ANTENNA ARRAYS AND OPTIMIZATION TECHNIQUES

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ABSTRACT

As the technology progresses towards the pinnacle of advancement, the popularity of antenna array increases with a constant rate. To achieve higher antenna parameters such as gain and directivity antenna array with optimum design are widely popular. Advance radio systems such as the Square Kilometer Array (SKA) are expected to contain thousands of antenna array elements working over a wide range of frequency. In a large antenna array system multiple signals from all the antenna are combined and processed simultaneously that increases the sensitivity of the system. Consequently crucial design aspect needs to be studied such as the array geometry pattern, array patterns of different types of antenna and other factors that would affect the performance and cost of the antenna array system. With the given array optimization techniques that rely heavily on genetic algorithms and pattern search techniques, it is difficult to achieve optimum optimization. In this paper, we explore the possible techniques we can use to optimize antenna arrays and antenna system performance and look for an alternative way to reach a better level of optimization.

1 INTRODUCTION

In many applications a single antenna may not suffice. We may need antenna parameters such as gain and directivity at a much higher value. Increasing the physical size of the antenna will cause unwanted characteristic defects and lead to high fabrication cost. In such a scenario combining multiple antenna elements to form a system of antenna such that collectively the gain or directivity or any other parameters can be increased, comes to us as a handy solution. Antenna array is defined as a system of multiple number of antennas (ranging from thousands to millions) working over bandwidths of several octaves.

The advantage of such array system is they can provide high sensitivity multiband instrument that are useful for radar and other radio related applications including radio telescopes. Such systems usually have large number of elements when sampled at the regular half wavelength. The large bandwidth that these systems have tend to make them extremely dense which consequently results in expensive structuring of the system. Hence, optimization of array distribution or the array geometry is such an important aspect to realize large scale antenna array systems. We study the ways to optimize different array systems of different antenna types ranging from linear wire antenna to Yagi Uda antenna. As the complexity of antenna systems increases, the scope of error or irregularity reduces drastically. Hence it is important to understand the possible optimization techniques so that utmost efficiency of our systems can be exploited. Advance algorithms such as IWO and PSO are used to explore the optimum criteria for array systems.

2 MICROSTRIP PATCH ANTENNAS

A microstrip antenna is a narrowband wide beam antenna fabricated by etching on to a dielectric substrate which forms a ground plane [4]. Microstrip antennas are easy to mount on planar and non planar surfaces, they are simple too and are deemed inexpensive [1]. A section of microstrip antennas are conformal antennas which are suitable for aerodynamic body design such as missile, satellite communication and installed in cars too for automatic cruise control applications [1].

2.1 Millimeter Wave Region

Antenna arrays operate in the millimeter wave region. Radio frequencies in the frequency range of 30-300 GHz are termed as the millimeter wave band [6]. The wavelengths are between 10-1 mm, hence the name millimeter wave [6].
2.2 Conformal Circularly Polarized Microstrip Antenna Array

A microstrip circularly polarized subarray operates in the millimeter wave band [1]. A circularly polarized element can be designed by adding a truncated element to a square patch antenna [1]. A circularly polarized element is narrowband and has a good axial ratio [1]. Chamfering depth is considered one of the important parameters for a circularly polarized element because as depth increases $S_{11}$ reduces and the bandwidth is broadened [1]. A parallel feed network is used to connect to every antenna element and the subsequent adjustment of the network yields a 90° phase shift [1]. A conformal array is defined from a planar array and the transformation formula for the same is as below [1].

\[ r = \rho + h, \quad \phi = \frac{W}{2\rho}, \quad z' = L \]

[1]

Fig 2(a) : $S_{11}$ and axial ratio for circularly polarized element [1] (b) : $S_{11}$ and axial ratio for circularly polarized antenna array [1] (c) : for conformal antenna arrays [1]

From the above graph comparison we infer that the $S_{11}$ bandwidth has been broadened and the axial ratio has been reduced.

2.3 High Gain Planar Antenna Arrays

A planar array has active and parasitic elements in a single plane. Active elements are electronically connected to a transmitter or receiver and the parasitic elements are not connected either way. For applications with higher efficiency the panel arrays are not suitable and hence the three substrate layer model is proposed with two microstrip lines for horizontal and vertical polarizations [2]. To achieve high gain we use low noise amplifiers and place the output ports and feed network on the same substrate [2]. A defected microstrip structure is introduced for phase shifting [2].
Table 1: The receiving array seems to have a higher gain and efficiency. The transmitting array operates in the band of 14-15 GHz and the design uses a coupling probe without any connectors to reduce power loss.

Table 2: The transmitting array also has high gain and efficiency compared to other models. Hence the system can be used in satellite communication and mobile communications as it overcomes losses with higher efficiency and gain.

2.4 Millimeter Wave Antenna Arrays

Millimeter wave antenna arrays are in demand of high speed communication and imaging systems [3]. Quasi planar arrays with microstrip patch, waveguide fed transducer antenna arrays were deemed bulky and hence did not match the gain requirements and so did two antenna systems [3]. Hence came in the helical antennas but they offered only one polarization state [3]. Hence came in dual linear and dual circular polarization technologies where dual linear takes care of gain requirements and dual circular covers the 3db axial ratio [3].

2.4.1 Substrate Integrated Waveguide

It's a synthetic electromagnetic waveguide formed in a dielectric substrate that connects upper and lower metals of the substrate [7]. The waveguide is fabricated at low cost and the advantage is that it carries signal greater than that of a microstrip antenna making conductor loss less [7]. On the other hand disadvantage can be substantial leakage losses [7].

2.4.2 Dual Linearly Polarized Antenna Array

A single aperture consists of horizontally and vertically polarized arrays using feed network and radiating element array respectively [3]. Radiating elements are soldered to avoid leakage losses and distance between elements is 0.7 times the wavelength [3]. Aperture width and side walls control cross polarization of antenna and reduce side lobe levels [3].

2.4.3 Dual Circular Polarized Antenna Array

A dielectric element is used in the design process and the matching between air and dielectric medium is obtained through tapered slot antenna [3]. Tapered antennas are used as they reduce reflections from open end [3]. The total length of the antenna is 4 times the wavelength [3].

The dual linear and dual circular polarized antenna arrays can be combined to achieve multi-dimensional scanned patterns with polarization agile compatibility i.e., ability to change the polarization depending upon specifications and requirements [3].

3 GOAL OF OPTIMIZATION

The main goal of optimization is to find the best decision values that satisfy all given constraints. This can be done by finding all values of variables that maximize or minimize all objective functions. In order to meet the above criteria we make use of several optimization techniques. This paper focuses on five such techniques namely Taguchi method, Particle Swarm optimization, Genetic Mutation Algorithm, Computational Intelligence and Simulated Annealing.

3.1 Taguchi Method

Taguchi's method was developed based on the concept of the orthogonal array (OA), which can effectively reduce the number of tests required in a design procedure [8]. This method provides an efficient way to choose the design parameters in an optimization problem. This paper shows that the proposed method is straightforward and easy to implement and can quickly converge to the optimum designs [9].

3.1.1 Orthogonal Array

Taguchi's method was developed based on the concept of orthogonal array (OA), which can effectively reduce the number of tests required in a design process [10]. An Orthogonal Array is defined as a table in which the entries are obtained from a fixed finite set of symbols. The fixed finite set of symbols occur in a way such that each pair of symbol needs to occur equally in every pair of column. Each array is assigned a specific number of independent design levels and variables.

![Fig 3: Examples of Orthogonal Arrays](image)

3.1.2 Linear Antenna Array

To illustrate implementation procedure of Taguchi's Method, a linear antenna array as shown in figure, which has 20 equally
spaced elements along the Z axis and element spacing of half-wavelength and the excitations of array elements symmetric with respect to the X axis is considered [9]. Synthesis of antenna pattern using Taguchi's method can be classified into two categories namely Null Controlled Pattern Design and Sector Beam Pattern Design.

Fig 4: Geometry of 20-element equally spaced linear array [9].

### 3.1.2.1 Null Controlled Pattern Design

The design objective is to optimize the excitation magnitudes of array elements so that the corresponding array factor has nulls at specified directions [11]–[12]. The two desired nulls are to exist between 50° and 60° and between 120° and 130°. Their magnitude should be lower than -55dB.

Fig 5: The prescribed nulls located between 50° and 60° and between 120° and 130° are below to -55dB [9].

### 3.1.2.2 Sector Beam Pattern Design

In this method, the 20 element array is used for both magnitude and phase excitation of the array are optimized to shape the antenna pattern. Hence, an orthogonal array offering ten columns for magnitude and phase respectively is used for pattern synthesis. An optimum sector beam pattern is obtained after 60 iterations.

Fig 6. The optimal normalized sector beam pattern [9].

### 3.2 Particle Swarm Optimization

This method is inspired from the social behavior of birds and fishes. It has been shown to have excellent abilities in optimizing multi-dimensional, discontinuous, and multi-objective problems recently [13]. This concept makes use of a number of particles that constitute a swarm moving around in the search space looking for the best solution. Every particle adjusts its velocity with respect to its own experience as well as the experience of the neighboring particle. Status of the particle in the search space is characterized by its position and velocity. Velocity value of a particle is calculated based on the individual's distance from the target. Further the particle, larger is the velocity value.

### 3.2.1 Linear Antenna Array

A 2N element periodically spaced linear antenna array along x axis is considered. The array factor in the azimuth plane [14] is

\[ AF(\theta) = \sum_{n=1}^{2N} \text{In} \cos[kx_n \cos(\Theta) + \Psi_n] \]

where k is wave number, \( \theta \) is azimuth angle, \text{In} is excitation amplitude of element n, \( \Psi_n \) is phase of element n, \( x_n \) is position of element n.

Fig 7. Geometry of the 2N-element linear array placed along x-axis [14].

### 3.3 Optimization Comparison between Taguchi’s Method and PSO

A slot antenna as depicted in figure is considered for comparison between Taguchi’s Method and Particle Swarm Optimization Method. As nine parameters are to be optimized, we consider the following OA(27, 9, 3, 2) [16] for Taguchi’s optimization. In the case of PSO, 27 rows are taken for fair comparison. Performance of the two optimization methods under same optimization conditions can be compared with each other by comparing the number of iterations needed.

It is observed that 29 iterations are required to meet the design goal using Taguchi’s method whereas 124 iterations are required using PSO to meet the same design goal. Both return losses show good impedance matching at 5 GHz and 6 GHz. Hence, Taguchi’s method is quicker than PSO to achieve the same optimization goal. Taguchi’s method is also found to be more efficient in the case of slot antenna example considered here.
4. OPTIMISATION TECHNIQUES IMPLEMENTED IN YAGI UDA ANTENNA

Yagi Uda Antenna or commonly referred to as the Yagi Antenna is a highly directional antenna consisting of a driven element, a reflector and N number of directors and all the driven element is excited by the transmission line placed in the transmitter or the receiver. It is used widely used as a very high gain antenna in HF, VHF and UHF bands.[25]. There are plenty of methods devised to optimize the gain, directivity, bandwidth and impedance of the Yagi Uda antenna. A few of the most popular methods have been discussed in this work.

![Image of Yagi Uda Antenna structure]

4.1. Optimisation Using Trial and Error Method

This is the most fundamental method used for optimization of the gain of the Yagi Uda Antenna. It involves variation of the lengths of the driven element, reflector, director elements, the distances between the elements and the radius of the corresponding antenna elements.

This method has not proved to be really advantageous because of the amount of iteration taken for it to reach the optimal point.

4.2. Gain, Bandwidth and Impedance Optimisation Using Genetic Algorithm

The Genetic Algorithm is more of a kind of a search heuristic that mimics the use of natural selection. The two most important components of the GA is cross over and mutation. For antennas application, GA works especially well because of its capability of dealing with several parameters and variables at the same time.[18] To use GA, it is necessary to associate antenna with an individual (chromosome). Each one is evaluated and receives his fitness value. To evaluate all these antennas, the program uses a dynamic-link library (DLL) generated by the authors using moment method. The DLL returns gain and impedance values of each possible antenna and fitness value is evaluated by

\[ FV = W \times G(x) - 150 - \text{Re}(x) - \text{Im}(x) \]  

[18]
The steps involved in the genetic algorithm are at first to choose a random antenna population, measure its performance, perform crossover, mutation and elitism on it and further measure the offspring’s performance and replacing the parent by the offspring if the performance is better.

### 4.3 Gain Optimisation of Yagi Uda Antenna Using Computational Intelligence

In this paper, we introduce a population-based, stochastic, zero-order optimization algorithm and use it to solve single and multi objective Yagi Uda design optimization problems.[19]. The algorithm introduced in this paper is built upon the following generic notions. The algorithm drives the set of solutions towards feasibility first before trying to improve an infeasible individuals' objective function value. A feasible solution is preferred over an infeasible solution. Between two feasible solutions, the one with a better objective function value is preferred over the other. Between two infeasible solutions, the one with a lower non-dominated rank based on the constraint matrix is preferred over the other.[19]

The Pseudo Code for the algorithm is[19] :

1. Update \( t \rightarrow 0 \)
2. Generate \( M \) individuals representing a population: \( \text{Pop}(t)=[I_1,I_2,\ldots,I_n] \) uniformly in the parametric space.
3. Evaluate the objective and analyse the different constraints.
4. Identify the leaders and the followers in the population of the antenna.
5. Preserve the leaders and move the followers in the population of the antenna.
6. Update \( t \rightarrow t+1 \).
7. If \( t \leq T_{\text{max}} \) then proceed to step 3. Else go to step 8.
8. Stop.

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<td>3</td>
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<tr>
<td>6</td>
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<td>0.373λ</td>
</tr>
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</table>

| Gain (dBi) | 11.91dB |
| Relative Side lobe level | -12.10dB |

**Fig 13:** Table showing the increase in value of gain and improved radiation pattern of the CI algorithm implemented Yagi Uda Antenna.[19]
enables it to bounce over any mountain to access any valley, given enough bounces. As the temperature declines the ball cannot bounce so high and it can also settle to become trapped in relatively small ranges of valleys. A generating distribution generates possible valleys or states to be explored. An acceptance distribution is also defined, which depends on the difference between the function value of the present generated valley to be explored and the last saved lowest valley. The acceptance distribution decides probabilistically whether to stay in a new lower valley or to bounce out of it. All the generating and acceptance distributions depend on the temperature. It has been proved that by carefully controlling the rate of cooling of the temperature, SA can find the global optimum.

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<td>5.67+j217.60</td>
<td>39.63+j174.13</td>
<td>3.9+j24.19</td>
<td>4.63+j84.81</td>
</tr>
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Table 3: Observed values of Gain and impedances using the Simulated Annealing Method

The antenna gain of Yagi Uda antenna is a highly nonlinear function of the design variables. The local methods applied previously were not able to find global solution. The GA and CLPSO are global solution finding methods and have obtained good solutions but applying SA we have been able to obtain good results as compared to the above techniques. Moreover, SA is very easy to implement and is a robust technique. It can further be applied to optimize other parameters of Yagi antenna and also other antennas which have large number of parameters.

5 MIMO SYSTEM

Multiple Input Multiple Output is a demanding technology in today’s world of communication. It uses multiple transmitters and receivers to significantly improve performance. It is based on the principle: The natural multipath propagation can be exploited to transmit multiple, independent information streams using co-located antennas and multi-dimensional signals. The advantages that a MIMO communication system offers are huge increase in data throughput and link coverage without using additional bandwidth or transmit power, in presence of multipath scattering. Consequently we can increase the channel capacity to a higher level by optimizing the antenna array. Although, the channel capacity in a MIMO system is high, to achieve highest channel capacity the choice of array type and configuration at transmitter and receiver is a key design issue. To achieve this, antenna engineers should have a tool which would help in designing antenna array systems. One such tool is the Particle Swarm Optimization (PSO) PSO is a new yet popular tool inspired from the swarm behavior of bees and hence the name.

5.1 Linear Wire antenna array Optimization

The MIMO system can be modelled by using the following equations:

\[
C = \log_2 \left( I + \frac{P_T}{T} HH^* \right)
\]

\[
P_T = E[\bar{v}_t x^* \bar{v}_t x]
\]

C is the channel capacity which is given by Shannon’s Capacity formula. Pt is the total power of the transmitted antenna. H is the channel matrix and H* it’s conjugate. vtx is the transmitted signal vector whereas E[ ] is the expectation function. We use the Particle Swarm Optimization (PSO) as a guidance tool on a lambda by 2 Linear wire antenna and try to optimize it for MIMO application by increasing the channel capacity. PSO optimizes a problem by iteratively trying to improve a candidate solution with regard to a given measure of quality. A basic variant of the PSO algorithm works by having a population (called a swarm) of candidate solutions (called particles). These particles are moved around in the search-space according to a few simple formulae. A basic flow diagram of the PSO algorithm is given in Fig 2.

Fig 14: PSO Flow [1]
The technique used in optimization is a random process (different mean capacity values can be obtained with a change in the volume). Hence we have to take in account the coincidence interval of the mean capacity values, which is given by:

\[ C_i = \sigma \sqrt{2 \operatorname{erf}^{-1}(P)} \]

We then apply the PSO algorithm to generate the swarm particles and optimize the antenna array. To achieve optimum inter-element spacing the TX array are placed in a circular fashion. We achieve maximum optimization with TX array as 6.

5.2 Dipole model Optimization

We try providing a fast and efficient way to design compact antenna arrays preserving the maximum channel capacity of MIMO systems. We use Infinitesimal Dipole Model theory (IDM). Each antenna is replaced by a set of infinitesimal dipoles radiating the same amount of electric fields as that of the antenna. The Invasive Weed Optimization Algorithm is implemented (IWM). In a MIMO system, the efficiency is affected by spatial correlation. Spatial correlation is a function of array elements mutual coupling. Hence array elements relative position and orientation can be designed in such a way to minimize spatial correlation so as to increase channel capacity. In order to minimize the correlation in a MIMO system, a very high isolation between the antenna elements is required. However, in a MIMO system the space is limited for antenna placement. In order to achieve maximum optimization proper antenna placement is required. In this procedure of maximizing the channel capacity we proceed in two steps:

Step 1: Each antenna element is replaced with infinitesimal electric dipole producing the same electric field as the original antenna. IWO Optimization method is applied to the electric dipole.

Step 2: IDM is used to find the antenna parameters and optimize them, rather than a full wave technique.

In order to accurately represent the antenna with dipoles a large number of dipoles is required. However, increasing the number of dipoles slows the optimization process as more computation is required. On the other hand if the number of dipoles are not enough, the optimization fields cannot achieve fields similar to the replacing antenna. To solve this problem the modified Inter Weed Optimization or IWO is made use of. In this algorithm, IDM and efficient number of dipoles can be traded off for bandwidth performance while the minimum separation required for element design can be accounted for. The technique relaxes on applying simple controlled randomization and space tapering of the aperture distribution which allows for directivity, side lobes and beam width to be traded off for bandwidth performance while the minimum separation required for element design can be accounted for. Since no iteration or search algorithm is needed, this technique is particularly useful when the required number of elements and bandwidth are large. An example is given for the design optimization of the SKA-MA-low station [28]. The technique shows how the performance can be optimized with the same number of element over a broadband and hence, the number of elements can be reduced for a given minimum performance requirement [28].

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