Optimal design of UHF TV band log-periodic antenna using invasive weed optimization

P. I. Lazaridis, Z. D. Zaharis C. Skeberis, T. Xenos, E. Tziris, and P. Gallion

***Abstract*— A powerful evolutionary method called Invasive Weed Optimization (IWO) is applied to achieve optimal designs of log-periodic antennas. The antennas are designed for operation in the UHF-TV band, i.e. 470-860 MHz, and are optimized with respect to the standing wave ratio (SWR), the front-to-rear (F/R) ratio, and the forward gain. The parameters under optimization are the dipole lengths, the dipole diameters, the distances between adjacent dipoles and the characteristic impedance of the transmission line that feeds the dipoles. The optimized antenna geometries that resulted from the above method seem to be significantly better than the respective ones derived from the classical design method.**

Keywords*— *Invasive Weed Optimization; IWO; Log-periodic antenna; LPDA; UHF TV Band;

I. INTRODUCTION

Log-periodic antenna optimization is of great importance because this type of antenna is widely used in a multitude of applications, e.g. TV reception, wideband precision measurements, electromagnetic compatibility (EMC) measurements, spectrum surveillance, etc. Log-periodic antennas, or equivalently Log-Periodic Dipole Arrays (LPDAs), have a relatively flat gain curve over several frequency octaves and are of a simple construction. The somewhat low gain of LPDAs is easily increased by using arrays of 2, 4, 6, 8, etc. antennas and thus high-gain simultaneously with flat frequency response is achieved. On the contrary, the higher gain of Yagi-Uda antennas is achieved over a much narrower bandwidth and the gain curve has a marked slope with higher gain at higher frequencies. The classical design algorithm for log-periodic antennas dates from the 1960s and can be further improved by automated optimization algorithms.

II. PRIOR ART

In prior-art publications dealing with Yagi-Uda and LPDA modeling and optimization of antenna performance with respect to specific antenna geometry parameters, evolutionary optimization algorithms are frequently used.

P. I. Lazaridis is with Alexander Technological Educational Institute of Thessaloniki, 57400, Sindos, Greece. (email: pavloslazaridis@hotmail.com).
Z. D. Zaharis is with the Telecommunications Centre, Aristotle University of Thessaloniki, Thessaloniki 54124, Greece (e-mail: zaharis@auth.gr).
C. Skeberis and T. D. Xenos are with the Department of Electrical and Computer Engineering, Aristotle University of Thessaloniki, Thessaloniki 54124, Greece (e-mail: cskeberis@auth.gr; tdxenos@eng.auth.gr). E. Tziris is with the School of Engineering and Design, Brunel University, London UB8 3PH, U.K. P. Gallion is with Ecole Nationale Supérieure des Télécommunications, Telecom ParisTech, CNRS, LTCI, 46, rue Barrault, 75634, Cedex 13, Paris (email : philippe.gallion@telecom-paristech.fr).

In [1], the Particle Swarm Optimization (PSO) algorithm is applied in conjunction with the Numerical Electromagnetics Code (NEC) in order to extract optimized LPDA geometries. A parametric study is presented in this paper with respect to several performance parameters such as the gain, the half power beam-widths (HPBWs) respectively on E–plane and H–plane, the front-to-back (F/B) ratio and the standing wave ratio (SWR). Specific results are presented for an optimized ten element LPDA. In [2], a multi-objective version of differential evolution (GDE3) and the Nondominated Sorting Genetic Algorithm II (NSGA-II) are applied to a Yagi-Uda antenna design. The numerical solver is the SuperNEC, which is an object oriented version of the numerical electromagnetic code (NEC-2). Three antenna configurations composed respectively of four, six and 15 elements are optimized by using GDE3 and NSGA-II, and the optimized geometries are compared with other results from the literature. In [3], the maximum forward gain of a Yagi antenna is optimized with six optimization variables. For all the antenna simulations, the WIPL-D Pro v6.1 software package is used. The Yagi antenna has a driving element, a reflector, and 10 directors, and is optimized in the frequency range 295-305 MHz. The gain is calculated at five equidistant frequencies. PSO is also compared to genetic algorithms (GAs) in this publication. In [4], an LPDA is optimized for the WiMAX, GSM-I, GSM-II, and Wi-Fi communication bands. Smaller size and higher gain is the result for the optimized 10-element LPDA. In [5], an LPDA is optimized in the GSM, WiMAX, Bluetooth, Wi-Fi, and 3G communications bands using the PSO algorithm. The simulations are performed in MATLAB for a 13-element LPDA, the antenna gain is improved by 0.6-0.8 dB and the VSWR is reduced below 1.5. In [6], the Invasive Weed Optimization (IWO) method is used in conjunction with Ansoft HFSS commercial full-wave electromagnetic solver in order to optimize a 6-element Yagi-Uda antenna with respect to inter-element distances. In this example the element lengths are fixed. The maximum number of iterations is only 15 and the results are compared to the PSO algorithm and to another method. In [7], the IWO method is used to optimize a printed Yagi antenna for a VSWR of less than 1.5 and a high-gain radiation pattern. The fitness function is calculated by the commercial software FEKO, which uses the method of moments. The maximum number of iterations for the IWO algorithms is fixed to 110. A C-band optimized version of the Yagi antenna is fabricated and tested with good agreement between experimental data and simulation results. In [8], the IWO algorithm is used in 4 benchmark antenna problems together with the FEKO software for electromagnetic calculations. The maximum number of iterations is set to 100. A good agreement is found between the optimization results obtained by the IWO and PSO and the execution times are similar.

The IWO algorithm was originally introduced by Mehrabian & Lucas, in 2006, [9], and it was compared to various existing evolutionary optimization algorithms, such as: GAs, PSO, simulated annealing (SA), etc. The comparisons were made for the minimization of various mathematical functions, and also an example application of the IWO to an optimum control system is given. In this paper, it is found that the performance of IWO is comparable with other evolutionary algorithms and IWO results are satisfactory for all test functions. Furthermore, it is shown that a colony with a population of 10 to 20 weeds leads to good performance, and a suitable value of the non-linear modulation index is found equal to 3 in most simulations.

In [10], the IWO is compared to four other state-of-the-art optimization techniques for a 12-element, 22-element and 26-element linear antenna array and is found to be superior in a statistically significant fashion (each simulation is executed 50 times in order to get statistical results). Compared to other algorithms such as GAs, PSO and SA, IWO achieves better convergence of the fitness value, it is much easier to understand and implement, and minimizes the need for problem-dependent parameter tuning.

Finally, in [11-12], two variants of the IWO algorithm are used in order to solve the antenna array synthesis problem with null-filling and main lobe tilting for broadcasting applications, and the beam-forming problem respectively.

IWO is a novel, very simple and intuitive optimization method with improved convergence to a global optimum of a multivariable optimization problem. Furthermore, this is the first time to the best knowledge of the authors, that IWO is used to optimize an LPDA antenna design.

This paper is organized as follows: after a short introduction I, and prior-art section II, the classical design algorithm for LPDAs is briefly presented in section III. Section IV explains the IWO method in some detail, while section V presents the optimization results, followed by section VI with the conclusions.

III. CLASSICAL DESIGN ALGORITHM FOR LPDAS

The most complete and practical design procedure for a Log-Periodic dipole array (LPDA) is that by Carrel, [13-14]. The configuration of the log-periodic antenna is described in terms of the design parameters: τ, α, and σ, related by:

$$\alpha = \tan^{-1}\left[\frac{1-\tau}{4\sigma}\right] \tag{1}$$

Once two of the design parameters are specified, the other can be found. The proportionality factors that relate lengths, diameters, and spacings between dipoles are:

$$\tau = \frac{L_{n+1}}{L_n} = \frac{d_{n+1}}{d_n}, \qquad \sigma = \frac{s_n}{2L_n} \tag{2}$$

where, L_n and d_n are respectively the length and the diameter of the n-th dipole, and s_n is the spacing between the n-th and (n+1)-th dipoles. However, for the majority of practical log-periodic array designs, wire dipoles of equal diameters d_n are used, or for some more advanced designs, 3 groups of equal diameter dipoles are used to cover the whole frequency range. In order to reduce some anomalous resonances of the antenna, a short-circuited stub is usually placed at the end of the feeding line at a distance behind the longest dipole. Directivity in dB contour curves as a function of τ for various values of σ are shown in [14], as they have been corrected in [15]. A set of design equations and graphs are used, but in practice it is much easier to use a software incorporating all the necessary design procedure, such as LPCAD, [16-17]. LPCAD also produces a file that can be used for the detailed simulation of the antenna using the NEC software, which employs the Method of Moments for wire antennas, [18-20].

IV. INVASIVE WEED OPTIMIZATION

The IWO algorithm mimics the colonizing behavior of weeds in nature. Initially, a population of weeds is dispersed at random positions inside an N-dimensional search space, where N is the number of parameters to be optimized by the IWO algorithm for the given problem. These positions are produced by a uniform random number generator. The optimization algorithm is an iterative process and consists of three basic steps repeatedly applied at each i-th iteration. These steps are:

A. Reproduction

Each w-th weed produces a number of seeds ns, which depends linearly on the fitness value of the weed, according to the following expression:

$$ns(w,i) = \mathrm{int}\left[ns_{\min} + \left(ns_{\max} - ns_{\min}\right)\frac{fit(w,i) - fit_{\max}(i)}{fit_{\min}(i) - fit_{\max}(i)}\right], \qquad w = 1,2,\dots,W \quad \& \quad i = 0,1,2,\dots,I \tag{3}$$

where $fit(w,i)$ is the fitness value of the w-th weed at the i-th iteration, $fit_{\min}(i)$ and $fit_{\max}(i)$ are respectively the minimum and the maximum fitness value at the i-th iteration, $ns_{\min}$ and $ns_{\max}$ are the limits of ns, W is the population size, I is the maximum number of iterations, and finally int[·] defines the integer part of a number. The parameters W, I, $ns_{\min}$ and $ns_{\max}$ are defined by the user. Provided that the optimization process aims at minimizing the fitness function, $fit_{\min}(i)$ and $fit_{\max}(i)$ are respectively the best and the worst fitness value. Consequently, the "bad" weeds (with high fitness values) are given the possibility to produce less seeds than the "good" weeds (with low fitness values) according to (3). By producing more seeds, a weed is more likely to find positions with better fitness values and thus approach the optimum position.

B. Spatial Dispersion

The seeds produced by every weed are randomly dispersed around the weed. The dispersion is performed according to a Gaussian distribution with standard deviation σ, which decreases as a function of the number of iterations i, according to the expression:

$$\sigma(i) = \frac{(I-i)^{\mu}}{I^{\mu}}(\sigma_{max} - \sigma_{min}) + \sigma_{min}, \qquad i = 0,1,2,\ldots,I \tag{4}$$

where, σ_{min} and σ_{max} are the limits of σ, and μ is a positive real number called *nonlinear modulation index*. The value of μ controls the decreasing rate of σ. It is obvious that σ is the same for all the seeds at a certain iteration. The parameters σ_{min} , σ_{max} and μ are defined by the user.

C. Competitive Exclusion

Due to their invasive nature, the good weeds survive while the bad weeds are eliminated. So, the population size W is restricted according to a maximum allowed number of weeds P ($W \leq P$), which is also user-defined. In order to determine which weeds are going to survive and which ones are going to be eliminated at the end of each i-th iteration, the fitness function is calculated for every seed being inside the search space, while the fitness values of the weeds have already been calculated in the previous iteration. Then, all the members of the colony (i.e., weeds and dispersed seeds) are sorted according to their fitness values and the P best ones with the lowest fitness values survive and thus are able to produce seeds at the next iteration, while the rest of the sorted members are eliminated. Seeds dispersed out of bounds are assigned a very high fitness value (penalty value) that is practically excluding them from further consideration. In this way, only weeds within the bounds survive. The algorithm terminates when the maximum number of iterations I is reached.

V. Antenna Optimization Results

A. Optimized LPDA with 10 dipoles in 450-900 MHz range

The IWO algorithm is applied to optimize a 10-dipole LPDA with respect to the SWR (required less than 2), the front-to-rear (F/R) ratio, equivalent to SLL-Side Lobe Level (required above 20dB) and the forward gain in the frequency range 450-900 MHz. Therefore, the fitness function has to be a linear combination of the above three parameters, which are calculated by applying the 4NEC2 software, [18], for every weed or seed and for all frequencies which are defined in the above range by steps of 10MHz. The optimization variables are the dipole lengths, the dipole diameters, the distances between adjacent dipoles and the characteristic impedance of the transmission line that feeds the dipoles. The execution of the IWO algorithm coded in MATLAB terminates after 6000 iterations producing the NEC file of the optimized antenna geometry. The radiation characteristics of the optimal antenna are extracted by simply running the 4NEC2 software using the above NEC file and are shown in Figs. 1, 2, and 3.

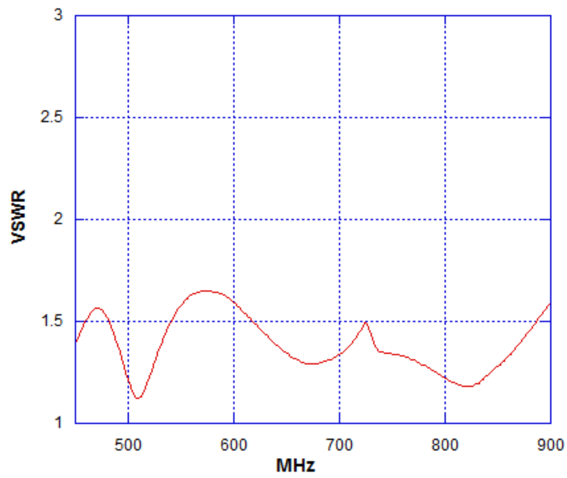

Fig. 1. VSWR of the IWO optimized 10-dipole LPDA.

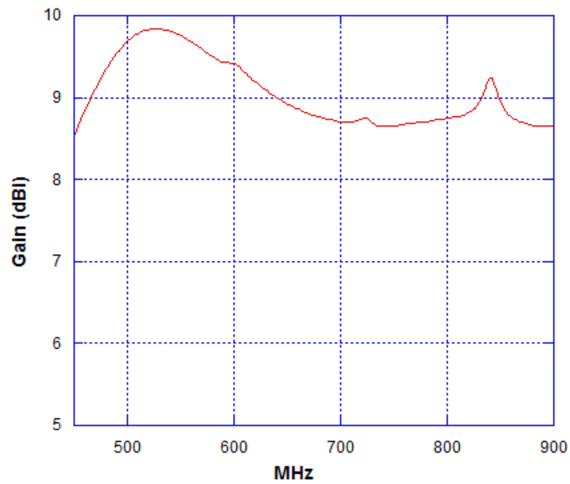

Fig. 2. Gain (dBi) of the IWO optimized 10-dipole LPDA.

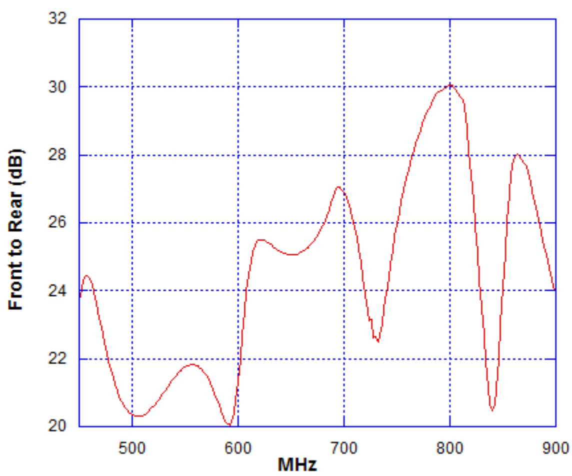

Fig. 3. F/ R ratio (dB) of the IWO optimized 10-dipole LPDA.

It is observed that the SWR is below 2.0 (even below 1.6) for the whole useful bandwidth of the antenna as it was required, or equivalently the reflection coefficient is below –10dB. The forward gain of the antenna is very high for this kind of short LPDA, varying between 8.5 and 9.8 dB. Also, the F/R ratio is between 20 and 30 dB and thus always above 20dB in the entire frequency range, as required in the optimization procedure. The characteristic impedance of the feeding transmission line is calculated to around 102 Ohms. Overall this is a very satisfactory design. The total length of the antenna is around 63 cm and a rear shorting stub is used 12 cm behind the longest dipole. The IWO-optimized design results in a lower fitness value than the one obtained with other evolutionary methods, e.g. with the PSO method, [21], due to the better convergence of IWO to a global optimum.

B. *Equivalent performance classical design LPDA with 16 elements*

In order to obtain a similar performance as that of the IWO optimized 10-element log-periodic antenna by using the *tau* and *sigma* curves of the classical design, 16 dipoles are required. Classical designs with less than 16 dipoles suffer from unacceptably low F/R ratios and therefore cannot be compared to the IWO-optimized design. A design with $\tau = 0.94$, $\sigma = 0.08$, and a length of 53cm yields satisfactory results as shown in Figs. 4-6. The SWR is below 2.0 (even below 1.9) for the whole useful bandwidth of the antenna as it is required, although with a somewhat worse peak on 800 MHz compared to the IWO-optimized design. The forward gain varies from 8.1 to 9.5 dB which is 0.3-0.4 dB lower than the IWO-optimized design. On the other hand, the F/R ratio is higher than 20 dB in the whole frequency range and in general higher than the F/R of the IWO-optimized design. However, this is due to the much bigger number of dipoles used in this case (16 dipoles instead of only 10 dipoles) which results in a more directive radiation pattern.

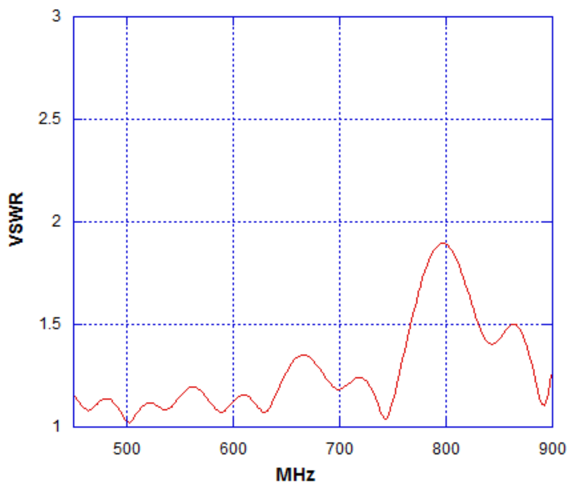

Fig. 4. VSWR of the classical design 16-dipole LPDA with $\tau = 0.94$, $\sigma = 0.08$.

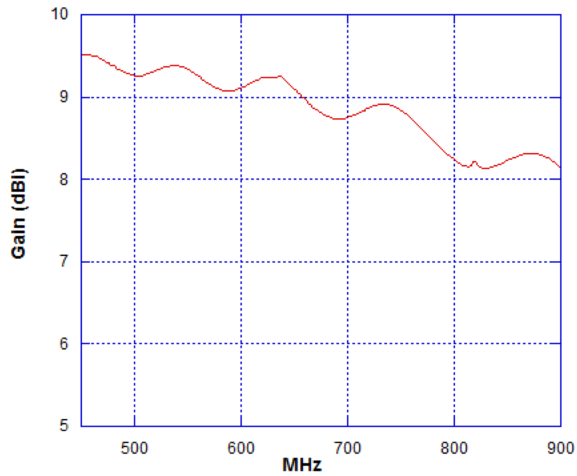

Fig. 5. Gain (dBi) of the classical design 16-dipole LPDA with $\tau = 0.94$, $\sigma = 0.08$.

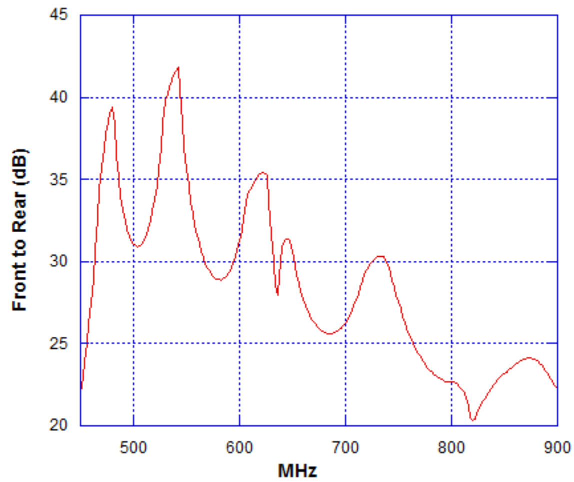

Fig. 6. Front to Rear ratio (dB) of the classical design 16-dipole LPDA with $\tau = 0.94$, $\sigma = 0.08$.

VI. Conclusions

Log-periodic antennas with significantly improved properties (SWR, Gain, F/R ratio) have been designed using an Invasive Weed Optimization (IWO) method for the first time. This evolutionary optimization algorithm is found to be very simple and efficient for LPDA antenna design. An example case shows that in order to achieve similar results with the classical design method we would need an antenna with much more dipoles. Likewise, it is expected that by using the same number of dipoles the IWO optimized antenna will exhibit an even better performance.

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