Multi-Objective Optimization of Yagi-Uda Antenna Applying Enhanced Firefly Algorithm with Adaptive Cost-Function

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Due to high gain and low production costs, Yagi-Uda antennas still find wide applications in wireless communication systems. The sensitivity of the gain due to variations of the element lengths and distances between the elements makes the design optimization quite challenging. In the present paper the multi-objective optimization of a six-element Yagi-Uda antenna applying an enhanced version of the firefly algorithm is proposed. The application of this optimization algorithm in the multi-objective sense allows the finding of local solutions, too. To minimize the computational time an adaptive cost function is applied. The numerical analyses are performed by the Partial Element Equivalent Circuit (PEEC) method.

***Index Terms*—Antenna arrays, Firefly optimization, Partial element equivalent circuit, Yagi-Uda antennas.**

I. Introduction

YAGI-UDA antennas are widely used antenna systems for highly directive applications. Due to the high gain and low production cost they have become one of the most used antennas for television reception as well as for radar applications. As shown in Fig. 1, a simple Yagi-Uda antenna consists of a number of linear dipole elements. Besides one directly driven element, there is one reflector and a variable number of directors which act as parasitic radiators. Their currents are a result of mutual coupling between all elements. To get the required end-fire behavior, the amplitude and phase conditions have to be satisfied. This is being fulfilled by varying the spacing between the elements and the length of the individual dipoles.

The design goal for Yagi-Uda antennas is to find optimal distances and antenna lengths to fulfill a set of performance requirements such as gain, input impedance, sidelobe level or/and efficiency. To meet up with these partly conflicting criteria, different stochastic single-objective [1] and multi-objective optimization techniques have been applied [2]-[3].

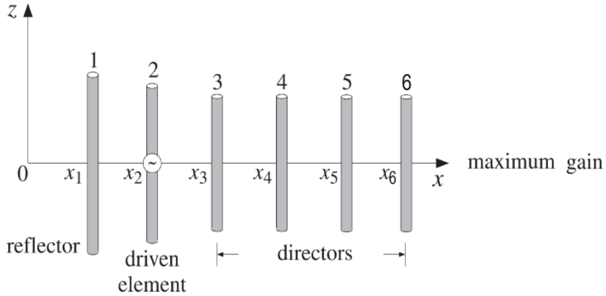

Fig. 1. Yagi-Uda array with four directors the driven element and a reflector [1].

In this work the multi-objective optimization of a Yagi-Uda antenna with an enhanced version of the Firefly algorithm (FFA) is performed. In this study the input-impedance, the gain and the lobe-efficiency of the main lobe are optimized. For obtaining the electromagnetic characteristics of the antenna, the PEEC method is used. Since the evaluation of the electromagnetic behavior is the most time-consuming part, the complexity of the underlying model is scaled in an adaptive way.

II. PEEC method

The PEEC method, first introduced by Ruehli [4] is an integral-equation based method which main idea is to describe the antenna structure by means of an equivalent electric circuit. Therefore, the cylindrical antenna is subdivided into stick elements. The underlying integral equation is the so called Electric Field Integral Equation (EFIE) in the frequency domain:

$$\begin{aligned}\frac{\mathbf{J}(\mathbf{r},\omega)}{\sigma} = & \frac{-j\omega\mu_0}{4\pi}\int_{\Omega}\mathbf{J}(\mathbf{r}',\omega)G(\mathbf{r},\mathbf{r}')d\Omega' \\ & -\frac{1}{4\pi\varepsilon_0}\nabla\int_{\Omega}\rho(\mathbf{r}',\omega)G(\mathbf{r},\mathbf{r}')d\Omega'\end{aligned} \quad . \tag{1}$$

In (1) **J** is the current density, **r** and **r'** represent the field point and source point vectors, respectively, ω is the angular frequency, ρ is the charge density, μ_0 and ε_0 are the permeability and the permittivity of the free space and G is the free space Green's function [5].

The main advantages using the PEEC method for antenna problems compared to e.g. Finite Element Method lies in the fact that the surrounding air need not be discretized. Another benefit of this method is the possibility of a simple post processing of chosen characteristics e.g. power loss or input impedance from the equivalent circuit model.

The idea for obtaining the electric field intensity in the far-field-region, needed for calculating the gain and beam efficiency, is to treat each stick of the antenna structure as an Hertzian dipole. Since every stick is orientated in the z-direction according to Fig. 1, the contribution of a single stick is given by [5]

$$E_\theta = j\eta \frac{k I_s l_s e^{-jkR}}{4\pi R} \sin(\theta), \qquad (2)$$

where I_s and l_s are the current and the length of the single sticks, R is the distance between the source point and the observation point in free space, η is the intrinsic wave impedance, k is the phase constant and θ is the azimuthal angle between the stick-midpoint and the observation point. Within the superposition of the individual field contributions the displacement between the mid-point of the stick and the origin has to be taken into account.

III. Optimization Strategy: Extended Firefly Algorithm

Stochastic optimization algorithms for the optimization of technical design problems have been growing rapidly in popularity over the last decades. Especially algorithms adopted from natural processes like the applied FFA have been favored in the last years. Therefore, an enhanced version of the FFA is used in this work, which also takes care of local solutions by means of an additional cluster algorithm [6].

The main idea of the basic FFA, developed by Yang in 2007 [7], is based on the natural swarm characteristics of fireflies. The movement of the individual flies of the swarm is described by

$$\mathbf{x}_i^{t+1} = \mathbf{x}_i^{t} + \beta e^{-\gamma r_{ij}} (\mathbf{x}_j^{t} - \mathbf{x}_i^{t}) + \alpha \boldsymbol{\varepsilon}_{ij}. \qquad (3)$$

In (3) the new position of the fly i consists of three parts. The first term is the old position of the fly, the second term $\beta_0\, e^{(-\gamma r_{ij})}$ describes the attractiveness between two flies, where r_{ij} is the distance between the two fireflies i and j, and γ is the so called light absorption factor. The third term in (3) is a randomized move with $\boldsymbol{\varepsilon}_{ij}$ as a random vector and α is the randomized parameter.

IV. Yagi-Uda Antenna Design Problem

This paper investigates the design of a six-element Yagi-Uda antenna as shown in Fig. 1. The optimized parameter vector $\mathbf{x}$ consists of the lengths l_1-l_6 of the single elements and the distances d_1-d_5 between these dipoles. All dipoles are orientated along the z-axis. The radii are fixed to be $a = 0.0033\lambda$, the length of l_i and the distances d_i were limited between 0.1 λ and 1 λ. As mentioned above only the second dipole is voltage excited with a voltage of U =1V.

As a first test problem the input impedance should be optimized for a specific value Z_0 at the operating frequency, the gain and the lobe efficiency should be maximized. Introducing weighted fuzzy member functions μ [8] a scalar objective function is obtained:

$$\begin{aligned} f(\mathbf{x}) = (w_1 + w_2 + w_3) - w_1 \mu_{ZAnt}(\mathbf{x}, Z_0) - \\ - w_2 \mu_{Gain}(\mathbf{x}) - w_3 \mu_{LobeEfficiency}(\mathbf{x}), \end{aligned} \qquad (4)$$

where w_1, w_2 and w_3 are weights to control the contribution of the single objectives.

As can be seen in Fig. 2 in early iteration steps the error is above ten percent, which makes it useful to adapt the solver for the forward problem to be less time consuming. Typically in integral-based methods the post-processing, in this case the field-computation, is the most time-consuming part. The level of accuracy of this part can easily be adjusted according to the relative error which brings a significant decrease in computation time without a loss of accuracy for the final result.

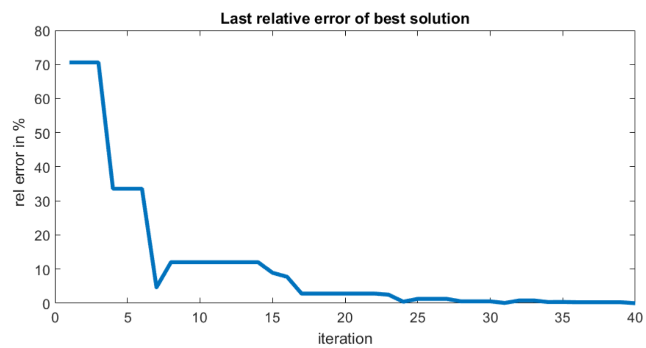

Fig. 2. Relative error as a function of the iteration.

First tests show satisfying results and a decrease in computational time. In the full paper results obtained with FFA will be compared with those of other comparable stochastic optimizers e.g. evolution strategy [9] and, in addition with adaptive fuzzy sets [8]. Furthermore, details about the algorithm as well of the cost function will be published.

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