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Optimal Wideband LPDA Design for Efficient Multimedia Content Delivery Over Emerging Mobile Computing Systems

Zaharias D. Zaharis, *Member, IEEE*, Christos Skeberis, Pavlos I. Lazaridis, *Member, IEEE*, and Thomas D. Xenos

***Abstract*—An optimal synthesis of a wideband log-periodic dipole array (LPDA) is introduced in this paper. The LPDA optimization is performed under several requirements concerning the standing wave ratio, the forward gain, the gain flatness, the front-to-back ratio, and the sidelobe level, over a wide frequency range. The LPDA geometry that complies with the aforementioned requirements is suitable for efficient multimedia content delivery. The optimization process is accomplished by applying a recently introduced method called invasive weed optimization (IWO). The method has already been compared to other evolutionary methods and has shown superiority in solving complex nonlinear problems in telecommunications and electromagnetics. In this paper, the IWO method has been chosen to optimize an LPDA for operation in the frequency range of 800–3300 MHz. Due to its excellent performance, the LPDA can effectively be used for multimedia content reception over future mobile computing systems.**

***Index Terms*—Invasive weed optimization (IWO), log-periodic dipole array (LPDA) design, optimization algorithms.**

I. Introduction

MOBILE computing systems have been increasingly developed in recent years due to the need for high-quality multimedia services. This development leads to the demand for network resources and efficient telecommunications equipment [1]–[5]. Antenna arrays play an important role in wireless communications, [6]–[10]. The radiation characteristics of an antenna array specify the operation efficiency of a communications base station in a real complex environment. Log-periodic dipole arrays (LPDAs) are special linear arrays composed of parallel dipoles of gradually increasing length along the array axis from the feeding source to the end of the axis, and a pair of booms used to feed the dipoles in such a way that the feeding is inverted when passing from one dipole to the next one [11]. These arrays usually demonstrate wideband behavior and low gain flatness (i.e., the difference between the maximum and the minimum forward gain values, respectively $FG_{\max}$ and $FG_{\min}$, over the operating bandwidth). This is due to the fact that, at every operating frequency, some of the array elements act as active dipoles while the rest of them behave as parasitic ones. Of course, these characteristics are achieved by properly selecting the geometrical parameters of the LPDA, such as the lengths and radii of the LPDA elements as well as the distances between adjacent elements.

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Z. D. Zaharis, C. Skeberis, and T. D. Xenos are with the Department of Electrical and Computer Engineering, Aristotle University of Thessaloniki, 54124 Thessaloniki, Greece (e-mail: zaharis@auth.gr; cskeberis@auth.gr; tdxenos@auth.gr).

P. I. Lazaridis is with the Department of Engineering and Technology, University of Huddersfield, Huddersfield HD1 3DH, U.K. (e-mail: p.lazaridis@hud.ac.uk).

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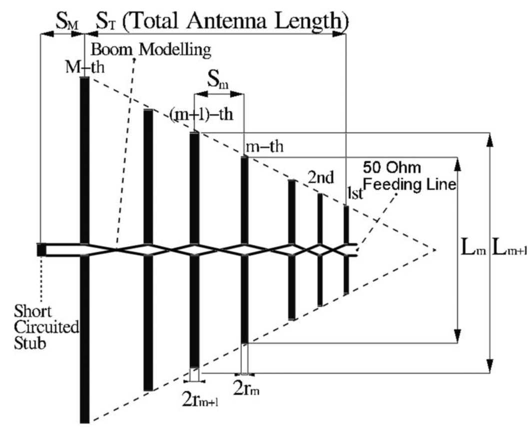

Fig. 1. Carrel's LPDA geometry.

The first and also most popular procedure for LPDA design has been introduced by Carrel [12]. This method has later been corrected by Butson and Thompson [13] and is still used until today. The main consideration of this method is that all the LPDA elements are located inside the same angular sector (see Fig. 1). Also, the two booms that feed the elements are modeled as a transmission line of two conductive wires, which are inverted when passing from one element to the next one. Therefore, the whole geometry, i.e., the element lengths, radii, and distances, of an M-element LPDA can be easily defined by using two special geometrical parameters, known as *scale factor* τ and *relative spacing* σ. If the desired value of the average directivity is known, the aforementioned two parameters can be calculated from the constant directivity contour curves of the well-known Carrel graph introduced in [12] and corrected in [13]. According to Carrel's method, the LPDA geometry is then estimated by using the expressions given in the following:

$$L_m = \tau^{M-m} L_M, \qquad m = 1, \ldots, M \tag{1}$$

$$r_m = \tau^{M-m} r_M, \qquad m = 1, \ldots, M \tag{2}$$

$$S_m = 2\sigma\tau^{M-m-1} L_M, \qquad m = 1, \ldots, M-1 \tag{3}$$

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where L_m and r_m are respectively the length and the radius of the mth element, while S_m is the distance between the mth and the $(m+1)$th element. In order to use the aforementioned three equations, the values of L_M and r_M (i.e., the length and the radius of the largest element) must be known. L_M is set equal to half wavelength at the lower operating frequency and is then reduced approximately by 5% due to the dipole thickness. The radius r_M is set equal to a value that can easily be found in practice (e.g., 5 mm).

The aforementioned design procedure is an easily applicable method. However, it is based on a rough consideration of the LPDA model, and therefore, it cannot estimate the exact behavior of the LPDA inside a wide bandwidth. Moreover, it generally has the ability to control the standing wave ratio (SWR), the forward gain (FG), and the front-to-back ratio (FBR). However, the method cannot control the sidelobe level (SLL) as well as the gain flatness (GF) in cases of wide operating bandwidths. The need for low SLL is very critical since it helps to reduce the signal degradation due to multipath fading and, also, it avoids unnecessary spatial spread of radiated power. Also, a low GF value is desirable in order to keep the signal reception at similar levels over the entire operating bandwidth. It is therefore obvious that a design method capable of controlling the values of SWR, FG, FBR, SLL, and GF would result in an LPDA suitable for efficient content delivery. Such a method can be constructed by combining an optimization technique with a full-wave analysis of the LPDA.

The design method proposed here combines a recently introduced global optimization method called invasive weed optimization (IWO) [14]–[17] and the numerical electromagnetics code (NEC) [18], which implements a well-known full-wave analysis method called method of moments [19]. The NEC calculates the radiation characteristics of the LPDA inside the operating bandwidth and returns them to the IWO method every time it is required for fitness function calculations. To the best of the authors' knowledge, the IWO has not been applied so far to optimize LPDAs. Unlike Carrel's method, the proposed technique is an effective design tool that provides excellent approximation of the antenna behavior and has the ability to control all the electromagnetic characteristics mentioned earlier (i.e., SWR, FG, GF, FBR, and SLL) inside a wide bandwidth. Also, this paper is the first effort recorded in the literature to optimize simultaneously all these characteristics over a wide frequency range. The results shown hereinafter exhibit the superiority of the IWO-based technique over Carrel's design method.

II. Design Problem Description

The IWO method is applied in this paper to design an optimal 12-element LPDA $(M = 12)$ for operation in the frequency range of 800–3300 MHz. Specific requirements have to be satisfied: 1) $SWR \leq 1.8$; 2) FG as high as possible; 3) $GF = FG_{\max} - FG_{\min} \leq 2$ dB; and 4) $SLL \leq -20$ dB on the E-plane of the radiation pattern of the LPDA. In the literature, the operating bandwidth is usually defined as the frequency range where $SWR \leq 2$ at the input of the RF system. To be sure that the LPDA will be in matching condition even in practice, the more strict value of 1.8 has been chosen in the first requirement. It must also be noted that the SLL estimation takes into account all the secondary lobes on the E-plane of the radiation pattern, including the back lobe. Therefore, an additional requirement that concerns the FBR is satisfied together with the fourth requirement, i.e., if the requirement for $SLL \leq -20$ dB is satisfied then the requirement for $FBR \geq 20$ dB is automatically satisfied as well.

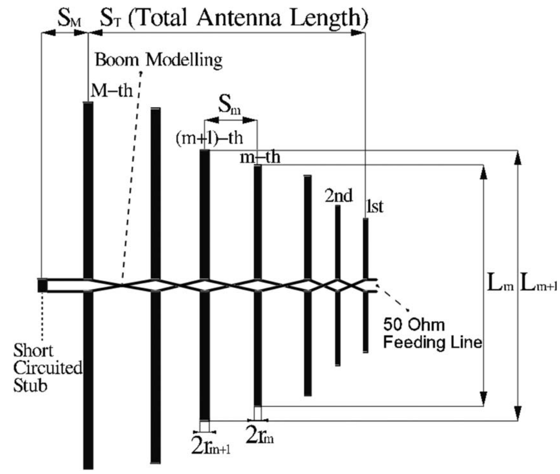

Fig. 2. Proposed LPDA geometry.

In order to increase the degrees of freedom in comparison to Carrel's method and thus help the IWO method to find an optimal LPDA geometry, the LPDA elements are not considered inside the same angle, and therefore, their lengths L_m $(m = 1, \ldots, M)$, radii r_m $(m = 1, \ldots, M)$, and distances S_m $(m = 1, \ldots, M-1)$ are independently optimized by the IWO algorithm (see Fig. 2). There are two additional optimization parameters: The first one is the distance S_M between the largest element (Mth) and a short-circuited stub located behind this element. The second is the characteristic impedance Z_0 of the line that models the booms of the LPDA. In total, there are $3M + 1$ variables to be optimized.

To exhibit the superiority of the proposed method, the IWO-based LPDA is compared to a respective LPDA of the same total length S_T derived by Carrel's method. It must be noted that a short-circuited stub of proper length is used by both the LPDAs (see Figs. 1 and 2) since it helps the large LPDA elements to reduce the current that may arise due to high-order resonances induced on those elements.

III. Related Work on LPDA Optimization

A deterministic design technique is not always capable of satisfying all the requirements defined by a nonlinear design problem. Problems, where multiple requirements have to be met, can only be solved by applying evolutionary optimization methods. Several of these problems that concern the LPDA design can be found in the literature [20]–[29]. In some of these, a comparison between the proposed evolutionary method and other evolutionary or nonevolutionary methods is given regarding the satisfaction of the design requirements. In any case, Carrel's method is a reference LPDA design method for comparison.

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A genetic algorithm (GA), the Nelder–Mead downhill simplex method, and a hybrid method that combines the aforementioned two methods are used in [20] in order to optimize LPDAs under requirements that concern the average values of FG and SWR as well as their maximum deviation over the whole bandwidth. In [21] and [22], GAs are employed to maintain the values of FG and SWR over the entire operating bandwidth and simultaneously minimize the LPDA length as well as the number of LPDA elements. The nondominated sorting genetic algorithm II is applied in [23] to optimize LPDAs for operation in the range of 3–30 MHz under requirements for minimum SWR, maximum FG, and minimum LPDA length. A particle swarm optimization (PSO) algorithm is employed in [24] to design an optimal 10-element LPDA for operation in the range of 450–1350 MHz under requirements that concern the average values of SWR, FG, and FBR. In [25], an inverted-V LPDA is optimized in the range of 6–30 MHz by using GAs under requirements that concern the values of SWR, FG, and SLL as well as the LPDA size. In [26], planar LPDAs are optimized for operation in the S-band by applying a PSO algorithm under requirements that concern the values of FG and SWR. In [27], a 13-element LPDA is optimized for operation in the Global System for Mobile Communications (GSM), Worldwide Interoperability for Microwave Access (WiMAX), Bluetooth, Wi-Fi, and third generation of mobile telecommunications technology (3G) bands by applying PSO under requirements for the values of FG and SWR. Also, a GA is applied in [28] to optimize a 10-element LPDA for operation in the GSM, WiMAX, and Wi-Fi bands under requirements for higher FG and smaller size. Finally, the bacteria foraging algorithm is employed in [29] to optimize LPDAs for operation in the UHF television (TV) band under requirements that concern the average values of SWR, FG, FBR, and SLL.

In all the aforementioned studies, FG and SWR are considered under optimization, except for [28] where requirements are set for high FG and small LPDA size. Requirements for low SLL values are considered only in [25] and [29]. Nevertheless, the requirement for $SLL \leq -6$ dB in [25] is soft enough (since values of SLL equal to -6 dB are easy to be achieved) and is just defined to prevent main lobe splitting. It is also shown in [29] that the requirement for average SLL equal to -40 dB is not satisfied by any of the LPDAs considered for optimization. In addition, the operating bandwidth considered in [29] is not as wide as that considered in the present optimization. In this paper, practical requirements concerning the values of SWR, FG, GF, FBR, and SLL have to be satisfied inside a wide frequency range (i.e., the range of 800–3300 MHz). It has to be noted that the minimization of the LPDA length is not of our concern since our intention is to show that the proposed design method is capable of producing an optimized geometry with better radiation characteristics than those of an LPDA geometry with the same length S_T produced by Carrel's method.

IV. IWO

Many studies are found in the literature where evolutionary optimization techniques are applied to solve complex nonlinear problems [14]–[17], [30]–[45]. The IWO method was initially proposed in [14]. Thereafter, the method was used to solve several problems of antenna optimization and has exhibited superiority in terms of performance compared to other evolutionary methods. However, IWO has never been applied so far to perform LPDA optimization.

The IWO is an iterative method, completed within a predefined number I of iterations and inspired by the behavior of weeds in nature. The mathematical model of this behavior forms the IWO algorithm. According to this model, three phases are applied at every ith ($i=1,\ldots,I$) iteration: 1) *Reproduction*; 2) *Spatial Dispersion*; and 3) *Competitive Exclusion*.

In the beginning of the optimization process, a population of W weeds is distributed in an N-dimensional space, where N is the number of optimization variables x_n. Therefore, the position of each wth weed is defined by the vector $X(w) = [x_1(w)\ x_2(w)\ \ldots\ x_N(w)]$. Also, in the beginning, the values of $x_n(w)$ $(n = 1,\ldots,N, w = 1,\ldots,W)$ are produced by a uniform random number generator inside the interval $[x\min_n, x\max_n]$, where $x\min_n$ $(n = 1,\ldots,N)$ and $x\max_n$ $(n = 1,\ldots,N)$ are user-defined parameters. The interval $[x\min_n, x\max_n]$ is actually the search space of variable x_n. Moreover, every weed is assigned a fitness value, which depends on the weed position as given in the following:

$$fit(w) = fit\left(x_1(w), x_2(w), \ldots, x_N(w)\right). \quad (4)$$

In the reproduction phase, every weed produces a number of seeds $s_i(w)$, which is a linear function of the weed fitness as given in the following:

$$s_i(w) = \text{int}\left[\frac{fit\max_i - fit_i(w)}{fit\max_i - fit\min_i}(s_{\max} - s_{\min}) + s_{\min}\right], \quad i = 1,\ldots,I \quad \& \quad w = 1,\ldots,W \quad (5)$$

where $fit\min_i$ and $fit\max_i$ are the extreme fitness values at the ith iteration, while $s_{\min}$ and $s_{\max}$ are user-defined parameters that represent the extreme values of s_i. It seems that weeds with low fitness values (good weeds) produce more seeds than weeds with high fitness values (bad weeds). Therefore, a good weed is more capable of finding better positions inside the search space than a bad one.

The spatial dispersion is the second phase, where the seeds produced by a weed in the previous phase are dispersed around this weed according to a normal distribution with standard deviation given by the following expression:

$$\sigma_i = \left(\frac{I-i}{I-1}\right)^{\mu}(\sigma_{\max} - \sigma_{\min}) + \sigma_{\min}, \quad i = 1,\ldots,I \quad (6)$$

where $\sigma_{\min}$ and $\sigma_{\max}$ are the extreme values of σ_i, while μ determines the decreasing rate of σ_i and is called *nonlinear modulation index*. It is obvious that σ_i is the same for all the population at a given iteration. However, σ_i refers to seed dispersion in a unitary search space (i.e., the search space where $x\max_n - x\min_n = 1$). If an optimization variable x_n corresponds to a nonunitary search space, then the actual standard deviation for this variable is set equal to $(x\max_n - x\min_n) \times \sigma_i$.

In the competitive exclusion phase, all the members of the colony (weeds and seeds) are sorted according to their fitness values, and only the best $W_{\max}$ ones (i.e., the $W_{\max}$

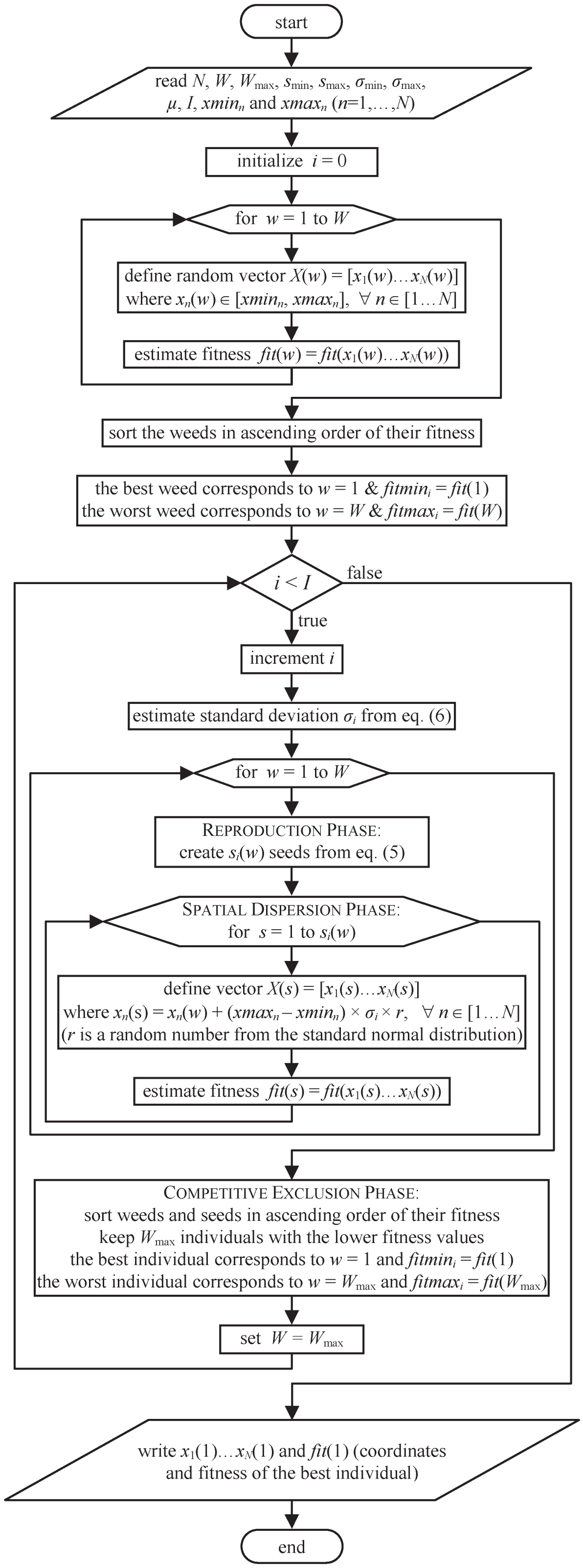

Fig. 3. Flowchart of the IWO method.

members with the lower fitness values) survive, while the rest are terminated. In this way, only the good weeds are able to keep searching for better positions in the next iterations.

In total, the user-defined parameters required by the IWO algorithm are the following: $x\min_n$ $(n = 1,\ldots,N)$, $x\max_n$ $(n = 1,\ldots,N), I, W, W_{\max}, s_{\min}, s_{\max}, \sigma_{\min}, \sigma_{\max}$, and μ. The aforementioned optimization procedure of the IWO method is graphically given in Fig. 3.

V. Fitness Function Description

It is obvious that the optimization problem is inherently multiobjective since several requirements must be satisfied at the same time. On the other hand, the IWO, like every other evolutionary optimization method, aims at minimizing a single mathematical function, which is the fitness function mentioned earlier. In order to simultaneously satisfy multiple requirements by applying such a method, the fitness function must be described as a linear combination of terms, where each term is an expression of a respective requirement. When the fitness function finds the global minimum point, all the terms have achieved their respective minimum values, which means that all the requirements have been satisfied. According to the requirements described in Section II, the fitness function is defined as follows:

$$\begin{aligned} fit = & -k_1 FG_{\min} + k_2 \left[\max(GF, 2) - 2\right] \\ & + k_3 \left[\max(SLL_{\max}, -20) + 20\right] \\ & + k_4 \left[\max(SWR_{\max}, 1.8) - 1.8\right] \end{aligned} \tag{7}$$

where $FG_{\min}$, GF, $SLL_{\max}$, and $SWR_{\max}$ are respectively the minimum forward gain [in deciBel isotropic (dBi)], the gain flatness (in decibels), the maximum SLL (in decibels), and the maximum SWR found over the entire operating bandwidth, which, in our case, is 800–3300 MHz. To estimate the aforementioned four values, the values of FG, SLL, and SWR are calculated over the range of 800–3300 MHz at steps of 10 MHz by employing the NEC software. Finally, k_1, k_2, k_3, and k_4 are user-defined positive coefficients which aim to balance the minimization of the four terms shown in (7) or reinforce the minimization of any of these terms in cases when one term is not minimized like the rest.

As the value of $FG_{\min}$ increases, the first term of (7) decreases. Thus, this term aims at maximizing FG over the entire bandwidth. The next three terms are formed so that values of GF less than 2 dB, values of $SLL_{\max}$ less than -20 dB, and values of $SWR_{\max}$ less than 1.8 do not cause further minimization of the fitness function since the desired values of GF, SLL, and SWR have already been achieved. Finally, it has to be noted that the third term of (7) aims at satisfying not only the SLL requirement but also the requirement for the desired value of FBR $(FBR \geq 20$ dB).

VI. Optimization Results

The IWO method is used here to design an optimal 12-element LPDA $(M = 12)$ for operation in the frequency range of 800–3300 MHz under the requirements given in Section II. As mentioned in the last paragraph of Section IV, some parameters need to be defined in order to execute the IWO algorithm. Therefore, the initial and the maximum weed population are both considered to be composed of 20 weeds $(W = W_{\max} = 20)$. The number of seeds produced by a weed

TABLE I
INITIAL ELEMENT LENGTH VALUES DERIVED FROM CARREL'S METHOD AND ELEMENT LENGTH LIMITS

Element m	Initial Length L_m (meters)	Lower Length Limit D_m (meters)	Upper Length Limit U_m (meters)
1	0.034	0.031	0.037
2	0.039	0.037	0.043
3	0.046	0.043	0.050
4	0.053	0.050	0.058
5	0.062	0.058	0.067
6	0.072	0.067	0.078
7	0.084	0.078	0.091
8	0.097	0.091	0.105
9	0.113	0.105	0.123
10	0.132	0.123	0.141
11	0.153	0.142	0.164
12	0.178	0.166	0.191

TABLE II
IWO-BASED LPDA GEOMETRY

Element m	Element Length L_m (meters)	Element Distance S_m (meters)	Element Radius r_m (meters)
1	0.034	0.012	0.0017
2	0.039	0.016	0.0017
3	0.047	0.021	0.0024
4	0.054	0.022	0.0031
5	0.062	0.031	0.0042
6	0.076	0.040	0.0047
7	0.090	0.040	0.0049
8	0.105	0.038	0.0041
9	0.120	0.070	0.0047
10	0.129	0.068	0.0021
11	0.157	0.035	0.0041
12	0.184	0.061	0.0023
$Z_0 = 108.6\Omega$			

TABLE III
CARREL'S LPDA GEOMETRY

Element m	Element Length L_m (meters)	Element Distance S_m (meters)	Element Radius r_m (meters)
1	0.034	0.015	0.0010
2	0.039	0.018	0.0011
3	0.046	0.020	0.0013
4	0.053	0.024	0.0015
5	0.062	0.028	0.0017
6	0.072	0.032	0.0020
7	0.084	0.037	0.0024
8	0.097	0.043	0.0027
9	0.113	0.050	0.0032
10	0.132	0.058	0.0037
11	0.153	0.068	0.0043
12	0.178	0.087	0.0050
$Z_0 = 80\Omega$			

ranges from $s_{\min}=0$ (for the worst weed) to $s_{\max}=5$ (for the best weed) and is calculated from (5) according to the weed fitness value. The boundary values for the standard deviation of the seed dispersion are $\sigma_{\min}=0$ and $\sigma_{\max}=0.15$, while the nonlinear modulation index μ is set equal to 2.5. The optimization procedure is completed within 2000 iterations ($I=2000$).

The optimization variables are L_m $(m = 1, \ldots, 12)$, r_m $(m = 1, \ldots, 12)$, S_m $(m = 1, \ldots, 12)$, and Z_0, i.e., 37 variables in total $(3M + 1 = 37)$, as explained in Section II. Therefore, the weed position is defined by the vector

$$X = [x_1 x_2 \ldots x_{37}] = [L_1 L_2 \ldots L_{12} r_1 r_2 \ldots r_{12} S_1 S_2 \ldots S_{12} Z_0] \quad (8)$$

which means that the variables x_n $(n = 1, \ldots, 12)$ are the dipole lengths L_m, the variables x_n $(n = 13, \ldots, 24)$ are the radii r_m, the variables x_n $(n = 25, \ldots, 36)$ are the distances S_m, and, finally, x_{37} is equal to Z_0. The radius limits are $r_{\min} = 0.001$ m and $r_{\max} = 0.005$ m. In order to avoid elements touching each other, the lower limit of the distances between adjacent elements is considered to be $S_{\min} = 2r_{\max} + 0.002 = 0.012$ m. The upper limit of the distances is considered to be $S_{\max} = \lambda_{\max}/4 = 0.094$ m, where $\lambda_{\max}$ is the wavelength at 800 MHz, considering that the maximum variation of voltage, current, or impedance is obtained along a quarter of the maximum wavelength (i.e., at 800 MHz). The values of Z_0 range from 50 to 200 Ω. Finally, the limits of the element lengths are derived separately for each element and are based on length values derived from Carrel's method. In particular, from the corrected Carrel's graph [46] and by considering an antenna directivity equal to 7.5 dBi, it results in $\tau = 0.86$ and $\sigma = 0.16$ (optimum σ value). The length L_{12} of the largest element is set equal to half wavelength at the lower operating frequency (i.e., at 800 MHz) and is then reduced approximately by 5% due to the element thickness. The rest of the lengths $(L_1, \ldots, L_{11})$ are calculated from (1). These initial values are shown in the second column of Table I. The average length value $(L_m + L_{m+1})/2$ of two adjacent elements is considered to be the upper limit U_m for L_m and the lower limit D_{m+1} for L_{m+1}. In this way, all the length limits are estimated except for D_1 and U_{12}. These can be considered to be at the same distance from the respective lengths as the opposite limits (U_1 and D_{12}) from the same lengths, i.e., $U_1 - L_1 = L_1 - D_1$ and $U_{12} - L_{12} = L_{12} - D_{12}$. All the length limits are given in columns 3 and 4 of Table I. The idea for different length limits restricts the search space of the element lengths and helps, in this way, the optimization procedure to reach the optimum result faster.

The geometry of the optimized LPDA extracted from the IWO algorithm is given in Table II. The total LPDA length is calculated from the expression

$$S_T = \sum_{m=1}^{11} S_m \quad (9)$$

and is found equal to 0.393 m. In order to examine the performance of the proposed method, a new LPDA is designed by applying Carrel's method and is compared to the IWO-based LPDA. To have a fair comparison between the two LPDAs, the new LPDA is composed of the same number of elements (i.e., 12 elements), has the same length (0.393 m), operates in the same frequency range (800–3300 MHz), and uses a short-circuited stub of proper length as does the IWO-based LPDA. As mentioned in Section II, the short-circuited stub helps the large LPDA elements to reduce the current that may arise due to high-order resonances induced on these elements. The geometry of this LPDA is given in Table III. From both the LPDA geometries given in Tables II and III, the values of SWR, FG, and SLL versus frequency are extracted by

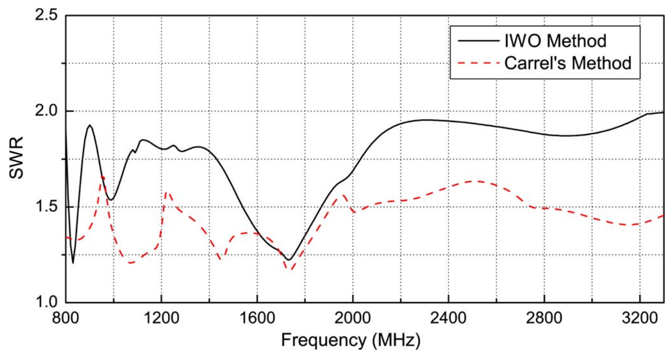

Fig. 4. SWR versus frequency.

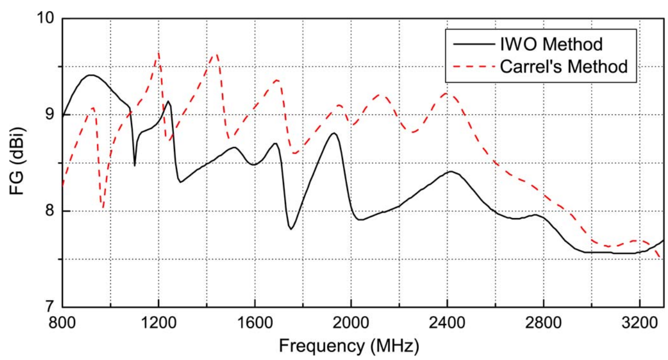

Fig. 5. Gain versus frequency.

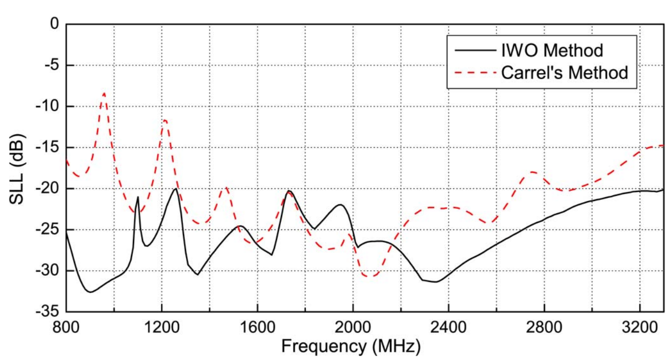

Fig. 6. SLL versus frequency.

applying the NEC software and are displayed respectively in the comparative graphs of Figs. 4–6. These graphs are used to find the minimum, the maximum, and the mean value as well as the standard deviation of SWR, FG, and SLL and, finally, the value of GF over the entire frequency range. These values are given in Table IV.

From Fig. 4, it is easy to realize that the LPDA derived from Carrel's method has better behavior in terms of SWR within the entire bandwidth. Nevertheless, the IWO-based LPDA produces SWR values less than 2, which means that it satisfies the impedance-matching condition over the entire bandwidth according to the literature.

In addition, as shown in Fig. 5, the values of FG produced by the Carrel-based LPDA have rapid variations with significant drops, which cause an increase in the value of GF. It seems that this behavior is due to high-order resonances induced on large

TABLE IV
LPDA PERFORMANCE PARAMETERS

Performance Parameter	IWO Method	Carrel's Method
SWR_{min}	1.21	1.17
SWR_{max}	1.99	1.66
SWR_{mean}	1.77	1.44
SWR_{std}	0.21	0.12
FG_{min} (dBi)	7.56	7.45
FG_{max} (dBi)	9.41	9.64
FG_{mean} (dBi)	8.30	8.68
FG_{std} (dBi)	0.52	0.55
GF (dB)	1.85	2.19
SLL_{min} (dB)	–32.60	–30.72
SLL_{max} (dB)	–20.00	–8.39
SLL_{mean} (dB)	–25.71	–21.50
SLL_{std} (dB)	3.56	4.32

LPDA elements despite the use of the stub. On the contrary, the IWO-based LPDA exhibits a smoother variation of FG and a value of GF less than the required value of 2 dB (also see Table IV).

Finally, the SLL values produced by the IWO-based LPDA are kept below the desired value of -20 dB inside the whole operating bandwidth, as shown in Fig. 6. On the other hand, Fig. 6 confirms the inability of Carrel's method to perform SLL control. It seems that the IWO method has the ability to suppress high-order resonances, while Carrel's method does not, even with the use of a short-circuited stub of proper length.

Overall, the IWO-based LPDA geometry satisfies all the design requirements and has better behavior in terms of GF and SLL than the Carrel-based geometry. In other words, the IWO-based LPDA has all the desired radiation characteristics that make it suitable for efficient multimedia content reception. Also, the IWO method seems to be a very useful design tool for future mobile computing systems.

VII. CONCLUSION

The IWO method has been applied in combination with the NEC software to design an optimal 12-element LPDA for operation in the frequency range of 800–3300 MHz. The optimization has been performed under multiple requirements concerning the desired values of FG, GF, SLL, FBR, and SWR. The optimized LPDA geometry has better radiation characteristics inside the entire operating bandwidth compared to a respective LPDA with the same length produced by Carrel's method, which is the basic technique for LPDA design. This work is the first effort recorded in the literature to optimize simultaneously the values of FG, GF, SLL, FBR, and SWR over a wide frequency range. The LPDA derived from the optimization procedure is suitable for efficient multimedia content reception. Due to its effectiveness, the IWO method can be a very useful design tool for emerging mobile computing systems.

REFERENCES

[1] C. X. Mavromoustakis, E. Pallis, and G. Mastorakis, Eds., *Resource Management in Mobile Computing Environments*, vol. 3, *Modeling and Optimization in Science and Technologies*. New York, NY, USA: Springer-Verlag, 2014.

[2] C. X. Mavromoustakis, A. Bourdena, G. Mastorakis, E. Pallis, and G. Kormentzas, "An energy-aware scheme for efficient spectrum utilization in a 5G mobile cognitive radio network architecture," *Telecommun. Syst.*, Nov. 2014.

[3] K. Papanikolaou, C. X. Mavromoustakis, G. Mastorakis, A. Bourdena, and C. Dobre, "Energy consumption optimization using social interaction in the mobile cloud," in *Proc. 6th Int. Conf. MONAMI*, Sep. 22–24, 2014, pp. 1–14.

[4] S. Jia, C. Xu, J. Guan, H. Zhang, and G.-M. Muntean, "A novel cooperative content fetching-based strategy to increase the quality of video delivery to mobile users in wireless networks," *IEEE Trans. Broadcast.*, vol. 60, no. 2, pp. 370–384, Jun. 2014.

[5] C. X. Mavromoustakis *et al.*, "Dynamic cloud resource migration for efficient 3D video processing in mobile computing environments," in *Novel 3D Media Technologies*, M. K. Khan, Ed. New York, NY, USA: Springer-Verlag, 2015, pp. 119–134.

[6] A. Hornbostel, A. Konovaltsev, H. Denks, and F. Antreich, "Simulation of multi-element antenna systems for navigation applications," *IEEE Syst. J.*, vol. 2, no. 1, pp. 7–19, Mar. 2008.

[7] E. Chiu and V. K. N. Lau, "Precoding design for multi-antenna multicast broadcast services with limited feedback," *IEEE Syst. J.*, vol. 4, no. 4, pp. 550–560, Dec. 2010.

[8] A.-H. Tsai, L.-C. Wang, J.-H. Huang, and R.-B. Hwang, "High-capacity OFDMA femtocells by directional antennas and location awareness," *IEEE Syst. J.*, vol. 6, no. 2, pp. 329–340, Jun. 2012.

[9] T. Ali, A. Z. Sadeque, M. Saquib, and M. Ali, "MIMO radar for target detection and localization in sensor networks," *IEEE Syst. J.*, vol. 8, no. 1, pp. 75–82, Mar. 2014.

[10] H. Xu, H. Aliakbarian, E. Van der Westhuizen, R. Wolhuter, and G. A. E. Vandenbosch, "An architectural scheme for real-time multiple users beam tracking systems," *IEEE Syst. J.*, to be published.

[11] C. A. Balanis, *Antenna Theory, Analysis, and Design*, 3rd ed. Hoboken, NJ, USA: Wiley, 2005, pp. 611–652.

[12] R. L. Carrel, "Analysis and Design of the Log-Periodic Dipole Antenna," Ph.D. dissertation, Dept. Elect. Eng., University of Illinois, University Microfilms, Inc., Ann Arbor, MI, USA, 1961.

[13] P. C. Butson and G. T. Thompson, "A note on the calculation of the gain of log-periodic dipole antennas," *IEEE Trans. Antennas Propag.*, vol. AP-24, no. 1, pp. 105–106, Jan. 1976.

[14] A. R. Mehrabian and C. Lucas, "A novel numerical optimization algorithm inspired from weed colonization," *Ecol. Inform.*, vol. 1, no. 4, pp. 355–366, Dec. 2006.

[15] Z. D. Zaharis, C. Skeberis, and T. D. Xenos, "Improved antenna array adaptive beamforming with low sidelobe level using a novel adaptive invasive weed optimization method," *Prog. Electromagn. Res.*, vol. 124, pp. 137–150, 2012.

[16] Z. D. Zaharis, C. Skeberis, T. D. Xenos, P. I. Lazaridis, and J. Cosmas, "Design of a novel antenna array beamformer using neural networks trained by modified adaptive dispersion invasive weed optimization based data," *IEEE Trans. Broadcast.*, vol. 59, no. 3, pp. 455–460, Sep. 2013.

[17] Z. D. Zaharis, P. I. Lazaridis, J. Cosmas, C. Skeberis, and T. D. Xenos, "Synthesis of a near-optimal high-gain antenna array with main lobe tilting and null filling using Taguchi initialized invasive weed optimization," *IEEE Trans. Broadcast.*, vol. 60, no. 1, pp. 120–127, Mar. 2014.

[18] G. J. Burke and A. J. Poggio, "Numerical electromagnetics code (NEC)—Method of moments," Naval Ocean Systems Center, San Diego, CA, USA, Tech. Doc. 116, Jan. 1981.

[19] R. C. Hansen, *Moment Methods in Antennas and Scattering*. Norwood, MA, USA: Artech House, 1990.

[20] Y. C. Chung and R. Haupt, "Log-periodic dipole array optimization," *J. Electromagn. Waves Appl.*, vol. 15, no. 9, pp. 1269–1280, 2001.

[21] M. A. Mangoud, M. A. Aboul-Dahab, A. I. Zaki, and S. E. El-Khamy, "Genetic algorithm design of compressed log periodic dipole array," in *Proc. IEEE 46th Midwest Symp. Circuits Syst.*, Dec. 27–30, 2003, vol. 3, pp. 1194–1197.

[22] S. E. El-Khamy, M. A. Mangoud, M. A. Aboul-Dahab, and A. I. Zaki, "Fractal multiband antennas using GA/MOM optimized log periodic dipole arrays," in *Proc. IEEE Antennas Propag. Soc. Int. Symp.*, Jun. 20–25, 2004, vol. 4, pp. 3433–3436.

[23] T. L. Pitzer, A. James, G. B. Lamont, and A. J. Terzuoli, "Linear ensemble antennas resulting from the optimization of log periodic dipole arrays using genetic algorithms," in *Proc. IEEE Congr. Evol. Comput.*, Jul. 16–21, 2006, pp. 3189–3196.

[24] M. Fernandez Pantoja, A. R. Bretones, F. Garcia Ruiz, S. G. Garcia, and R. G. Martin, "Particle-swarm optimization in antenna design: Optimization of log-periodic dipole arrays," *IEEE Antennas Propag. Mag.*, vol. 49, no. 4, pp. 34–47, Aug. 2007.

[25] X.-L. Zhang and H.-T. Gao, "An optimum design of miniaturized high frequency inverted-V log-periodic dipole antenna," in *Proc. IEEE CIE Int. Conf. Radar*, Oct. 24–27, 2011, vol. 2, pp. 1185–1188.

[26] S. M. Hashemi, V. Nayyeri, M. Soleimani, and A.-R. Mallahzadeh, "Designing a compact-optimized planar dipole array antenna," *IEEE Antennas Wireless Propag. Lett.*, vol. 10, pp. 243–246, 2011.

[27] M. Aziz-ul-Haq *et al.*, "Log periodic dipole antenna design using particle swarm optimization," *Int. J. Electromagn. Appl.*, vol. 2, no. 4, pp. 65–68, 2012.

[28] M. Touseef *et al.*, "Genetic algorithm optimization of log-periodic dipole array," *Int. J. Electromagn. Appl.*, vol. 2, no. 6, pp. 169–173, 2012.

[29] B. B. Mangaraj, I. S. Misra, and S. K. Sanyal, "Application of bacteria foraging algorithm in designing log periodic dipole array for entire UHF TV spectrum," *Int. J. RF Microw. Comput-Aid. Eng.*, vol. 23, no. 2, pp. 157–171, Mar. 2013.

[30] D. Kampitaki, A. Hatzigaidas, A. Papastergiou, P. Lazaridis, and Z. Zaharis, "Dual-frequency splitter synthesis suitable for practical RF applications," *WSEAS Trans. Commun.*, vol. 5, no. 10, pp. 1885–1891, Oct. 2006.

[31] D. G. Kampitaki, A. T. Hatzigaidas, A. I. Papastergiou, and Z. D. Zaharis, "On the design of a dual-band unequal power divider useful for mobile communications," *Electr. Eng.*, vol. 89, no. 6, pp. 443–450, Jun. 2007.

[32] Z. D. Zaharis *et al.*, "Improving the radiation characteristics of a base station antenna array using a particle swarm optimizer," *Microw. Opt. Technol. Lett.*, vol. 49, no. 7, pp. 1690–1698, Jul. 2007.

[33] Z. D. Zaharis, D. G. Kampitaki, P. I. Lazaridis, A. I. Papastergiou, and P. B. Gallion, "On the design of multifrequency dividers suitable for GSM/DCS/PCS/UMTS applications by using a particle swarm optimization-based technique," *Microw. Opt. Technol. Lett.*, vol. 49, no. 9, pp. 2138–2144, Sep. 2007.

[34] J. C. Chen, M. H. Chiu, Y. S. Yang, and C. P. Li, "A suboptimal tone reservation algorithm based on cross-entropy method for PAPR reduction in OFDM systems," *IEEE Trans. Broadcast.*, vol. 57, no. 3, pp. 752–756, Sep. 2011.

[35] S. Chen, "An efficient predistorter design for compensating nonlinear memory high power amplifiers," *IEEE Trans. Broadcast.*, vol. 57, no. 4, pp. 856–865, Dec. 2011.

[36] Y. Wang, W. Chen, and C. Tellambura, "Genetic algorithm based nearly optimal peak reduction tone set selection for adaptive amplitude clipping PAPR reduction," *IEEE Trans. Broadcast.*, vol. 58, no. 3, pp. 462–471, Sep. 2012.

[37] A. H. Abdelhafiz, O. Hammi, A. Zerguine, A. T. Al-Awami, and F. M. Ghannouchi, "A PSO based memory polynomial predistorter with embedded dimension estimation," *IEEE Trans. Broadcast.*, vol. 59, no. 4, pp. 665–673, Dec. 2013.

[38] T. Niknam and F. Golestaneh, "Enhanced bee swarm optimization algorithm for dynamic economic dispatch," *IEEE Syst. J.*, vol. 7, no. 4, pp. 754–762, Dec. 2013.

[39] H. M. Hasanien, "Design optimization of PID controller in automatic voltage regulator system using Taguchi combined genetic algorithm method," *IEEE Syst. J.*, vol. 7, no. 4, pp. 825–831, Dec. 2013.

[40] S. Saha, "GARO framework: A genetic algorithm based resource optimization for organizational efficiency," *IEEE Syst. J.*, vol. 7, no. 4, pp. 889–895, Dec. 2013.

[41] A. K. Jain, S. C. Srivastava, S. N. Singh, and L. Srivastava, "Bacteria foraging optimization based bidding strategy under transmission congestion," *IEEE Syst. J.*, to be published.

[42] M. Naeem, A. S. Khwaja, A. Anpalagan, and M. Jaseemuddin, "Green cooperative cognitive radio: A multiobjective optimization paradigm," *IEEE Syst. J.*, to be published.

[43] M. de Paula Marques, F. R. Durand, and T. Abrao, "WDM/OCDM energy-efficient networks based on heuristic ant colony optimization," *IEEE Syst. J.*, to be published.

[44] S. Jia *et al.*, "Reliability-oriented ant colony optimization-based mobile peer-to-peer VoD solution in MANETs," *Wirel. Netw.*, vol. 20, no. 5, pp. 1185–1202, Jul. 2014.

[45] C. Xu, S. Jia, L. Zhong, H. Zhang, and G.-M. Muntean, "Ant-inspired mini-community-based solution for video-on-demand services in wireless mobile networks," *IEEE Trans. Broadcast.*, vol. 60, no. 2, pp. 322–335, Jun. 2014.

[46] R. Cox, The WB0DGF Antenna Site. LPCAD Software, May 2013. [Online]. Available: http://wb0dgf.com/LPCAD.htm

Zaharias D. Zaharis (M'13) received the B.Sc. degree in physics, the M.Sc. degree in electronics, the Ph.D. degree, and the Diploma degree in electrical and computer engineering from the Aristotle University of Thessaloniki, Thessaloniki, Greece, in 1987, 1994, 2000, and 2011, respectively.

From 2002 to 2013, he has been working in the administration of the telecommunications network at the Aristotle University of Thessaloniki. Since 2013, he has been with the Department of Electrical and Computer Engineering, Aristotle University of Thessaloniki. His research interests include the design and optimization of antennas and microwave circuits, mobile communications, RF measurements, radiowave propagation, and electromagnetic scattering.

Dr. Zaharis is a member of the Greek Physics Society and the Technical Chamber of Greece.

Christos Skeberis received the Diploma degree in electrical and computer engineering from the Aristotle University of Thessaloniki, Thessaloniki, Greece, in 2010, where he is currently working toward the Ph.D. degree.

His research interests include the design and optimization of antennas, mobile communications systems, neural networks, machine learning, radiowave propagation, and ionospheric phenomena.

Mr. Skeberis is a member of the Technical Chamber of Greece.

Pavlos I. Lazaridis (M'13) was born in Larissa, Greece. He received the Electrical Engineering degree from the Aristotle University of Thessaloniki, Thessaloniki, Greece, in 1990, the M.Sc. degree in electronics from Université Pierre et Marie Curie, Paris, France, in 1992, and the Ph.D. degree in electronics and telecommunications from Ecole Nationale Supérieure des Télécommunications (ENST), Paris, in 1996.

From 1991 to 1996, he was involved with research on semiconductor lasers, wave propagation, and nonlinear phenomena in optical fibers for the Centre National d'Etudes des Télécommunications and teaching at the ENST. In 1997, he became the Head of the Antennas and Propagation Laboratory, TDF-C2R Metz (Télédiffusion de France/France Télécom Research Center), where he was involved with research on antennas and radio coverage prediction algorithms for cellular mobile systems, Digital Audio Broadcasting (DAB), and Digital Video Broadcasting-Terrestrial (DVB-T). From 1998 to 2002, he was with the European Patent Office, Rijswijk, The Netherlands, as a Senior Examiner in the field of electronics telecommunications. From 2002 to 2014, he was involved with teaching and research at the Alexander Technological Educational Institute of Thessaloniki, Thessaloniki, Greece, and Brunel University, West London. He is currently a Reader in electronic and electrical engineering at the University of Huddersfield, Huddersfield, U.K.

Thomas D. Xenos was born in Thessaloniki, Greece, in 1955. He received the Diploma in electrical engineering from the University of Patras, Patras, Greece, in 1978 and the Ph.D. degree in wireless communications from the Aristotle University of Thessaloniki, Thessaloniki, in 1991.

Since then, he has joined the Department of Electrical and Computer Engineering, Aristotle University of Thessaloniki, where he is currently a Professor. He has participated in many national and international projects. He is the author of over 85 scientific papers. His research interests include wireless communications, radiowave propagation, nonionizing electromagnetic radiation measurements, and electromagnetic compatibility.