Lazaridis, Pavlos

IWO-based Synthesis of Log-Periodic Dipole Array

IWO-based Synthesis of Log-Periodic Dipole Array

Zaharias D. Zaharis,
Christos Skeberis, Thomas D. Xenos
Department of Electrical and Computer Engineering
Aristotle University of Thessaloniki
Thessaloniki, Greece
zaharis@auth.gr,
cskeberis@auth.gr, tdxenos@auth.gr

Pavlos I. Lazaridis
Department of Electronic Engineering
Alexander Technological Educational Institute of Thessaloniki
Thessaloniki, Greece
pavloslazaridis@hotmail.com

Dimitrios I. Stratakis
Department of Informatics Engineering
Technological Educational Institute of Crete
Heraklion, Greece
dstrat@staff.teicrete.gr

***Abstract*—The Invasive Weed Optimization (IWO) is an effective evolutionary and recently developed method. Due to its better performance in comparison to other well-known optimization methods, IWO has been chosen to solve many complex non-linear problems in telecommunications and electromagnetics. In the present study, the IWO is applied to optimize the geometry of a realistic log-periodic dipole array (LPDA) that operates in the frequency range 800-3300 MHz and therefore is suitable for signal reception from several RF services. The optimization is applied under specific requirements, concerning the standing wave ratio, the forward gain, the gain flatness and the side lobe level, over a wide frequency range. The optimization variables are the lengths and the radii of the dipoles, the distances between them, and the characteristic impedance of the transmission line that connects the dipoles. The optimized LPDA seems to be superior compared to the antenna derived from the practical design procedure.**

Keywords—Antenna array design; invasive weed optimization; log-periodic antenna; LPDA

I. Introduction

Log-periodic dipole arrays (LPDAs) are special linear arrays composed of parallel dipoles of different length [1]. They exhibit wideband behavior and gain flatness (i.e., the difference between the maximum and the minimum gain values inside a frequency range) over several frequency octaves, depending on the dipole lengths and radii as well as on their distances. In comparison to Yagi-Uda antennas, LPDAs have lower gain values but better gain flatness, since the higher gain of Yagi-Uda antennas is restricted over a narrow bandwidth. Therefore, LPDAs are preferred in several applications where a wideband behavior is needed, such as TV and FM-radio reception and RF measurements.

The first design procedure of LPDAs was proposed by Carrel in [2] and corrected by Butson and Thompson in [3]. This procedure is mostly a practical design method that considers all the dipoles inside the same angular sector. According to this method, the whole antenna geometry, i.e., the dipole lengths, radii and distances, can be calculated, if two design parameters, defined as *scale factor* τ and *relative spacing* σ, are known. These parameters are found from the constant directivity contour curves of the well-known Carrel's graph initially given in [2] and corrected in [3]. In order to facilitate the LPDA design, computer software based on the above practical method has been developed, such as the LPCAD [4], [5]. However, this method is based on a rough description of the exact antenna model and therefore it cannot accurately estimate the behavior of the antenna inside a wide frequency band. In addition, the method provides the ability to control the operating bandwidth, and thus the standing wave ratio (SWR) inside this bandwidth, as well as the forward gain and the front-to-back (F/B) ratio. However, the side lobe level (SLL) cannot be controlled and thus it results in unnecessary spatial spread of radiated power. A full wave analysis method in conjunction with an optimization method would be an excellent design tool that provides fair approximation of the antenna behavior and also controls all the parameters of the radiation pattern including the *SLL*. Such an analysis method is the Method of Moments (MoM) [6] incorporated in several software packets, like the Numerical Electromagnetics Code (NEC) [7].

In the present work, the Invasive Weed Optimization (IWO) recently introduced, [8]-[11], is used together with the NEC as a design tool of LPDAs. The IWO is applied here to optimize a 12-element LPDA (M=12) for operation in the frequency range 800-3300 MHz under specific requirements. These are: (i) $SWR \leq 1.8$, (ii) gain as high as possible, (iii) gain flatness ≤2dBi, and (iv) $SLL \leq -20$dB. In order to increase the degrees of freedom in comparison to the practical design method given in [2], the dipoles are not considered inside the same angular sector, and thus their lengths L_m (m=1,...,M), radii r_m (m=1,...,M) and distances S_m (m=1,...,M–1) from their next dipole ((m+1)-th) are independently optimized (see Fig. 1). Two additional parameters complete the above optimization variable set. These are the distance S_M between the largest dipole (M-th) and the short-circuited stub located behind this dipole, and the characteristic impedance Z_0 of the transmission line used to model the boom of the LPDA. These are $3M+1$ optimization variables in total. The NEC has been chosen for the antenna analysis at frequency steps of 10 MHz inside the operating bandwidth and returns to the IWO algorithm the extracted radiation characteristics, which are used for the fitness calculations. The optimized LPDA geometry is compared to a respective LPDA of the same total length S_T derived by the practical design method, [2]. The comparison exhibits the superiority of the proposed method.

II. RELATED WORK

In several studies, evolutionary methods have been proposed to optimize log-periodic arrays under specific requirements. In [12], eight-element log-periodic monopole arrays (LPMAs) are optimized for operation in the range 25-88 MHz by applying a Pareto multi-objective genetic algorithm (GA). The LPMAs are required to achieve F/B ratio >10dB, half power beamwidth (HPBW) equal to 30°, *SWR*<1.8 and feed efficiency >1/2. For comparison reasons, the LPMAs are also optimized by a standard GA and the simplex method. A GA, the Nelder-Mead downhill simplex method and a hybrid GA/Nelder-Mead method are used in [13] to optimize LPDAs under requirements concerning the average values of the gain and *SWR* as well as their maximum deviation over the entire bandwidth. GAs are used in [14] and [15] to maintain the gain and the *SWR* over the operating bandwidth, while the LPDA length and the number of dipoles are reduced compared to those of the initial array. In [16], a multi-objective optimization is applied to LPDAs for operation in the range 3-30 MHz under requirements for minimum *SWR*, minimum antenna length and maximum gain by employing the Non-dominated Sorting Genetic Algorithm II (NSGA-II). The Particle Swarm Optimization (PSO) is applied in [17] for a 10-element LPDA operating in the range 450-1350 MHz under requirements for the average values of the gain, the F/B ratio and the *SWR*. A circular parasitic array of four 12-element LPDAs is optimized in [18] under constraints for gain close to 8dBi and minimum *SWR* in the range 3.1-10.6 GHz. The optimization process is implemented by using GAs. A hybrid Taguchi-GA is proposed in [19] to optimize a wideband zigzag log-periodic antenna, while in [20] a HF inverted-V LPDA is optimized under constraints for the *SWR*, the *SLL* and the gain by using GAs. Due to operation in the range 6-30 MHz, restrictions are set on the antenna size. Planar LPDAs are optimized in [21] for operation in the S-band by using PSO under constraints for the *SWR* and the gain, while in [22] a 13-element LPDA is optimized for operation in the GSM, WiMAX, Bluetooth, Wi-Fi and 3G bands using PSO and under the same constraints as given above. Also, a 10-element LPDA is optimized in [23] for operation in the GSM, WiMAX and Wi-Fi bands using a GA under requirements for smaller size and higher gain. Finally, three LPDAs composed respectively of six, nine and twelve elements are optimized in [24] using the Bacteria Foraging Algorithm for operation in the UHF TV band under requirements for the average values of the gain, the F/B ratio, the *SLL* and the *SWR*.

It is noticed that the gain and the *SWR* are always considered under optimization (except for [23] where the *SWR* is not optimized). Requirements for the *SLL* are defined only in [20] and [24]. In fact, the requirement for $SLL \le -6$dB in [20] is light enough and is defined just to prevent the main lobe from splitting. In [24], the requirement for average *SLL* equal to −40dB cannot be satisfied by any of the three LPDAs. On the other hand, the operating bandwidth is not as wide as that considered here. In our study, all the above requirements including the *SLL* are taken into account during the optimization process. It must be noted that the *SLL* calculation takes into account all the secondary lobes including the back lobe. Consequently, the F/B ratio requirement is included in the *SLL* requirement (if $SLL \le -20$dB then F/B ratio ≥20dB). In addition, all these requirements have to be satisfied inside a wide frequency range, where the upper and the lower frequency have a ratio value approximately equal to 4:1.

However, the reduction of the LPDA length is not taken into account, since we intend to show that the IWO method produces an optimized LPDA with better radiation characteristics than those of an LPDA with the same length S_T produced by the practical design method, [2].

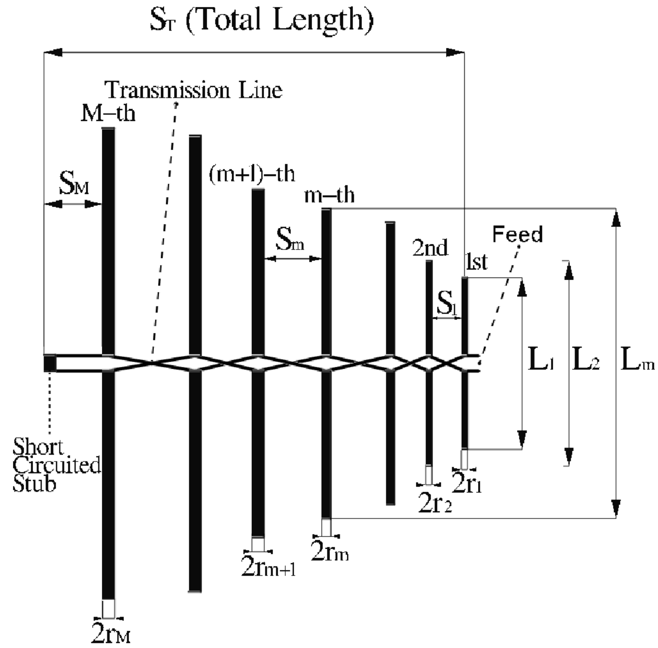

Fig. 1. Geometry of LPDA.

III. INVASIVE WEED OPTIMIZATION

So far, many problems of telecommunications and electromagnetics have been solved by applying evolutionary optimization, [9]-[11], [25]-[33]. The IWO is a heuristic method that simulates the invasive nature of weeds. It was introduced by Mehrabian and Lucas in [8]. Since then, several problems of antenna optimization have been solved by applying IWO. The IWO is initialized by uniformly dispersing W weeds in an N-dimensional space, where N is the number of optimization variables. Three steps are applied at every i-th (i=1,…,I) iteration: *Reproduction*, *Spatial Dispersion* and *Competitive Exclusion*.

During the reproduction phase, each weed produces a population of seeds, which is a linear function of the weed fitness. In this way, the good weeds produce more seeds than the bad weeds. During the spatial dispersion phase, every weed disperses its seeds according to a normal distribution with standard deviation σ which decreases as the number of iterations i is increased, according to the following expression:

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

where $\sigma_{\min}$ and $\sigma_{\max}$ are the limits of σ, and μ is the *nonlinear modulation index*. In the competitive exclusion phase, only the best $W_{\max}$ individuals (weeds or seeds) survive, while the rest ones are deleted. It must be noted that the quantity that determines a good or a bad weed is the fitness value of the weed.

IV. Fitness Function Description

Since several requirements have to be satisfied, the fitness function is defined as a linear combination of terms, where each term is the mathematical expression of the respective requirement. When the fitness function achieves its global optimum (i.e., minimum in our study), all the terms reach their respective minimum values meaning that all the requirements have been satisfied. According to the requirements given in Section I, the fitness function is defined by the following formula:

$$\begin{aligned} F = -k_1 G_{\min} &+ k_2 \left[\max\left(G_{\max} - G_{\min}, 2\right) - 2 \right] \\ &+ k_3 \left[\max\left(SLL_{\max}, -20\right) + 20 \right] \\ &+ k_4 \left[\max\left(SWR_{\max}, 1.8\right) - 1.8 \right] \end{aligned} \qquad (2)$$

In the above formula, $G_{\max}$, $G_{\min}$, $SLL_{\max}$ and $SWR_{\max}$ are respectively the maximum gain in dBi, the minimum gain in dBi, the maximum *SLL* in dB and the maximum *SWR*, found inside the operating bandwidth 800-3300 MHz. In order to estimate the above extreme values, the antenna gain *G*, the *SLL* and the *SWR* are calculated for every frequency inside the operating bandwidth at steps of 10MHz by applying the NEC software [7]. Also, k_1, k_2, k_3 and k_4 are positive coefficients used to balance the minimization of the four terms given in (2). As $G_{\min}$ increases, the 1st term of (2) decreases and thus is used for the maximization of the antenna gain. The next three terms are formed so that values of gain flatness $G_{\max} - G_{\min} < 2\text{dB}$, values of $SLL_{\max} < -20\text{dB}$ and values of $SWR_{\max} < 1.8$ do not cause further minimization of *F*, since the desired values of gain flatness, $SLL_{\max}$ and $SWR_{\max}$ have already been obtained.

V. Optimization Results

The IWO is applied on a 12-element LPDA (M=12) for operation in the frequency range 800-3300 MHz under the requirements given in the last paragraph of Section I. Both the initial and the maximum population, respectively W and $W_{\max}$, used by the IWO algorithm consist of 20 weeds (W=$W_{\max}$=20). The number of seeds generated by a weed varies from zero (for the worst weed) to five (for the best weed). The standard deviation σ of the seed dispersion considered in a unitary interval varies from zero to 0.15 ($\sigma_{\min}$=0 and $\sigma_{\max}$=0.15). These limits are properly adapted according to the range of values of each optimization variable. The nonlinear modulation index is set equal to 2.5 (μ=2.5) and the optimization process terminates after 2000 iterations (I=2000).

The optimization variables are the dipole lengths L_m (m=1,...,12), the dipole radii r_m (m=1,...,12), the dipole distances S_m (m=1,...,12) and the characteristic impedance Z_0 of the line that models the boom of the LPDA. These are 37 optimization variables in total (3M+1=37).The radii vary from 1mm to 5mm, i.e., $r_{\min}$=0.001m and $r_{\max}$=0.005m. The lower limit of S_m is set equal to 2$r_{\max}$+0.002=0.012m in order to avoid dipoles touching each other, while the upper limit of S_m is set equal to $\lambda_{\max}$/4, where $\lambda_{\max}$ is the wavelength at 800MHz, considering that the maximum variation of voltage, current or impedance is observed along a quarter of the maximum wavelength (i.e., at 800MHz) and therefore the appropriate dipole spacing must be less than 0.094m ($\lambda_{\max}$/4). Z_0 varies from 50 Ohm to 200 Ohm. Finally, the limits of L_m are derived by utilizing the dipole lengths extracted from the practical design method. In particular, from the constant directivity contour curves (Carrel's graph, [1]-[3]) and considering antenna directivity equal to 7.5dBi, it results τ=0.86 and σ=0.16 (optimum σ value). Using these values, the LPCAD, [4], [5], is applied to extract the values of L_m (m=1,...,12). These values are given in the 2nd column of Table I. The average value $(L_m + L_{m+1})/2$ of the lengths of two adjacent dipoles, m-th and (m+1)-th, is simultaneously the upper limit U_m for L_m and the lower limit D_{m+1} for L_{m+1}. In this way, we can find the length limits U_m and D_m for every dipole, except for D_1 and U_{12}. These two limits are considered to be at the same distance from the respective lengths as the opposite limits from the same lengths, i.e., $U_1 - L_1 = L_1 - D_1$ and $U_{12} - L_{12} = L_{12} - D_{12}$. Finally, all the length limits are given in columns 3 and 4 of Table I.

TABLE I. Initial Dipole Lengths Derived from LPCAD and Length Limits

Dipole m	*Initial Dipole Length L_m (meters)*	*Lower Limit D_m (meters)*	*Upper Limit U_m (meters)*
1	0.0350	0.0321	0.0378
2	0.0406	0.0378	0.0440
3	0.0473	0.0440	0.0511
4	0.0550	0.0511	0.0594
5	0.0639	0.0594	0.0691
6	0.0743	0.0691	0.0804
7	0.0864	0.0804	0.0934
8	0.1005	0.0934	0.1087
9	0.1168	0.1087	0.1264
10	0.1359	0.1264	0.1469
11	0.1580	0.1469	0.1708
12	0.1837	0.1708	0.1965

The geometry of the optimized LPDA is given in Table II. By using the LPCAD again, an LPDA with the same number of dipoles *M* and the same length S_T can be designed. The geometry of this LPDA is given in Table III. The *SWR*, the gain and the *SLL* versus frequency of both the LPDA geometries are displayed respectively in Figs. 2, 3 and 4. The comparison exhibits explicitly the superiority of the IWO method. Not only is the IWO-based antenna geometry capable of satisfying the four requirements defined above, it has also better behavior in terms of *SWR*, gain, gain flatness and *SLL* than the LPCAD-based antenna geometry.

TABLE II. IWO-BASED LPDA GEOMETRY

m	L_m *(meters)*	r_m *(meters)*	S_m *(meters)*
1	0.0336	0.0017	0.0120
2	0.0394	0.0017	0.0164
3	0.0476	0.0024	0.0206
4	0.0542	0.0031	0.0214
5	0.0622	0.0042	0.0310
6	0.0766	0.0047	0.0397
7	0.0916	0.0049	0.0408
8	0.1064	0.0041	0.0382
9	0.1196	0.0047	0.0692
10	0.1288	0.0021	0.0688
11	0.1572	0.0041	0.0349
12	0.1844	0.0023	0.0609
Z_0 = 109 Ohm			

TABLE III. LPCAD-BASED LPDA GEOMETRY

m	L_m *(meters)*	r_m *(meters)*	S_m *(meters)*
1	0.0342	0.0009	0.0151
2	0.0399	0.0011	0.0176
3	0.0465	0.0013	0.0205
4	0.0542	0.0015	0.0239
5	0.0631	0.0017	0.0278
6	0.0735	0.0020	0.0325
7	0.0856	0.0023	0.0378
8	0.0997	0.0027	0.0440
9	0.1162	0.0032	0.0513
10	0.1354	0.0037	0.0598
11	0.1577	0.0043	0.0696
12	0.1837	0.0050	0.0381
Z_0 = 73 Ohm			

VI. CONCLUSION

The IWO method has been used to optimize a 12-element LPDA for operation in the range 800-3300 MHz. The optimization process has been performed under requirements for the gain, the gain flatness, the *SLL* and the *SWR*. The optimized antenna has better radiation characteristics inside the entire operating bandwidth compared to a respective LPDA with the same length produced by the practical design method. Due to its excellent performance, the IWO algorithm seems to be a very useful LPDA design tool.

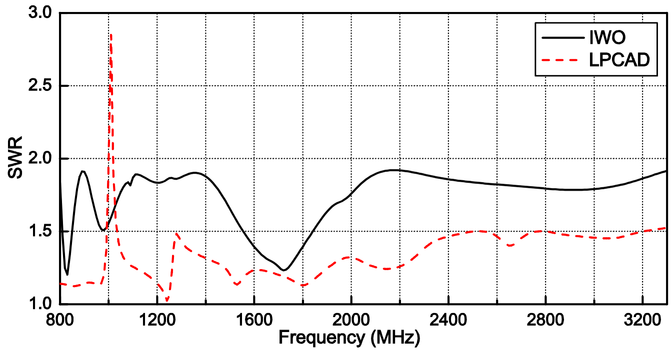

Fig. 2. SWR vs. frequency.

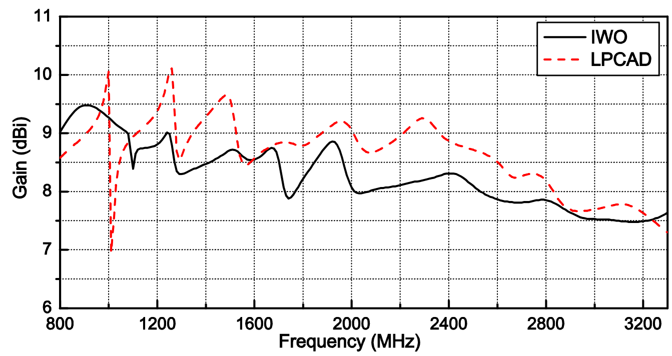

Fig. 3. Gain vs. frequency.

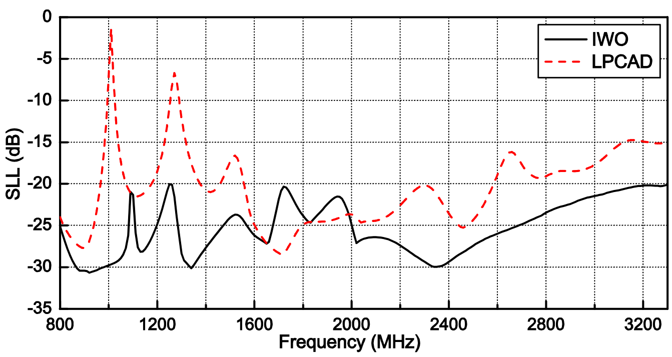

Fig. 4. SLL vs. frequency.

ACKNOWLEDGMENT

This work is supported by the Operational Program "Education and Lifelong Learning", which is co-financed by the European Union (European Social Fund) and Greek national funds (National Strategic Reference Framework 2007-2013).

REFERENCES

[1] C. A. Balanis, Antenna Theory, Analysis and Design, 3rd ed., New Jersey: John Wiley & Sons, 2005, pp. 611-652.

[2] 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, 1961.

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

[4] R. Cox. (2013, May). The WB0DGF Antenna Site. LPCAD software. [Online]. Available: http://wb0dgf.com/LPCAD.htm

[5] L. B. Cebik. (2006 , Feb.). LPCAD30 Software for Designing LPDAs: A Review. [Online]. Available: http://www.antennex.com/shack/Feb06/lpcad.html

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

[7] G. J. Burke and A. J. Poggio, "Numerical Electromagnetics Code (NEC) - Method of Moments," Naval Ocean Systems Center, San Diego, CA, Tech. Doc. 116, Jan. 1981.

[8] A. R. Mehrabian and C. Lucas, "A novel numerical optimization algorithm inspired from weed colonization," Ecological Informatics, vol. 1, no. 4, pp. 355-366, December 2006.

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

[10] 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, September 2013.

[11] 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, March 2014.

[12] S. E. Fisher, D. S. Weile, E. Michielssen, and W. Woody, "Pareto genetic algorithm based optimization of log-periodic monopole arrays mounted on realistic platforms," J. Electromagn. Waves Appl., vol. 13, no. 5, pp. 571-598, 1999.

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

[14] 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. 2003 IEEE 46th Midwest Symp. Circuits and Systems, 27-30 December 2003, vol. 3, pp. 1194-1197.

[15] 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. 2004 IEEE Antennas Propagat. Society Int. Symp., 20-25 June 2004, vol. 4, pp. 3433-3436.

[16] 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. 2006 IEEE Congress on Evolutionary Computation, 16-21 July 2006, pp. 3189-3196.

[17] 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 Propagat. Mag., vol. 49, no. 4, pp. 34-47, August 2007.

[18] C. I. Tsitouri, S. C. Panagiotou, T. D. Dimousios, and C. N. Capsalis, "A circular switched parasitic array of log-periodic antennas with enhanced directivity and beam steering capability for ultra wideband communications applications," in Proc. 2008 Loughborough Antennas Propagat. Conf., 17-18 March 2008, pp. 281-284.

[19] C. M. De J. van Coevorden, A. R. Bretones, M. F. Pantoja, S. G. García, A. Monorchio, and R. G. Martín, "A new implementation of the hybrid taguchi GA: application to the design of a miniaturized log-periodic thin-wire antenna," Applied Computational Electromagnetics Society Journal, vol. 24, no. 1, pp. 21-31, February 2009.

[20] Xiao-Lin Zhang and Huo-Tao Gao, "An optimum design of miniaturized high frequency inverted-V log-periodic dipole antenna," in Proc. 2011 IEEE CIE Int. Conf. on Radar, 24-27 October 2011, vol. 2, pp. 1185-1188.

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

[22] M. Aziz-ul-Haq, M. Tausif Afzal, Umair Rafique, Qamar-ud-Din, M. Arif Khan, and M. Mansoor Ahmed, "Log periodic dipole antenna design using particle swarm optimization," Int. J. Electromagnetics and Applications, vol. 2, no. 4, pp. 65-68, 2012.

[23] M. Touseef, Qamar-ud-Din, M. Aziz-ul-Haq, Umair Rafique, M. Arif Khan, and M. Mansoor Ahmed, "Genetic algorithm optimization of log-periodic dipole array," Int. J. Electromagnetics and Applications, vol. 2, no. 6, pp. 169-173, 2012.

[24] 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 and Microwave Comp. Aid. Eng., vol. 23, no. 2, pp. 157-171, March 2013.

[25] 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.

[26] 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, June 2007.

[27] Z. D. Zaharis, D. G. Kampitaki, P. I. Lazaridis, A. I. Papastergiou, A. T. Hatzigaidas, and P. B. Gallion, "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, July 2007.

[28] 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, Sept. 2007.

[29] 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, Sept. 2011.

[30] 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.

[31] 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, Sept. 2012.

[32] 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.

[33] P. I. Lazaridis, Z. D. Zaharis C. Skeberis, T. Xenos, E. Tziris, and P. Gallion, "Optimal design of UHF TV band log-periodic antenna using invasive weed optimization," in Proc. 4th Int. Conf. Wireless Communications, Vehicular Technology, Information Theory and Aerospace & Electronic Systems, 11–14 May 2014.