite large. Antenna arrays provide the alternative solution to this problem and has the ability of reducing the antenna dimensions to 1 or 2D [7]. Such structures are called as linear or planar array radars. The resonant nature of these antennas makes them rather narrowband, and usually less than 10 % bandwidth is achieved. The lower the frequency, the more difficult it is to design antennas with sufficient bandwidth, actually, this narrow beam becomes useful for some applications such as radar.

In case of direction finding applications, a completely occupied array will deliver a huge main lobe and also side lobe of considerable strength which is against the main goal of side lobe suppression. Thus the problem of optimal antenna geometry arises for such systems and applications. Using a non uniform excitation of the array elements can decrease the side lobe level. Low side lobes are of interest for several reasons: reduction of radar and communication intercept probability, reduction of radar clutter and jammer vulnerability. For example, arrays with this characteristic can be used in satellite transmissions.

The Direction of Arrival (DOA) estimation accuracy is critically dependent on the array size as large arrays can provide very accurate estimates. DOA estimation with arrays with many elements is, however, expensive to implement, both in terms of receiver hardware and computational complexity. For non ambiguous DOA estimation with uniform linear arrays, the inter element spacing should not exceed half a wavelength. In sparse arrays, elements are spaced further apart in order to obtain a large aperture with few elements. Sparse arrays thus have the potential of very accurate DOA estimation at low cost. This is because of high side-lobe suppression and the very narrowband main beam.

The two main EO techniques for antenna array optimization i.e. GA and PSO. The genetic algorithm invented by Holland is a search procedure that uses random selection for optimization of a function by means of parameters spaced coding. Genetic algorithms are different from more normal optimization and search procedures in the four ways [8].

1) Genetic algorithms work with a coding of parameter set, not the parameters themselves.
2) Genetic algorithm search from a population of points, not a single point.
3) Genetic algorithms use objective function information, not any derivative or auxiliary information.
4) Genetic algorithms use probabilistic transition rules, not deterministic rules.

The genetic algorithms find their application in various engineering problems like electromagnetic field theory, antenna arrays, VLSI circuit partitioning and many more.

Eberhert and Kennedy [9] have given the PSO algorithm, which is based on the intelligence and co operation of group of birds or fish schooling. It maintains a swarm of particles where each particle represents a potential solution. In PSO algorithm particles are flown through a multidimensional search space, where the position of each particle is adjusted according to its own experience and that of its neighbors. PSO has been found to outperform GA in some instances [10].

2. Optimization Techniques for Antenna Arrays

Arrays with fewer elements than required by λ/2 condition are called sparse arrays. Grating lobes in the radiation pattern of a sparse array can be reduced by eliminating the periodicity of the array. Many researchers have investigated the design of sparse 1D arrays that use non-random spacing between elements [11-14]. However, Steinberg [15] has shown that these algorithms produce sparse arrays that are no better, and often worse, in terms of average secondary side lobe level, than sparse arrays with randomly selected elements. G.R. Lockwood [4] has given the concept of effective aperture for designing sparse periodic linear antenna array. There is a similarity between the far field radiation pattern of equally spaced elements & frequency response of FIR filters. This similarity leads to the concept of effective aperture, which is very useful in designing sparse antenna arrays. The effective aperture is given by the convolution of transmit aperture and receive aperture functions.

In time frequency array processing, a filter is characterized by values of its impulse response *h(n)*, spaced regularly with a time *T* between samples. A linear shift-invariant filter is also characterized by its frequency response.

$$H(\omega) = \sum_{m=0}^{M-1} h(n) e^{-jm\omega T} \tag{3}$$

In order to avoid ambiguity, the relationship between angular frequency ω and time T should be $\omega T < \pi$ or $f_s > 2\,f_{max}$. Now, the far field radiation pattern at an angle θ normal to the array is given by,

$$P(u) = \sum_{n=0}^{N} w[n] e^{j[2\pi(u/\lambda)d]n} \tag{4}$$

where $u = Sin(\theta)$ and $\theta = 90 - \Phi$

Thus the function $P(u)$ can be considered as the DFT of $w[n]$ with frequency variable given by $2\pi(u/\lambda)d$. The array element weighing as a function of the element position is called the aperture function. The expression for $P(u)$ is identical to the frequency response of an FIR filter of length $N+1$. Hence FIR filter design methods can be readily applied to design arrays with specific radiation pattern.

The simulated annealing algorithm models the behavior of molecules of a pure substance during the slow cooling that results in the formation of perfect crystal [16]. The use of this technique to solve other problems is based on the analogy between the state of the molecule and the state of set of parameters that affect the performance of the system to be optimized. V. Murino *et.al*. [17] have used the simulated annealing for antenna array synthesis in order to reduce the peaks in side lobes by adjustment of array positions and weights of array elements. F. Ares *et.al*. [18] applied both simulated annealing and genetic algorithm to find optimum excitations for moderate and large linear arrays with null filling pattern, and has found that genetic algorithm gives better performance than simulated annealing for such problems.

Genetic algorithms have been successfully applied to a wide variety of problems of electromagnetics and antenna design [19] [20]. Table 2 shows the relationship between elements of GA and antenna arrays [21]. Thinning an array means turning off some elements in a uniformly spaced or periodic array to create a desired radiation pattern. In order to find the best-thinned aperture for low side lobes, a large number of possibilities to be checked. Lo and Lee [14], have obtained that exhaustive checking of all possible element combinations is not practical. R.L. Haupt [22] successfully applied Genetic algorithm for optimal thinning of linear and planar arrays. This work can be extended to circular arrays.

Table 2: Relationship between elements of GA and antenna array.

Genetic Parameter	Antenna Array
Gene	Bit chain (string): (amplitude, phase)
Chromosome	One element of array
Individual	One array
Population	Several arrays

Also, analytical techniques of optimization fail to deal with complex problems involving several parameters. To overcome this problem, M. Shimizu [23], has applied GA for determination of excitation coefficients to shape the radiation pattern. More work can be done to vary the spacing also along with amplitude and phase variables and optimal solution can be found which will give more control over the pattern.

Tennant *et.al*. [12], have applied GA for array pattern nulling in a desired direction. The analytical technique permits only small perturbations, but GA allows much more perturbations and gives superior results and maintains the required null depth. Marcano *et.al*. [21], have applied GA for the synthesis of radiation pattern having dual beam and low side lobes. To search effectively and reduce the computing time, gray code was employed for coding of GA unlike binary code present in traditional GA. The array factor of a linear array of N elements spaced $d = \lambda/2$ apart along the z axis is given by,

$$S(\theta) = \sum_{i=0}^{N-1} I_i e^{j(i\beta d\cos\theta + \Delta\psi_i)} \tag{5}$$

where I_i = amplitude of each element and $\Delta\Psi_i$ = phase shift of each element

Each array has an associated normalized fitness obtained from:

$$fitness = \frac{\sum_{i=1}^{K} \left| S\left(\theta_i\right) \right|}{K + \sum_{j=1}^{P} \left| S\left(\theta_j\right) \right| + SLL} \qquad (6)$$

where K is the number of beams in the radiation pattern, P is the number of nulls in the radiation pattern, θi is the beam location, θj is the null location and SLL is desired side lobe level. This fitness function takes into account, the beam location, null positions and relative side lobe level. J.T. Alander [24] has done the analysis of various fitness functions for antenna designing and found that its suitability depends upon the frequency band under consideration and the penalty coefficients in the fitness function.

K.K. Yan *et.al*. [25] have applied a simple and flexible GA for side lobe reduction that employs direct linear crossover unlike binary crossover in traditional GAs. This approach simplifies software programming and reduces CPU time. It has been applied to linear and circular arrays. More work can be done for arrays of any other arbitrary geometry.

E.A. Jones *et.al*. [26] have applied the GA for the design of Yagi Uda array. The performance evaluation of design generated by GA has been done using a method of moments code, NEC2. J.D. Lohn et.al. [27] have applied a relatively less complex evolutionary technique for optimization of Yagi-Uda array. Similarly optimization in the design of other antenna can be carried out further.

The GA has also been used for beam steering of smart antenna arrays [28]. The desired goals of beamwidth, relative side lobe level and impedance matching of the array have been achieved sucessfully. M.Donelli et al have presented a new hybrid genetic algorithm for the synhesis of linear antenna arrays[29]. The aim was minimization of side lobe level and obtain the desired pattern by optimizing element positions and weights. G.K.Mahanti et al have presented a comparative study between phase only and amplitude -phase synthesis of dual pattern linear antenna arrays employing floating point genetic algorithm [30]. Their results show the amplitude phase synthesis is better than phase only synthesis in terms of side lobe level and dynamic range ratio of excitation amplitude, but its amplitude distribution is very irregular. I.S.Misra *et. al.* have used GA for the optimal synthesis of V-Dipole and its three element Yagi-Uda Array [31].

Recently PSO algorithm has been applied for Electromagnetics and Linear Antenna Array Design problems [32]. Minimum side lobe level and control of null positions of a linear antenna array has been achieved by optimization of element positions using PSO. Consider the array of $2N$ isotropic radiators placed symmetrically along x axis as shown in Fig. 2. The array factor in x-y plane is given by

$$AF(\phi) = 2\sum_{n=1}^{N} I_n \cos\left[kx_n \cos(\phi) + \varphi_n\right] \tag{7}$$

where k is the wave number, and I_n, φ_n and x_n are respectively, the excitation amplitude, phase, location of the *nth* element. If uniform excitation of amplitude and phase is assumed (i.e. $I_n = 1$, $\varphi_n = 0$ for all elements), then array factor can be written as,

$$AF(\phi) = 2\sum_{n=1}^{N} \cos\left[kx_n \cos(\phi)\right] \tag{8}$$

The PSO algorithm has been used to find the locations, x_n, of the array elements to minimize side lobe level and if desired, to achieve nulls in specific directions.

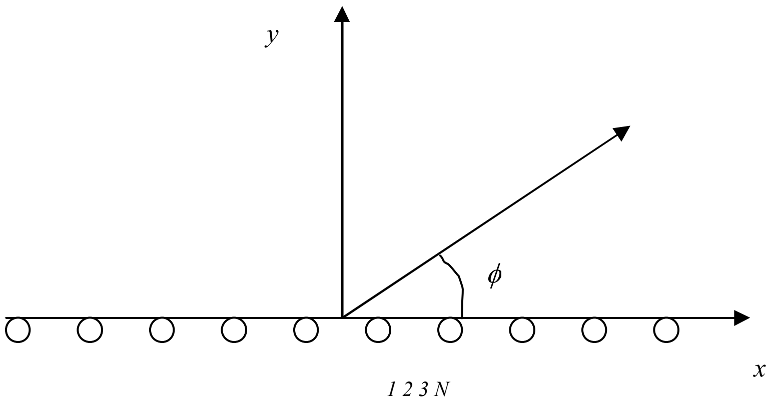

Figure 2: Geometry of the 2N-element symmetric linear array placed along the x axis

K. R. Mahmoud et al have presented the comparison between circular and hexagonal array geometries for mart antenna systems using particle swarm optimization algorithm [33]. The PSO has been integrated with method of moments and used it for the design of practical circular and hexagonal ring arrays. Baskar *et.al.* [34] have applied the PSO and Comprehensive learning PSO for design of Yagi-Uda arrays, and have found that CLPSO gives superior performance than PSO for this design. A new evolutionary technique Bees Algorithm has been used for achieved the nulls in desired directions for interference suppression in the pattern of linear arrays [35] . The Bees algorithm can obtain the patterns with satisfactory null depth and maximum sidelobe level.

3. Conclusion

The PSO algorithm has been used only to find the optimum element locations of linear antenna array. Other variables like amplitude and phase can be employed to get more control over the pattern. Most of the work has been done for linear array optimization, and optimization of other array geometries need to be done. Also, many variants of basic GA and basic PSO exist, and these have not been studied for antenna array optimization and can be explored further. GA and PSO are currently active area of research for application to antenna arrays and Yagi-Uda antenna designing. Further, optimization of antennas, other than isotropic array and Yagi, can also be carried out.

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