Biogeography Based Optimization for Gain Maximization of Fifteen-element Yagi-Uda Antenna

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***Abstract*—Biogeography-Based Optimization (BBO) is a recently introduced optimization technique based on science of biogeography, i.e., study of distribution of biological species over space and time. In BBO, potential solutions of a problem are grouped in integer vectors known as habitats. BBO uses migration operator for feature sharing among habitats and mutation operator to explore new features. Yagi-Uda antenna is a widely used directional antenna design due to various useful properties of high gain, low cost and ease of construction. Designing a Yagi-Uda antenna includes determination of element lengths and spacings between them to get desired radiation characteristics. The gain of Yagi-Uda antenna is hard to optimize as there is no analytical formula to determine gain directly, it makes relationship between antenna parameters and its characteristics highly complex and non-linear. In this paper, 15-element Yagi-Uda antenna is optimized for gain maximization using BBO. The results obtained by BBO are compared with Bi-Swarm optimization, Ellipsoid Algorithm and Genetic Algorithm (GA). BBO shows better results than other compared optimization techniques.**

Keywords: Biogeography Based Optimization, Yagi-Uda Antenna, Antenna Gain, Genetic Algorithm, Bi-Swarm Optimization, Ellipsoid Algorithm

I. INTRODUCTION

Antenna is an electrical device which converts electric signal into free space radiations and vice-versa. The various radiation characteristics that affect the design of an antenna are gain, impedance, bandwidth, frequency of operation, Side Lobe Level (SLL) etc. Yagi-Uda antenna is a widely used directional antenna design due to various desirable features, i.e., high forward gain, low cost and ease of construction. It is basically a parasitic linear array of parallel dipoles, one of which is energized directly by transmission line while the others act as parasitic radiators whose currents are induced by mutual coupling.

Yagi-Uda antenna was invented in 1926 by H. Yagi and S. Uda at Tohoku University [1] in Japan, however, published in English in 1928 [2]. The main objective, in design of Yagi-Uda antenna, is to find an optimum structure that meet certain radiation criteria like gain, impedance, SLL and beamwidth. However, due to its parasitic elements, it is extremely difficult to obtain an optimum design of Yagi-Uda antenna. Since its inception, Yagi-Uda antenna has been optimized several times for gain, impedance, SLL and bandwidth using different optimization techniques based on traditional mathematical approaches [3], [4], [5], [6], [7], [8], [9] and Artificial Intelligence (AI) techniques [10], [11], [12], [13], [14], [15], [16]. In 1949, Fishenden and Wiblin [17] proposed an approximate design of Yagi aerials for maximum gain, however, the approach was based on approximations. In 1959, Ehrenspeck and Poehler proposed a manual approach to maximize the gain of the antenna by varying various lengths and spacings of its elements [18].

Later on, with the availability of high performance computing, it became possible to optimize antennas numerically. Bojsen *et al*. in [4] proposed an optimization technique to find the maximum gain of Yagi-Uda antenna arrays with equal and unequal spacings between adjacent elements. Cheng *et al*., in [7] and [8] have used optimum spacings and lengths to optimize the gain of a Yagi-Uda antenna. In [9], Cheng has proposed optimum design of Yagi-Uda antenna where antenna gain function is highly non-linear. The performance of these gradient based techniques depends on choice of initial solution.

In 1975, John Holland introduced Genetic Algorithms (GAs) as a stochastic, swarm based AI technique, inspired from natural evolution of species, to optimize arbitrary systems for certain cost function. Since then many researchers have used GAs to optimize Yagi-Uda antenna designs for gain, impedance and bandwidth separately [19], [10], [20] and collectively [11], [21], [22]. Jones *et al*., in [10] have used GA to optimize Yagi-Uda antenna for various radiation characteristics and compared the result with steepest gradient method. Baskar *et al*. in [13], have used Comprehensive Learning Particle Swarm Optimization (CLPSO) to optimize Yagi-Uda antenna and obtained better results than other optimization techniques. In [14], Li has optimized Yagi-Uda antenna using Differential Evolution (DE) and illustrated the capabilities of the proposed method with several Yagi-Uda antenna designs. In [15], Singh *et al*. have analyzed another useful, stochastic global search and optimization technique known as Simulated Annealing (SA) for the optimization of Yagi-Uda antenna. In 2008, Dan Simon introduced a new optimization technique based on science of biogeography, in which information sharing among various habitats, i.e., potential solutions, is obtained via migration operator and exploration of new features is done with mutation operator [23]. Singh *et al*. have presented BBO as a better optimization technique for Yagi-Uda antenna designs, as compared to other optimization techniques in [16]. In [24], Li has proposed the Bi-Swarm optimization technique to optimize the Yagi-Uda antenna and produced better result than GA, Particle Swarm Optimization (PSO) and Computer Intelligence (CI) techniques. In 2011, Amaral *et al*. has applied Ellipsoid algorithm to optimization of Yagi-Uda antenna for gain maximization [25]. Li *et al*. in [26] have used Invasive Weed Optimization (IWO) technique to optimize a six element Yagi-Uda antenna for maximum directivity.

In this paper, 15 element Yagi-Uda antenna has been optimized for maximum gain using BBO and results are compared with other optimization techniques. A method of moments based freeware programme, Numerical Electromagnetics Code 2 (NEC2), is used to evaluate the antenna designs for gain.

After this brief introduction, the paper is structured as follows: In Section II, Yagi-Uda antenna is briefly discussed. Section III is dedicated to biogeography terminology and BBO technique. In Section IV, the design problem of 15 element Yagi-Uda antenna for gain maximization is presented and obtained results are compared with other optimization techniques. Finally, paper is concluded in Section V.

II. Antenna Design Parameters

Yagi-Uda antenna is basically made of three types of elements: (a) Reflector (b) Feeder and (c) Directors. *Reflector* is longest of all elements and blocks radiations in one direction. *Feeder* or driven element is fed with the signal to be trans-mitted, directly from transmission line. *Directors* are usually more than one in number and are responsible for unidirectional radiations. Normally, there is no limit on number of directors, however, as the number of directors are increased beyond a certain limit there is a reduction in the induced current in the most extreme elements. Figure 1 presents a basic Yagi-Uda antenna design where all elements are placed along y-axis and parallel to x-axis. Middle segment of the reflector is placed at origin and signal to be transmitted is fed to the middle segment of the feeder element. An incoming field induces resonant currents on all the antenna elements which causes parasitic (reflector and directors) elements to re-radiate signals. These re-radiated fields are then picked up by the feeder element, that makes total current induced in the feeder equivalent to combination of the direct field input and the re-radiated contributions from the director and reflector elements.

Element lengths and spacings between them are the variables/parameters which need to be determined for optimum design of Yagi-Uda antenna. An antenna with N elements requires $2N$-1 parameters, i.e., N wire lengths and N-1 spacings, to be determined. These $2N$-1 parameters, collectively, are represented as an integer vector referred as a *habitat* in BBO given as (1).

$$H = [L_1, L_2, \ldots, L_N, S_1, S_2, \ldots, S_{N-1}] \quad (1)$$

$$\alpha + \beta = \chi. \quad (1)$$

where L_N are the lengths and $S_{N-1}$are the spacings between antenna elements.

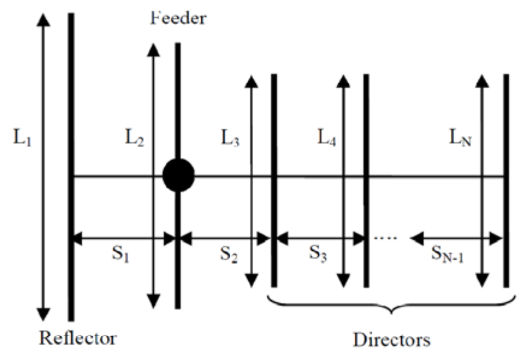

Fig. 1 Basic Yagi-Uda Antenna Design

III. Biogeography Based Optimization

Biogeography Based Optimization is a population based global optimization technique based on the science of bio-geography, i.e., study of the distribution of animals and plants among different habitats over time and space. BBO results presented by researches, to optimize Yagi-Uda antenna, are better than other optimization techniques like PSO, GAs, SA, DE etc. [10], [21], [13], [27].

Initially, biogeography was studied by Alfred Wallace [28] and Charles Darwin [29] mainly as descriptive study. However, in 1967, the work carried out by MacAurthur and Wilson [30] changed this perception by introducing a mathematical model for biogeography which made it possible to predict the number of species in a habitat. Mathematical models of biogeography describe the migration, speciation and extinction of species in various habitats.

A *habitat* or *island* is an ecological area inhabited by a particular animal species which is geographically isolated from other habitats. Each habitat is characterized by its Habitat Suitability Index (HSI). Habitats which are well suited as living places for biological species are referred to have high HSI value. HSI is analogues to fitness in other Evolutionary Algorithms whose value is a function of many features of the habitat such as rainfall, diversity of vegetation, diversity of topographic features, land area, and temperature etc. The features/variables that characterize habitability are known as Suitability Index Variables (SIVs). In other words, HSI is dependent variable whereas SIVs are independent variables.

The habitats with high HSI have large probability of emigration (hence high emigration rate, μ) simply due to large number of species they host and small probability of immigration (low immigration rate, λ) as they are already saturated with species. Immigration can be defined as the arrival of new species into a habitat, while emigration is the process of leaving one's native habitat. Similarly, habitats with low HSI tend to have low emigration rate, μ, due to sparse population, however, they will have high immigration rate, λ. Suitability of habitats having low HSI value is likely to increase with more number of species arriving from habitats having high HSI as suitability of a habitat depends upon its biological diversity. For sake of simplicity, it is safe to assume a linear relationship between HSI (or population) and immigration and emigration rates. Also maximum emigration and immigration rates are assumed equal, i.e., $E = I$, as shown graphically in Fig. 2.

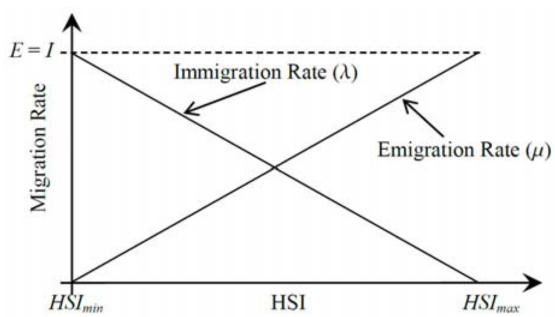

Fig. 2 Migration Curves

For k-th habitat, values of emigration rate, μ_k, and immigration rate, λ_k, are given by (2) and (3).

$$\mu_k = E.\frac{HSI_k}{HSI_{max}-HSI_{min}} \quad (2)$$

$$\lambda_k = I.\left(1-\frac{HSI_k}{HSI_{max}-HSI_{min}}\right) \quad (3)$$

$$\alpha + \beta = \chi. \quad (1)$$

Good solutions (habitats with high HSI) are more resistant to change than poor solutions (habitats with low HSI) whereas poor solutions are more dynamic in nature and accept a lot of new features from good solutions. This addition of new features to low HSI solutions from high HSI solutions may raise the quality of those solutions.

In a global optimization problem with number of possible solutions, each habitat or a solution in a population of size *NP* is represented by *M*-dimensional integer vector as $H = [SIV_1, SIV_2, \ldots, SIV_M]$ where M is the number of SIVs (features) to be evolved for optimal HSI. HSI is the fitness criteria that is determined by evaluating the cost/objective function, i.e., HSI $= f$(H). BBO consists of mainly two mechanisms: (A) Migration and (B) Mutation, these are discussed in the following subsections.

A. Migration

Migration is a probabilistic operator that improves HSI of poor habitats by sharing information from good habitats. During migration, *i*-th habitat, H_i (where i = 1, 2, . . . , *NP*) use its immigration rate, λ_i given by (3), to probabilistically decide whether to immigrate or not. In case the habitat is selected for immigration, then the emigrating habitat, H_j, is found probabilistically based on emigration rate, μ_j given by (2). The process of migration is then carried out by copying values of SIVs from $H_j$to H_i randomly, i.e., $H_i(SIV) \leftarrow H_j(SIV)$. The migration process is depicted in Algorithm 1.

Algorithm 1 Standard Pseudo Code for Migration

```
for i = 1 to NP do
    Select Hi with probability based on λi
    if Hi is selected then
for j = 1 to NP do
        Select Hj with probability based on μj
        if Hj is selected
        Randomly select a SIV(s) from Hj
        Copy them SIV(s) in Hi
        end if
end for
end if
end for
```

B. Mutation

Mutation is another probabilistic operator that alters the values of randomly selected SIVs of some habitats that are intended for exploration of search space for better solutions by increasing the biological diversity in the population. Here, higher mutation rates are investigated on habitats those are, probabilistically, participating less in migration process. Elitism approach is usually used along with mutation to preserve features of the best habitat. The mutation rate, $mRate$, for k-th habitat is calculated as (4)

$$mRate_k = C \times \min(\mu_k, \lambda_k) \quad (4)$$

where $\mu_k$and λ_k are emigration and immigration rates, respectively, given by (2) and (3) corresponding to HSI_k. Here C is a scaling constant and its value is equal to 1. The pseudo code of mutation operator is given in Algorithm 2.

Algorithm 2 Standard Pseudo Code for Mutation

$mRate = C \times \min(\mu_k, \lambda_k)$, where $C = 1$
for i = 1 to NP do
for j = 1 to length(H) do
  Select H_j(SIV) with $mRat$
  if H_j(SIV) is selected then
  Replace H_j(SIV) with randomly generated SIV
  end if
end for
end for

IV. Simulation Results and Discussions

Fifteen-wire Yagi-Uda antenna is optimized for maximum gain using BBO. To present a fair analysis, design is optimized with 30 habitats using 100 iterations. The C++ programming environment is used for development of optimization algorithm, whereas, a method of moments based software named as Numerical Electromagnetics Code 2 (NEC2) [31] used for determination of required antenna characteristic, i.e., gain. Each potential solution in BBO is encoded as an integer vector with 29 SIVs as given by (1). The radiation characteristics of Yagi-Uda antenna can change significantly by varying the element lengths and spacings up-to four decimal places, so this optimization algorithm finds the optimum element lengths and spacings between them. The search spaces for the search of optimum values of wire lengths and wire spacings are 0.30λ–0.50λ and 0.10λ–0.50λ, respectively. Cross sectional and segment sizes of all elements are kept constant, i.e., 0.003397λ and 0.1λ respectively, where λ is the wavelength corresponding to frequency of operation, i.e., 300 MHz. The scaling constant C, the maximum migration rates E and I, are set equal to 1. The corresponding lengths and spacings obtained during optimization of Yagi-Uda antenna with BBO are tabulated in Table I along with other optimization techniques from published work. It can be seen from the Table I that maximum gain of 18.41 dBi obtained with BBO is more than obtained by Bi-swarm optimization technique [24], Ellipsoid algorithm [25] and GA [10]. To the best of literature available, gain obtained by BBO, i.e., 18.41 dBi is the highest gain that is obtained from a 15-element Yagi-Uda antenna yet.

TABLE 1 RESULTS OF GAIN OPTIMIZED 15 ELEMENT YADI-UDA ANTEENA DESIGNS

	BBO		Bi-Swarm [24]		Ellipsoid [25]		GA [10]	
Element	**Length**	**Spacing**	**Length**	**Spacing**	**Length**	**Spacing**	**Length**	**Spacing**
1(λ)	0.4808	-	0.4855	-	0.4561	-	0.474	-
2(λ)	0.4581	0.2690	0.4557	0.2397	0.4510	0.3788	0.486	0.356
3(λ)	0.4441	0.1963	0.4399	0.2810	0.4490	0.3921	0.452	0.144
4(λ)	0.4274	0. 3716	0.4311	0.3688	0.4430	0.4036	0.436	0.340
5(λ)	0.4154	0.4199	0.4259	0.3881	0.4375	0.4088	0.414	0.447
6(λ)	0.4061	0.4782	0.4215	0.3837	0.4445	0.4249	0.420	0.362
7(λ)	0.4067	0.4460	0.4043	0.4850	0.4473	0.4307	0.414	0.370
8(λ)	0.4029	0.4410	0.4054	0.4712	0.4431	0.4272	0.398	0.395
9(λ)	0.3970	0.4728	0.4033	0.4845	0.4373	0.4301	0.414	0.414
10(λ)	0.4017	0.4597	0.4094	0.4144	0.4386	0.4874	0.376	0.425
11(λ)	0.4013	0.4458	0.4028	0.4614	0.4229	0.3911	0.338	0.296
12(λ)	0.3991	0.4811	0.4074	0.4580	0.4213	0.4391	0.398	0.334
13(λ)	0.3991	0.4472	0.3936	0.5157	0.4385	0.3977	0.410	0.348
14(λ)	0.4015	0.4530	0.3955	0.4537	0.4867	0.4057	0.408	0.392
15(λ)	0.4146	0.4579	0.4142	0.4317	0.4293	0.2263	0.398	0.450
Gain (dBi)	**18.41**		**18.31**		**17.48**		**17.07**	

V. Conclusions and Future Scope

In this paper, optimization of fifteen-element Yagi-Uda antenna for gain maximization using BBO is carried out. As per observations, the gain obtained with BBO is higher as compared to other optimization techniques. The results show that BBO is a robust optimization technique for optimizing Yagi-Uda antenna. In the future scope of this paper, migration and mutation variants can be explored for better convergence performance.

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