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APPLICATION OF BOOLEAN PSO WITH ADAPTIVE VELOCITY MUTATION TO THE DESIGN OF OPTIMAL LINEAR ANTENNA ARRAYS EXCITED BY UNIFORM-AMPLITUDE CURRENT DISTRIBUTION

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Abstract—This paper presents a new optimization technique for the design of linear antenna arrays. The proposed technique is based on a novel variant of PSO called Boolean PSO with Adaptive Velocity Mutation. The antenna arrays are optimized under requirements for maximizing the power gain at a desired direction and minimizing the side lobe level of the radiation pattern. The impedance-matching condition of all the array elements is also required by the algorithm. The optimization technique has been developed considering that the array elements are excited by uniform-amplitude current distribution. The radiation characteristics of the antenna array are extracted by using the method of moments. The technique has been applied in several broadside and non-broadside cases of collinear wire-dipole antenna arrays and seems to be capable of improving the radiation characteristics of the antenna arrays in practice.

1. INTRODUCTION

Antenna arrays are widely used in communications area. Many techniques have been proposed to design arrays that satisfy specific requirements. Beam-forming, beam-steering, switched-beam and pencil beam-shaping techniques have been studied in [1–5], while the design of sparse and slotted arrays is given in [6–10]. Special array structures such as fractal, ring and conformal arrays have been studied

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in [11–15], while pattern shaping techniques are given in [16, 17]. Finally, special planar and linear array design is presented in [18–23].

In practice, a linear array is required to satisfy three crucial conditions: First, the radiated power gain G_p must be maximized at a desired direction defined by the elevation angle θ_o in the spherical coordinate system. $G_p(\theta_o)$ is the maximum gain and corresponds to the peak of the main lobe of the radiation pattern. Second, the side lobe level (SLL) must be as low as possible in order to minimize the power loss caused by spatial spread of radiated power. In practice, the low SLL condition is considered to be satisfied when $SLL \leq -20\,\mathrm{dB}$. Third, all the array elements must satisfy the "impedance-matching condition", which means that the complex input impedance Z_m ($m = 1,\ldots,M$) of every m-th element must be as close as possible to the characteristic impedance Z_o of the feeding line. According to the transmission line theory [24], the impedance-matching condition is estimated by the standing wave ratio SWR_m at the input of every (m-th) element using the expression:

$$SWR_m = (1 + |r_m|)/(1 - |r_m|) \tag{1}$$

where r_m is the complex reflection coefficient calculated at the input of the m-th element using the expression:

$$r_m = (Z_m - Z_o)/(Z_m + Z_o) \tag{2}$$

The impedance-matching condition is usually considered to be satisfied when $SWR_m \leq 2$ ($m = 1, \ldots, M$).

The three above conditions are satisfied by choosing a suitable geometry for the antenna array and by defining the appropriate current excitation distribution applied on the elements of the array.

In order to achieve low SLL, most of the methods propose the use of non-uniform excitation distribution on the elements of the array. One of the most popular distributions is the Chebyshev distribution, which is calculated by applying the Dolph method [25]. However, non-uniform distributions are not recommended in practice, because the feeding networks are complex and quite inefficient. On the contrary, uniform distributions are preferable due to the simple and easily implemented feeding networks.

The present work introduces a new technique capable of designing linear antenna arrays that satisfy the above-mentioned conditions. The technique assumes unequal distances between adjacent elements, considering uniform-amplitude current distribution. In addition, if $\theta_o \neq 90^\circ$, the excitation currents are assumed to have different phases.

The technique has been applied to simulate broadside and non-broadside collinear antenna arrays. The optimal array geometry and the optimal phases of the array excitation are extracted by minimizing a properly chosen "fitness function" F, which is calculated from $G_p(\theta_o)$, SLL and SWR_m ($m = 1, \ldots, M$) by applying the Method of Moments (MoM) on the antenna array [26]. The use of MoM takes into account the mutual coupling between the array elements and thus the analysis of the array is close to the real conditions. The fitness function is minimized when SLL and SWR_m ($m = 1, \ldots, M$) are minimized while $G_p(\theta_o)$ is maximized, thus approaching the required conditions. The minimization of F is achieved by applying a novel variant of PSO called "Boolean PSO with Adaptive Velocity Mutation" (BPSO-avm). The necessary software for both MoM and BPSO-avm was developed by the authors in FORTRAN language. The BPSO-avm is compared to the conventional BPSO in terms of performance and thus comparative convergence graphs are presented. Finally, the results derived from the BPSO-avm are verified by applying the NEC software [27].

2. BOOLEAN PSO

Particle Swarm Optimization (PSO) is an evolutionary method found in many studies in the literature [7, 12, 28–35]. The PSO theory and the basic structure of a PSO algorithm are briefly described in [29]. The Boolean PSO (BPSO) is a novel binary version of PSO [36–38]. BPSO simulates the behavior of swarms, just like PSO does. The swarm consists of N_S individuals called "particles". The efficiency of the method seems to increase by choosing the value of the population size N_S between 10 and 50.

The first difference between PSO and BPSO, is that BPSO represents the position $X_n = [x_{n1}, \ldots, x_{nb}, \ldots, x_{nB}]$ and the velocity $V_n = [v_{n1}, \ldots, v_{nb}, \ldots, v_{nB}]$ of each n-th ($n = 1, \ldots, N_S$) particle as binary strings of B bits. Despite their binary presentation, the particle positions X_n ($n = 1, \ldots, N_S$) must lie inside the search space defined by a lower and an upper boundary, which are expressed respectively as $L_n = [l_{n1}, \ldots, l_{nb}, \ldots, l_{nB}]$ and $U_n = [u_{n1}, \ldots, u_{nb}, \ldots, u_{nB}]$.

The second difference between PSO and BPSO is the update formulae of V_n and X_n. In the BPSO, V_n and X_n are updated using exclusively Boolean expressions:

$$v_{nb} = w \cdot v_{nb} + c_1 \cdot (p_{nb} \oplus x_{nb}) + c_2 \cdot (g_b \oplus x_{nb}) \tag{3}$$

$$x_{nb} = x_{nb} \oplus v_{nb} \tag{4}$$

where $(\cdot)$, $(+)$ and $(\oplus)$ are respectively the *"and"*, *"or"* and *"xor"* operators, p_{nb} is the b-th bit of the best position P_n achieved so far by the n-th particle (p-best position) and g_b is the b-th bit of the best position G achieved so far by all the particles of the swarm (g-best position). Moreover, w, c_1, and c_2 are binary digits randomly chosen and their probabilities of being '1' are determined by the respective parameters Ω, C_1, and C_2. Due to the exclusively Boolean update of V_n and X_n, BPSO is more efficient and spends less CPU time than a well-known binary version of PSO given in [28], where the update is made by using real number expressions.

The third difference between PSO and BPSO lies in the way of controlling the convergence speed of the optimization process. The control parameter for both methods is the maximum allowed velocity $V_{\max}$. In BPSO, $V_{\max}$ is defined as the maximum number of '1's allowed in V_n (e.g., $V_{\max} = 4$). The actual number of '1's in V_n is expressed as l_n and is called "velocity length". The value of l_n is controlled by a fundamental mechanism of Artificial Immune Systems (AISs) called "negative selection" (NS) [36]. AISs are computational systems inspired by the biological processes of the vertebrate immune system. The NS is an important procedure of immunity in biology responsible for eliminating T-cells that recognize self antigens in the thymus. According to the NS, if $l_n > V_{\max}$, V_n is considered as self antigen and thus randomly chosen '1's in V_n are changed into '0's until $l_n = V_{\max}$. On the contrary, if $l_n \leq V_{\max}$, V_n is considered as non-self antigen and is not changed.

In fact, $V_{\max}$ prevents the particles from expanding their trajectories. However, $V_{\max}$ is not always able to keep the particles within the search space. The problem can be overcome by assigning a large value (penalty value) to the fitness function of the particles that lie outside the search space. Since the optimization process aims at minimizing the fitness function, these particles are gradually moved inside the search space.

2.1. Boolean PSO with Adaptive Velocity Mutation

When the NS has been completed, an adaptive mutation process is applied on every V_n. Specifically, the bits of V_n ($n = 1, \ldots, N_S$) are changed from '0' to '1' with probability m_p called "mutation probability". In the beginning of the optimization process, m_p starts from a relatively small value (e.g., $m_p = 0.10$) to avoid pure random search. In every iteration, m_p linearly decreases until it reaches zero at the end of the optimization process. The linear reduction in the values of m_p provides the adaptation feature to the mutation process. In order to increase the exploration ability of the particles, the mutation process may change the bits of V_n only from '0' to '1' and not from '1' to '0'.

The BPSO-avm algorithm is briefly described as follows:

1. Select the values of N_S, B, L_n and U_n ($n = 1,\ldots,N_S$), Ω, C_1, C_2 and $V_{\max}$, the initial value of m_p, and the total number of iterations

$t_{\max}$ of the optimization process.

2. Randomly initialize the particle positions X_n $(n = 1, \ldots, N_S)$ and their velocities V_n $(n = 1, \ldots, N_S)$ inside the search space.
3. Apply the NS to correct V_n $(n = 1, \ldots, N_S)$, so that $l_n \leq V_{\max}$.
4. Evaluate the fitness function $F(X_n)$ for $n = 1, \ldots, N_S$.
5. Set $P_n = X_n$ and $F(P_n) = F(X_n)$ for $n = 1, \ldots, N_S$.
6. Find the minimum fitness value $F_{\min}$ among $F(P_n)$ $(n = 1, \ldots, N_S)$. $F_{\min}$ corresponds to the g-best position G, so that $F_{\min} = F(G)$.
7. Update V_n $(n = 1, \ldots, N_S)$ using (3).
8. Apply the N_S to correct V_n $(n = 1, \ldots, N_S)$, so that $l_n \leq V_{\max}$.
9. Mutate every '0' of V_n $(n = 1, \ldots, N_S)$ according to the value of m_p.
10. Update X_n $(n = 1, \ldots, N_S)$ using (4).
11. Evaluate the fitness function $F(X_n)$ for $n = 1, \ldots, N_S$.
12. For $n = 1, \ldots, N_S$, if $X_n < L_n$ or $X_n > U_n$ (particle lying outside the search space) then assign a large value to $F(X_n)$.
13. For $n = 1, \ldots, N_S$, if $F(X_n) < F(P_n)$ then $P_n = X_n$.
14. For $n = 1, \ldots, N_S$, if $F(P_n) < F(G)$ then $G = P_n$.
15. Update m_p according to a linear decrease formula.
16. If $t_{\max}$ is not reached, repeat the algorithm from step (7), or else report results and terminate.

3. FORMULATION

The BPSO-avm algorithm described above and the BPSO given in [36–38] are applied on the collinear antenna array of Figure 1. Both algorithms use the same fitness function and the same parameter values, i.e., $N_S = 30$, $\Omega = 0.1$, $C_1 = C_2 = 0.5$, $V_{\max} = 4$, and $t_{\max} = 10000$. Also, in the BPSO-avm algorithm, m_p is initially set equal to 0.10. The antenna array consists of M wire dipoles along z-axis. All the dipoles have the same length d ($d_m = d$, $m = 1, \ldots, M$) and radius of 0.001λ, where λ is the wavelength. The dipoles are excited in the middle of their length by currents that have the same amplitude. The above array produces omni-directional radiation pattern on the xy-plane. However, the radiation pattern on a plane that contains the z-axis (θ-plane) depends on the geometry of the array as well as on the phases a_m $(m = 1, \ldots, M)$ of the excitation currents. The array geometry is determined by the dipole length d and the inter-element distances $z_{m,m-1}$ (m=2,...,M), where $z_{m,m-1}$ denotes the distance between the m-th and the (m–1)-th dipole. Any set of values of d, $z_{m,m-1}$ (m=2,...,M) and a_m (m=1,...,M) represents in binary form a particle position X_n in the BPSO and BPSO-avm algorithms.

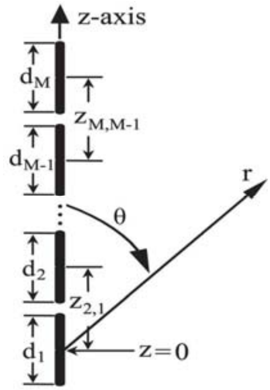


Figure 1. Collinear wire-dipole array.

For every set of values of d, $z_{m,m-1}$ (m=2,...,M) and a_m (m=1,...,M), the antenna array is analyzed by applying the MoM [26], in order to extract the values of Z_m (m=1,...,M) and to produce the θ-plane radiation pattern. Using (1) and (2), and considering that $Z_o = 50$ Ohms, the values of SWR_m (m=1,...,M) are derived. From the above pattern, the values of $G_p(\theta_o)$ and SLL are extracted and then are converted into deciBels (dBs) using the expressions:

$$G_p^{dB}(\theta_o) = 10\log\left[G_p(\theta_o)\right] \tag{5}$$

$$SLL^{dB} = 10\log(SLL) \tag{6}$$

The demand for satisfying all three above-described conditions is inherently multi-objective and no single solution exists. In such a problem, there may not exist one optimal solution with respect to all objectives. Therefore, the problem can be solved by converting it to a single-objective optimization problem. This can be accomplished by using weights for different objective functions and penalty terms for the constraint functions. Such a method leads to a single solution. Thus, the fitness function can be defined as follows:

$$F = w_G \cdot G_p^{dB}(\theta_o) + w_{SLL} \cdot F_{SLL} + w_{SWR} \cdot F_{SWR} \tag{7}$$

Obviously, $G_p^{dB}(\theta_o)$ is a positive quantity and has to be maximized to satisfy the maximum gain condition. Also, F_{SLL} corresponds to the low SLL condition and is described by the expression:

$$F_{SLL} = \begin{cases} SLL^{dB} + 20, & \text{if } SLL^{dB} > -20 \\ 0, & \text{if } SLL^{dB} \le -20 \end{cases} \tag{8}$$

F_{SLL} is a positive quantity and vanishes only when $SLL \le -20$ dB. Finally, F_{SWR} corresponds to the impedance-matching condition and is described as follows:

$$F_{SWR} = \sum_{m=1}^{M} b_m \tag{9}$$

where b_m is a penalty term defined by the expression:

$$b_m = \begin{cases} 10^6, & \text{if } SWR_m > 2 \\ 0, & \text{if } SWR_m \leq 2 \end{cases} \tag{10}$$

The penalty term is very effective because it creates a "wall" inside the search area that prohibits the algorithm from going into regions where $SWR_m > 2$. F_{SWR} has positive values and vanishes only when $SWR_m \leq 2$ $(m = 1, \ldots, M)$. The weights w_G, w_{SLL} and w_{SWR} in (7) declare the importance of the respective terms. Provided that $w_G < 0$, $w_{SLL} > 0$ and $w_{SWR} > 0$, the three above-mentioned conditions are satisfied when the fitness function finds its global minimum value.

Table 1. Optimization results from a 10-dipole array with $\theta_o = 90°$.

m	$z_{m,m-1}$ (λ)	a_m (deg)	SWR by authors' s/w	SWR by NEC	m	$z_{m,m-1}$ (λ)	a_m (deg)	SWR by authors' s/w	SWR by NEC
1		0.0	1.39	1.38	6	0.617	0.0	1.92	1.95
2	0.982	0.0	1.36	1.38	7	0.596	0.0	1.95	1.97
3	0.790	0.0	1.58	1.61	8	0.647	0.0	1.58	1.60
4	0.659	0.0	1.95	1.96	9	0.807	0.0	1.34	1.38
5	0.585	0.0	1.95	1.95	10	0.935	0.0	1.38	1.37
$d = 0.482\lambda$		authors' software: $G_p^{dB}(\theta_o) = 11.57$ $SLL^{dB} = -20.16$							
		NEC software: $G_p^{dB}(\theta_o) = 11.59$ $SLL^{dB} = -20.01$							

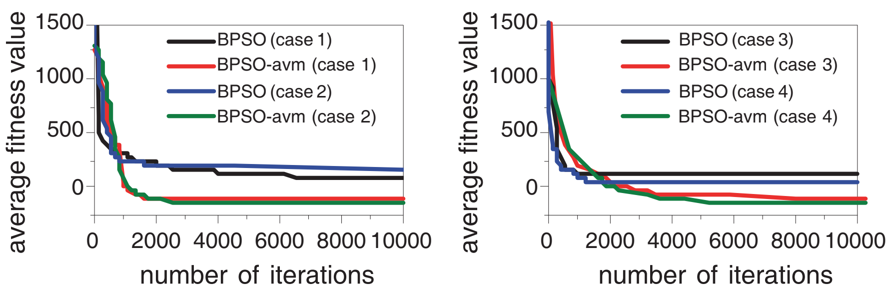


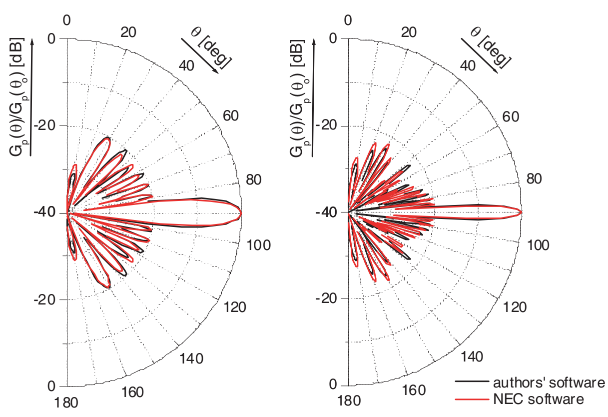
Figure 2. Convergence graphs for the first four cases.

4. NUMERICAL RESULTS

The BPSO-avm was applied in several cases and compared to the BPSO given in [36–38] in terms of performance. All the necessary software was executed on an Intel Core i5 computer running Microsoft Windows 7. The CPU time per execution was measured between 5

Table 2. Optimization results from a 20-dipole array with $\theta_o = 90°$.

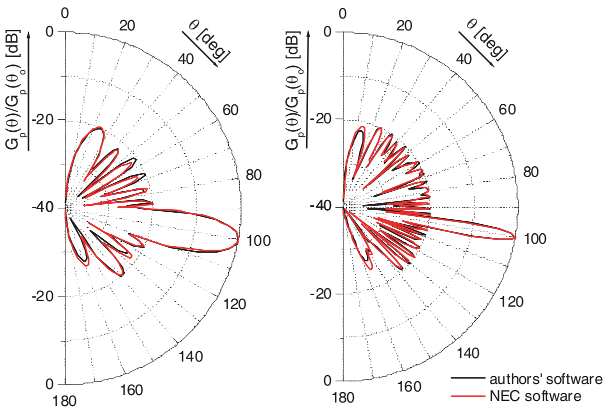
m	$z_{m,m-1}$ (λ)	a_m (deg)	SWR by authors' s/w	SWR by NEC	m	$z_{m,m-1}$ (λ)	a_m (deg)	SWR by authors' s/w	SWR by NEC
1		0.0	1.37	1.40	11	0.639	0.0	1.91	1.94
2	0.982	0.0	1.28	1.30	12	0.583	0.0	1.94	1.95
3	0.981	0.0	1.27	1.30	13	0.661	0.0	1.63	1.60
4	0.982	0.0	1.30	1.29	14	0.710	0.0	1.90	1.91
5	0.820	0.0	1.43	1.41	15	0.566	0.0	1.84	1.86
6	0.742	0.0	1.92	1.90	16	0.791	0.0	1.43	1.40
7	0.555	0.0	1.90	1.90	17	0.783	0.0	1.33	1.30
8	0.722	0.0	1.57	1.59	18	0.981	0.0	1.28	1.31
9	0.694	0.0	1.90	1.91	19	0.982	0.0	1.29	1.30
10	0.579	0.0	1.93	1.95	20	0.982	0.0	1.37	1.35
$d = 0.482\lambda$		authors' software: $G_p^{dB}(\theta_o) = 14.73$ $SLL^{dB} = -21.04$							
		NEC software: $G_p^{dB}(\theta_o) = 14.80$ $SLL^{dB} = -20.05$							



(a) (b)

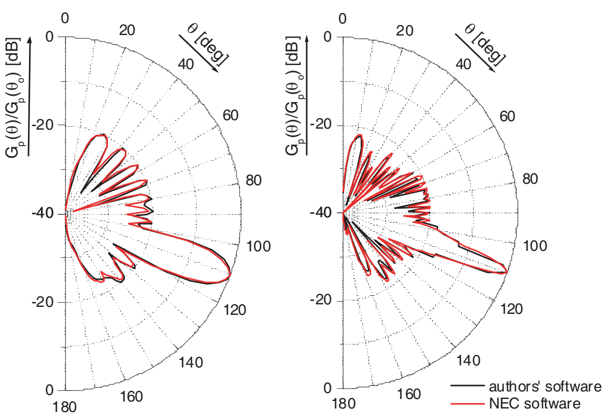
Figure 3. θ-plane radiation patterns of two optimized collinear arrays composed of (a) 10 dipoles and (b) 20 dipoles, with $\theta_o = 90°$.

and 10 minutes. The first two cases concern broadside antenna arrays ($\theta_o = 90°$) that consist respectively of 10 and 20 wire dipoles. The elements of a broadside array are in phase ($a_m = 0$, $m = 1, \ldots, M$). Therefore, the optimization process is applied to find only the optimal values of d and $z_{m,m-1}$ ($m = 2, \ldots, M$). The next two cases concern non-broadside arrays that consist respectively of 10 and 20 wire dipoles. The desired main lobe direction is chosen at $\theta_o = 100°$. The last two cases concern non-broadside arrays composed respectively of 10



(a) (b)

Figure 4. θ-plane radiation patterns of two optimized collinear arrays composed of (a) 10 dipoles and (b) 20 dipoles, with $\theta_o = 100°$.



(a) (b)

Figure 5. θ-plane radiation patterns of two optimized collinear arrays composed of (a) 10 dipoles and (b) 20 dipoles, with $\theta_o = 110°$.

and 20 wire dipoles while the desired main lobe direction is chosen at $\theta_o = 110°$. Therefore, in the last four cases, the optimization process seeks for the optimal values of d, $z_{m,m-1}$ ($m = 2, \ldots, M$) and a_m ($m = 1, \ldots, M$).

For each one of the first four cases, the BPSO and BPSO-avm algorithms were executed 100 times in order to derive comparative graphs that represent the average convergence of the fitness function (see Figure 2). Although the BPSO-avm converges a little slower than the BPSO, it finally leads to explicitly better solutions.

Table 3. Optimization results from a 10-dipole array with $\theta_o = 100°$.

m	$z_{m,m-1}$ (λ)	a_m (deg)	SWR by authors' s/w	SWR by NEC	m	$z_{m,m-1}$ (λ)	a_m (deg)	SWR by authors' s/w	SWR by NEC
1		0.0	1.80	1.78	6	0.488	-179.3	1.69	1.72
2	0.852	43.8	1.69	1.70	7	0.482	−138.5	1.71	1.72
3	0.638	91.8	1.69	1.71	8	0.470	−108.0	2.00	1.99
4	0.498	122.7	1.77	1.75	9	0.621	−78.2	1.87	1.88
5	0.492	159.3	1.85	1.86	10	0.657	−15.4	2.00	1.98
$d = 0.457\lambda$		authors' software: $G_p^{dB}(\theta_o) = 10.53$ $SLL^{dB} = -20.00$							
		NEC software: $G_p^{dB}(\theta_o) = 10.50$ $SLL^{dB} = -20.00$							

Table 4. Optimization results from a 20-dipole array with $\theta_o = 100°$.

m	$z_{m,m-1}$ (λ)	a_m (deg)	SWR by authors' s/w	SWR by NEC	m	$z_{m,m-1}$ (λ)	a_m (deg)	SWR by authors' s/w	SWR by NEC
1		0.0	1.42	1.45	11	0.648	119.6	1.74	1.74
2	0.983	30.0	1.45	1.47	12	0.628	158.5	1.73	1.72
3	0.966	132.8	1.71	1.70	13	0.697	−158.8	1.67	1.70
4	0.724	−172.6	1.28	1.30	14	0.655	−115.4	1.59	1.62
5	0.826	−170.5	1.54	1.55	15	0.786	−79.8	1.51	1.53
6	0.755	−95.0	1.36	1.40	16	0.770	−17.0	1.39	1.40
7	0.780	−52.7	1.51	1.53	17	0.817	28.7	1.35	1.37
8	0.682	−0.5	1.62	1.65	18	0.961	117.8	1.41	1.40
9	0.657	36.0	1.76	1.74	19	0.849	105.8	1.47	1.48
10	0.649	76.4	1.73	1.71	20	0.883	−148.4	1.49	1.49
$d = 0.483\lambda$		authors' software: $G_p^{dB}(\theta_o) = 14.40$ $SLL^{dB} = -20.00$							
		NEC software: $G_p^{dB}(\theta_o) = 14.43$ $SLL^{dB} = -20.01$							

Also, for every case, the optimal values of d, $z_{m,m-1}$ ($m = 2, \ldots, M$) and a_m ($m = 1, \ldots, M$) derived from a random execution of the BPSO-avm were used to produce the θ-plane radiation pattern as well as the values of $G_p(\theta_o)$, SLL and SWR_m ($m = 1, \ldots, M$) by applying the authors' MoM software. In order to verify the above pattern and the above values, the NEC software [27] was applied using the same optimal values of d, $z_{m,m-1}$ (m=2,...,M) and a_m ($m = 1, \ldots, M$). All the above results are presented in a respective table (see Tables 1–6), while the θ-plane radiation patterns are shown

Table 5. Optimization results from a 10-dipole array with $\theta_o = 110°$.

m	$z_{m,m-1}$ (λ)	a_m (deg)	SWR by authors' s/w	SWR by NEC	m	$z_{m,m-1}$ (λ)	a_m (deg)	SWR by authors' s/w	SWR by NEC
1		0.0	1.92	1.95	6	0.488	9.4	2.00	2.00
2	0.792	72.9	1.40	1.45	7	0.576	70.1	1.71	1.74
3	0.556	173.2	1.98	2.00	8	0.543	157.3	2.00	1.98
4	0.647	−126.6	1.43	1.45	9	0.770	−153.3	1.99	1.98
5	0.480	−56.4	2.00	1.97	10	0.462	−17.9	2.00	1.99
$d = 0.461\lambda$		authors' software: $G_p^{dB}(\theta_o) = 10.60$ $SLL^{dB} = -20.00$							
		NEC software: $G_p^{dB}(\theta_o) = 10.65$ $SLL^{dB} = -20.00$							

Table 6. Optimization results from a 20-dipole array with $\theta_o = 110°$.

m	$z_{m,m-1}$ (λ)	a_m (deg)	SWR by authors' s/w	SWR by NEC	m	$z_{m,m-1}$ (λ)	a_m (deg)	SWR by authors' s/w	SWR by NEC
1		0.0	1.58	1.60	11	0.707	126.6	1.48	1.50
2	0.707	101.4	1.40	1.43	12	0.666	−153.6	1.46	1.45
3	0.700	160.0	1.41	1.40	13	0.651	−72.6	1.45	1.44
4	0.689	−93.8	1.34	1.35	14	0.730	24.4	1.37	1.39
5	0.719	−10.7	1.36	1.37	15	0.734	99.3	1.38	1.37
6	0.711	77.7	1.36	1.36	16	0.730	−167.3	1.33	1.36
7	0.708	164.9	1.36	1.37	17	0.769	−88.5	1.40	1.42
8	0.683	−113.9	1.43	1.45	18	0.686	−16.5	1.32	1.35
9	0.631	−35.5	1.47	1.45	19	0.702	113.6	1.10	1.20
10	0.603	49.9	1.60	1.64	20	0.898	128.5	1.27	1.25
$d = 0.480\lambda$		authors' software: $G_p^{dB}(\theta_o) = 13.90$ $SLL^{dB} = -20.06$							
		NEC software: $G_p^{dB}(\theta_o) = 13.94$ $SLL^{dB} = -20.01$							

in a corresponding diagram (see Figures 3–5). Each pattern illustrates the angular distribution of relative values (in dBs) of G_p with respect to its maximum value $G_p(\theta_o)$. It is obvious that the patterns and the values of $G_p(\theta_o)$, SLL and SWR_m ($m = 1, \ldots, M$) derived by the NEC software are close enough to the respective patterns and values derived by the authors' MoM software.

5. CONCLUSION

The cases studied in the present work show that the BPSO-avm is a robust technique capable of improving the radiation characteristics of linear antenna arrays with better performance than the conventional BPSO. The broadside and non-broadside cases show that the conditions of maximum gain, low SLL and impedance matching can be satisfied using uniform-amplitude excitation which is easily implemented in practice. Therefore, the antenna arrays derived from the above study are practically useful for broadcasting and many other applications in communications technology.

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