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Pattern synthesis for multi-feed reflector antennas using invasive weed optimisation

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Abstract: The authors present a new optimisation method for pattern synthesis of multi-feed reflector antennas in this study. By using an invasive weed optimisation (IWO) algorithm, shaped beam antennas are designed. The results of the IWO algorithm for the synthesis of cosecant squared and contoured beam patterns are presented and compared with particle swarm optimisation algorithm results. The far-field radiation patterns of reflector antennas, fed by linear and planar array of conical horn antennas, are provided by a physical optics and the error between desired and provided radiation patterns is calculated by a root mean square method. The results show that the IWO algorithm, which provides good convergence, is stable and adaptive-to-change for different boundary conditions in pattern synthesis applications.

1 Introduction

Several methods have been used to achieve desired radiation patterns of antennas for different applications such as satellite communications, radar systems, direct broadcast satellite communications and radio astronomy. Whenever the mass of an antenna structure is critical, using shaped reflector antennas (SRAs) with a single feed can be a good solution. However, SRAs have several problems such as complexity of structure, single frequency usage and low reliability for satellite applications [1–5]. However, for the SRA the cross-polarisation was seen to be significantly larger in the parabolic reflectors of the same size [2]. Using multi-feed reflector antennas (MFRAs) has been widely studied in recent years for pattern synthesis. Their advantages include a simple structure, ease of fabrication, improved cross-polarisation, frequency reuse and higher reliability [3–10]. For large reflectors, the SRAs are shaped more heavily and finely to obtain the optimum performance. In MFRAs, the large reflector size requires more feeds to be used to obtain the optimum performance. Although the directivity is better for SRAs for smaller reflector sizes, the MFRAs perform slightly better for large diameters [11].

To synthesise a desired radiation pattern such as cosecant squared or contoured beam and so on, different methods such as the enumeration methods, calculus-based techniques and guided random search techniques have been used to find the excitation of radiating elements of MFRAs and deviation of SRAs surface [12–14]. Achieving desired radiation patterns without an optimisation algorithms are usually time consuming and inefficient. Moreover, for complicated radiation patterns, finding the excitation of source antennas in MFRAs as well as their spacing cannot be obtained analytically. Using optimisation algorithms in several electromagnetic problems such as shaped beam antenna design assist in finding the values of phase and/or amplitude of the source antennas or the spacing between antenna elements. Different evolutionary algorithms such as genetic algorithm (GA) and particle swarm optimisation (PSO) have been used for antenna applications [15–18]. Contrast to the GA and PSO, the invasive weed optimisation (IWO) algorithm [19] is inspired from the phenomena of colonisation of invasive weeds in nature which is based on the biology and ecology of weeds. The capability of IWO is discussed in [20–22] for simple electromagnetic problems.

In this paper, different patterns such as cosecant squared and contoured beam are synthesised in linear and planar feed configurations in MFRAs by using an IWO algorithm and the results are compared with other evolutionary algorithms. The aim of optimisation is to minimise the root mean square (RMS) value of the difference between the provided and desired patterns by the IWO algorithm. It is shown that the IWO algorithm provides a simple optimisation process and a few adjacent parameters, which make it a good candidate for the future applications in antenna design.

2 IWO algorithm

The IWO algorithm is inspired by colonisation of invasive weeds because of the biological and ecological effects. In the IWO algorithm, a solution space is defined for d parameters (d-dimensional space) of the problem to be optimised. The main parameters of the IWO are the initial population (ini_{pop}), maximum number of plants ($P_{\max}$), non-linear modulation index (n), initial standard deviation (σ_{ini}), final standard deviation (σ_{final}), maximum number of iteration ($\text{iter}_{\max}$), maximum number of seeds ($\text{Seed}_{\max}$) and minimum number of seeds ($\text{Seed}_{\min}$) to be produced by

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each flowering plant. The dynamic range of the solution space for each of d parameters should be set correctly to avoid producing worthless fitness values.

The IWO algorithm functions as below:

1. *Create initial population:* A set of ini_{pop} seeds within the d-dimensional search space are randomly generated and distributed for the initial iteration.
2. *Calculate the fitness value of each flowering plant:* The seeds grow and flowering plants are created.
3. *Sort the population:* The flowering plants are sorted by their fitness values in such a way that a lower fitness value has a better position than a higher fitness value.
4. *Produce next generation:* The best flowering plant leads to the production of $\text{Seed}_{\max}$ seeds for the next generation. For the next generation, only $P_{\max}$ sets of produced seeds can survive.
5. *Distribute next generation:* The produced seeds will be generated around the parent weed, leading to a local search around each plant. However, the standard deviation (σ) of the random function is made to decrease over the iterations. The standard deviation for a particular iteration can be expressed as follows

$$\sigma_{\text{iter}} = \frac{(\text{iter}_{\max} - \text{iter})^n}{(\text{iter}_{\max})^n}(\sigma_{\text{ini}} - \sigma_{\text{final}}) + \sigma_{\text{final}} \tag{1}$$

6. *Go to step 2 or terminate:* The optimisation process continues to obtain the global answer. The optimisation can be terminated when the maximum number of iterations is achieved. Moreover, when the fitness value goes below the desired fitness, the algorithm is terminated.

Maximum and minimum numbers of seeds are important parameters in IWO. Selecting $\text{Seed}_{\max} = 3-5$ and $\text{Seed}_{\min} = 0-1$, leads to a good performance. Also, σ_{ini} is set around 5–10% of the dynamic range of each variable. Moreover, it is seen that for different electromagnetic problems, $n = 3$ can provide good converging results [21].

In IWO, all of the plants are allowed to participate in reproduction, which is a feature not found in PSO and GA. This feature gives the opportunity to all agents to survive and reproduce based on their fitness [21]. Moreover, in the PSO algorithm, inertial weight (W), cognitive rate (c_1), social rate (c_2) and the maximum velocity ($V_{\max}$), should be controlled to achieve the desired convergence. These parameters are critical to the convergence of PSO [16, 18]. By capturing the properties of the invasive weeds, IWO provides a very robust adaptive-to-change behaviour in any environment, which leads to a powerful optimisation algorithm [20–23]. IWO shows a high stability with different boundary conditions [21] which makes it good candidates for different electromagnetic problems such as shaped beam antennas.

3 Pattern synthesis

To find the excitation values of an array of MFRAs, three methods are given in [5] as follows:

1. phase only,
2. amplitude and phase with no constraint,
3. amplitude and phase with a constraint on the level of the maximum and minimum radiated power in aperture.

In this paper, we consider first and second methods to find the values of excitation for reflector antennas. Different radiation patterns such as cosecant squared and contoured beam are considered as desired radiation patterns. For different configurations of MFRAs, the IWO algorithm is used to find the values of phase and/or amplitude of the array elements. An array of conical horn antennas with spacing $s = \lambda$ are used in the focal point to illuminate the surface of the reflector antenna. The conical horn antenna with flare diameter of 0.9λ and flare length of 0.6λ has 9 dB gain with 120° half-power beam width.

3.1 Cosecant squared beam

The geometry of an offset parabolic reflector antenna is shown in Fig. 1. As shown, D is the diameter of the offset parabolic reflector antenna, H is the offset height of the reflector and F is the focal point of the initial reflector with diameter of D_{p}. The array of feeds are located at the $(x_{\text{f}} - y_{\text{f}})$ plane at focal point of reflector antenna with ψ_B rotation towards the centre point of reflector. The element spacing between conical horns is $s = \lambda$. The following parameters are calculated to illuminate the surface of the offset reflector antenna efficiently [23]

$$D_{\text{p}} = 52.5\lambda, \quad D = 24\lambda, \quad d = 14.3\lambda, \quad F = 8\lambda, \quad H = 2.4\lambda$$

$$\Psi_U = 2\tan^{-1}((D+H)/2F) = 117$$

$$\Psi_L = 2\tan^{-1}(H/2F) = 17$$

$$\Psi_C = 2\tan^{-1}((D/2+H)/2F) = 84$$

$$\Psi_B = (\Psi_U + \Psi_L)/2 = 67$$

The far-field radiation pattern of the parabolic reflector antenna is calculated through the physical optics (PO) in the commercial FEKO package, by using Edit-FEKO section. By drawing proposed reflector antennas in Edit-FEKO, linear or planar array configurations of feed horn antennas are placed at the focal point with the optimum rotation angle of ψ_C toward the center point of the reflector surface. The Edit-FEKO enables us to have control on MFRAs parameters, such as amplitude or phase of multi-feed structures through the optimiser. The optimiser, such as GA, PSO and IWO, changes and optimises these parameters till the optimum or best radiation patterns are obtained by using Edit-FEKO section. The total feed field,

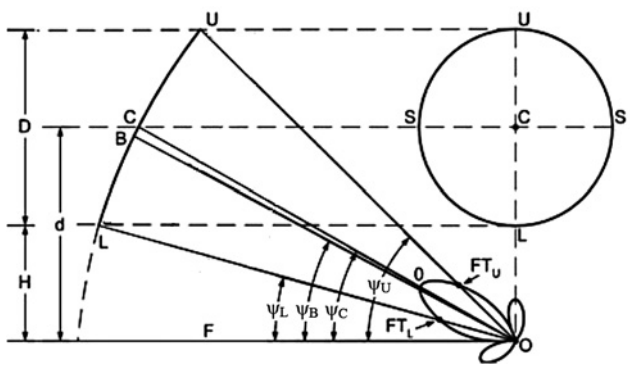

Fig. 1 *Geometry of offset parabolic reflector antenna which is fed by phased array antenna*

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E_f, is the sum of element fields

$$E_f = \sum_{i=1}^{n} E_{ei} \tag{2}$$

where it is assumed that each E_{ei} has been properly transformed to the feed array coordinate system in the $(x_f - y_f)$ plane [3].

To compute the fitness value of each plant, the desired radiation pattern is considered between $-40°$ and $40°$ in five regions. Between $-40°$ and $-1°$ is considered for Region 1. Also, between $31°$ and $40°$ is named Region 5. Then, a threshold of -18 dB is defined for these two regions which are outside of the main lobe of the cosecant squared beam. It means that the normalised computed radiation pattern of each sample in these two regions is desired to be below -18 dB. When the computed pattern in these two regions is below the threshold of -18 dB, the error value is zero. Whereas, for the pattern above the threshold, the difference between the computed pattern and desired value is considered for the cost value. Moreover, $0°–1°$ is transit region in pattern which is named Region 2. In this region, the normalised radiation pattern should increase from -18 to 0 dB in only two samples. Also, $2°–3°$ is peak gain region for far-field pattern (Region 3). For normalised radiation pattern, this region is equal to 0 dB. Finally, the cosecant squared pattern is defined between $4°$ and $30°$ as Region 4. It should be noted that a 1 dB variation around the desired pattern for Regions 2–4 is acceptable. By using the RMS, the values of the errors between the desired and the calculated pattern are computed to be used in both IWO and PSO algorithms. The RMS value is computed by using the weighted coefficients error for each region as below:

Weight of Region 1 (W_{R1}): 7.5
Weight of Region 2 (W_{R2}): 1
Weight of Region 3 (W_{R3}): 0.5
Weight of Region 4 (W_{R4}): 12.5
Weight of Region 5 (W_{R5}): 0.1

$$\text{Cost} = \text{RMS} \sum_{i=1}^{5} W_{Ri}\Delta_{Ri} \tag{3}$$

where Δ_{Ri} shows the error differences for each region.

The proposed offset parabolic reflector antenna, illuminated by a linear array of 11 conical horn antennas in the focal point in the $(x_f - y_f)$ plane, is considered. The amplitudes and phases of 11 source antennas (22

Table 1 IWO parameters for the multi-feed offset reflector antenna design

Variable	Value
iter_{max}	50
dimension	22
ini_{pop}	40
P_{max}	40
n	3
σ_{ini}	0.1
σ_{final}	0.001
Seed_{max}	5
Seed_{min}	0

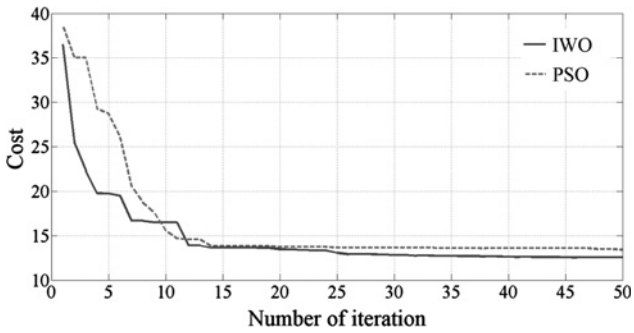

Fig. 2 *Convergence diagram of the IWO and PSO algorithms to synthesise the cosecant squared beam by linear array of conical horn antenna in MFRAs*

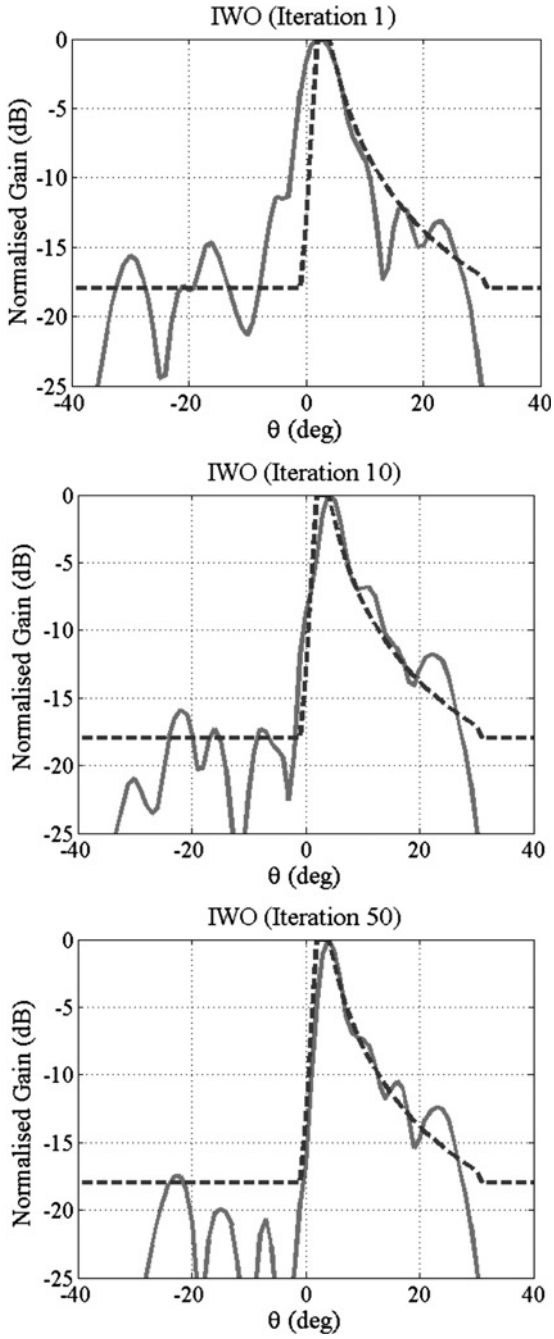

Fig. 3 *Simulation results of the IWO algorithm to synthesise the cosecant squared beam by MFRAs (solid lines are the provided pattern and dashed lines are the desired pattern)*

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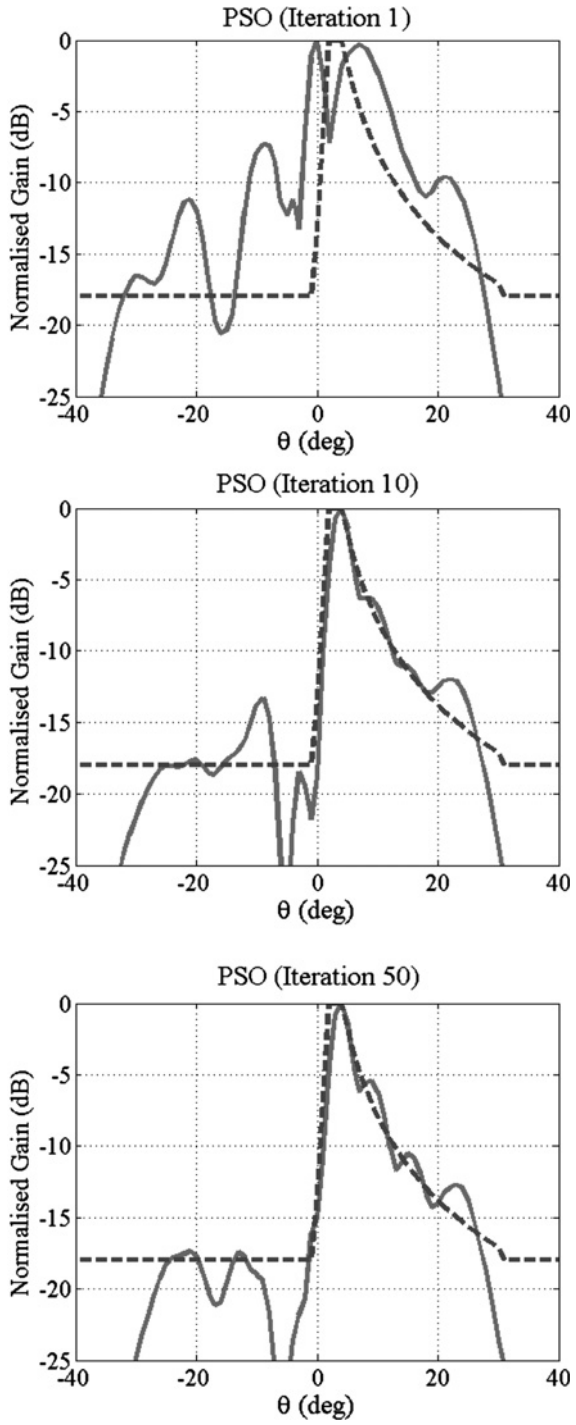

Fig. 4 *Simulation results of the PSO algorithm to synthesise the cosecant squared beam by MFRAs (solid lines are the provided pattern and dashed lines are the desired pattern)*

parameters for optimisation) are optimised by using IWO and PSO algorithms with no constraint for the parameters [4]. The solution space for amplitudes and phases for both algorithms are chosen in the range of (0–1) and (0–360°), respectively. The initial population for both algorithms is considered to be the same. Table 1 shows the parameters of the IWO algorithm for a multi-feed offset reflector antenna design. The main parameters of the PSO algorithm for a multi-feed offset reflector antenna design are $c_1 = 2$, $c_2 = 2$, $W = 0.9$ and $V_{\max} = 0.1$.

The convergence diagram is shown in Fig. 2. The simulated radiation patterns after 1, 10 and 50 iterations for

Table 2 MFRA excitations by the IWO algorithm

Port excitation	Iteration 1	Iteration 10	Iteration 50
$a1\angle b1$	0.40∠275	0.14∠221	0.23∠147
$a2\angle b2$	0.83∠246	0.94∠202	1∠217
$a3\angle b3$	0.93∠315	0.63∠360	0.94∠360
$a4\angle b4$	0.50∠63	0.58∠95	0.77∠126
$a5\angle b5$	0.81∠29	1∠16	0.97∠16
$a6\angle b6$	0.69∠23	0.22∠88	0.03∠40
$a7\angle b7$	0.17∠173	0.11∠279	0.01∠228
$a8\angle b8$	0.08∠227	0.09∠238	0.04∠315
$a9\angle b9$	0.27∠4	0.41∠39	0.33∠3
$a10\angle b10$	0.48∠265	0.64∠291	0.57∠266
$a11\angle b11$	0.82∠182	0.54∠180	0.16∠222

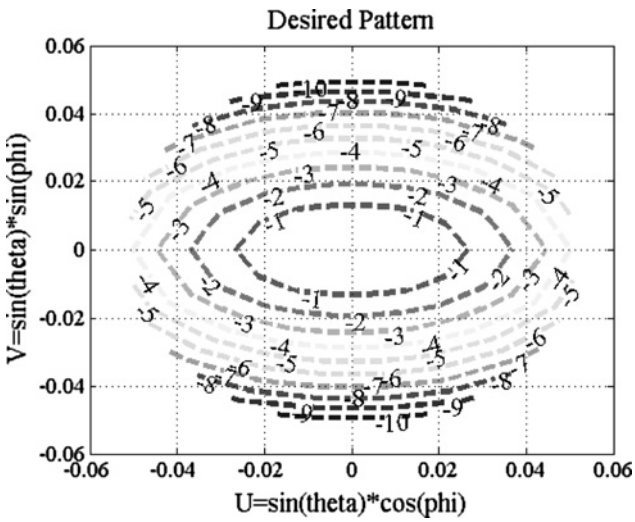

Fig. 5 *Desired simple elliptical beam in the U–V plane for MFRAs*

the both PSO and IWO algorithms are shown in Figs. 3 and 4, respectively. The IWO algorithm provides reasonable results after ten iterations. Moreover, the IWO has the capability to be used in shaped beam antenna design for MFRAs. Table 2 shows the amplitudes and phases of 11 source antennas for a multi-feed offset reflector antenna design for the initial iteration and after 10 and 50 iterations.

3.2 Elliptical contour beam

3.2.1 Simple elliptic: In this section, a simple elliptical-shaped beam in the $U - V$ plane ($U = \sin\theta\ \cos\varphi$ and $V = \sin\theta\ \sin\varphi$) is considered, as the desired radiation

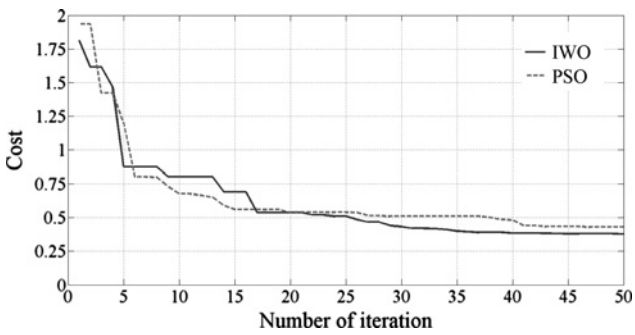

Fig. 6 *Convergence diagram of the IWO and PSO algorithms to synthesise simple elliptical beam in the U–V plane for MFRAs*

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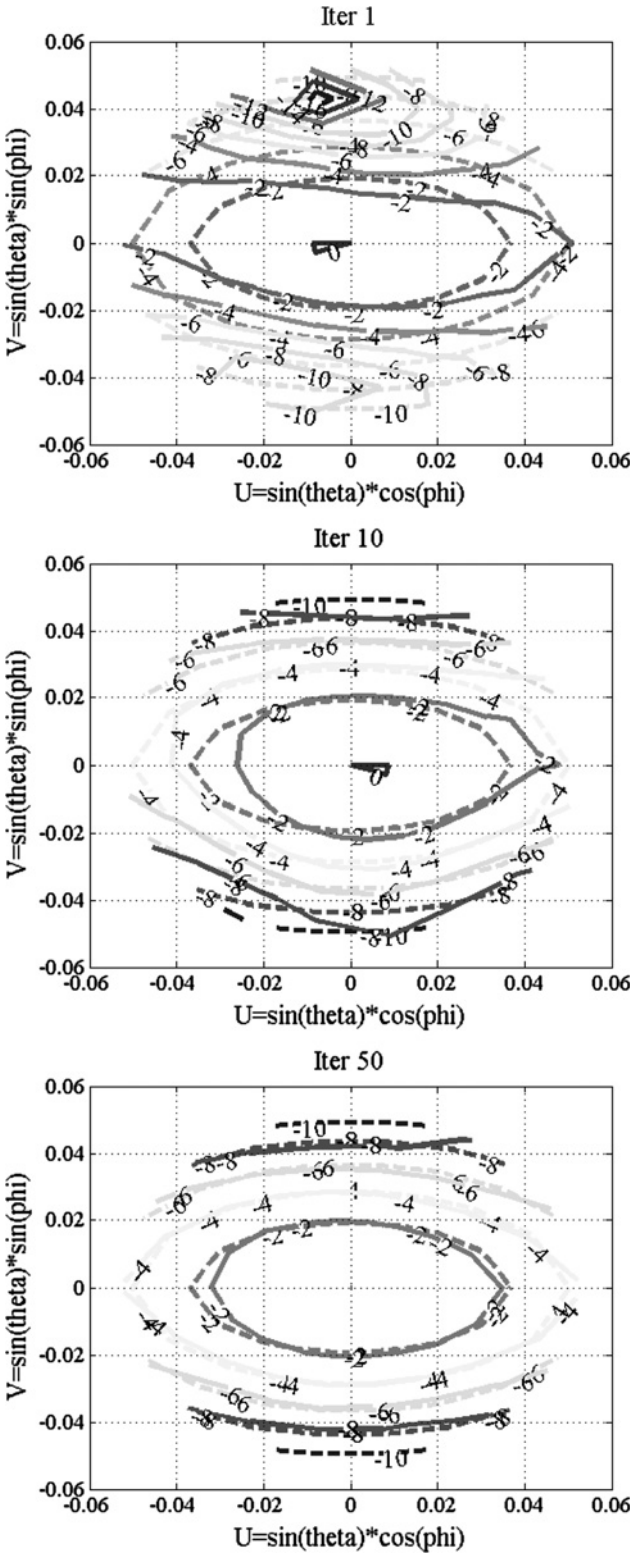

Fig. 7 *Simulation results of the IWO algorithm to synthesise the simple elliptical contour beam of MFRAs by phase only synthesis (solid lines are the provided pattern and dashed lines are the desired pattern)*

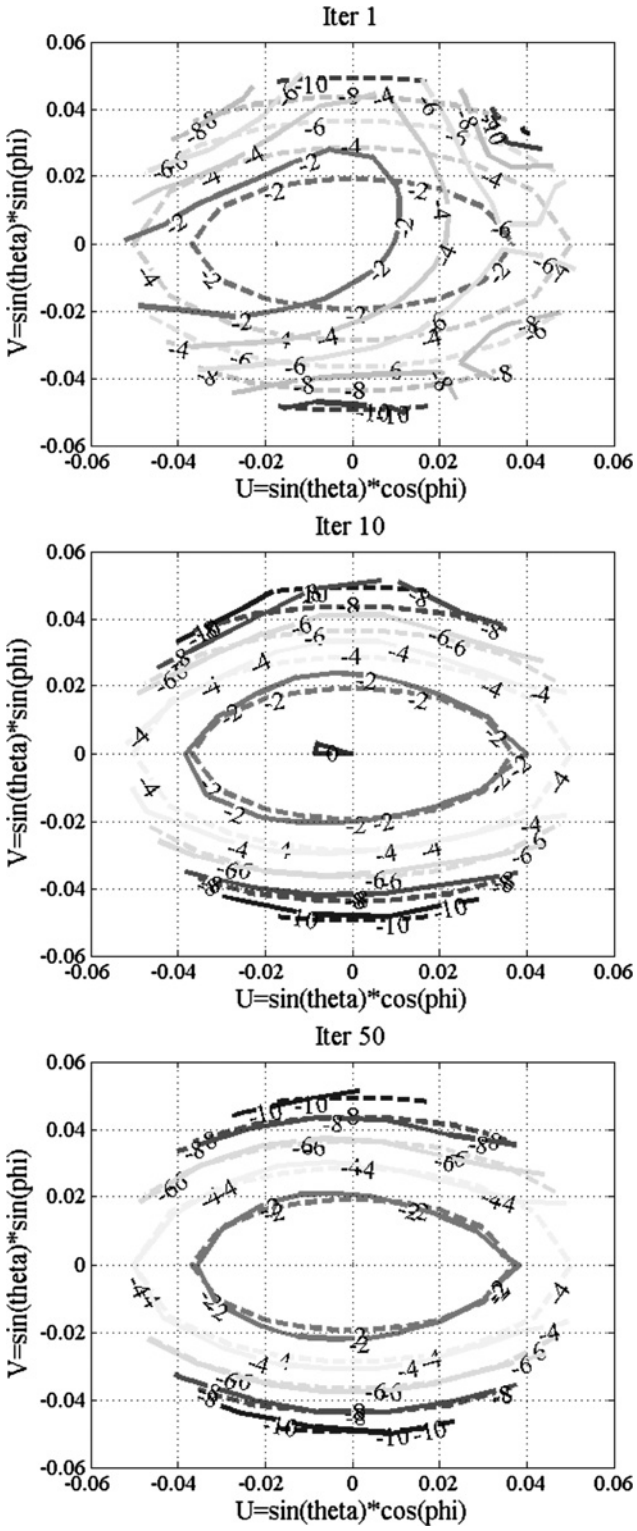

Fig. 8 *Simulation results of the PSO algorithm to synthesise the simple elliptical contour beam of MFRAs by phase only synthesis (solid lines are the provided pattern and dashed lines are the desired pattern)*

pattern shown in Fig. 5. At first, by using an array feed of 25 elements (5 × 5 array configuration) for symmetric reflector antennas, only phase excitation for array elements is considered. The dimensions of the reflector antennas are $F = 14\lambda$ and $D = 20\lambda$. The IWO parameters are set as presented in Table 1 (the only difference is dimension, $d = 25$). The PSO parameters are considered the same as the previous example.

By employing the PO to analyse diffraction of reflector antennas and RMS to compute the error values in each iteration, the convergence diagram of the IWO and PSO algorithms are obtained as illustrated in Fig. 6. The radiation pattern of MFRAs by only phase excitation which

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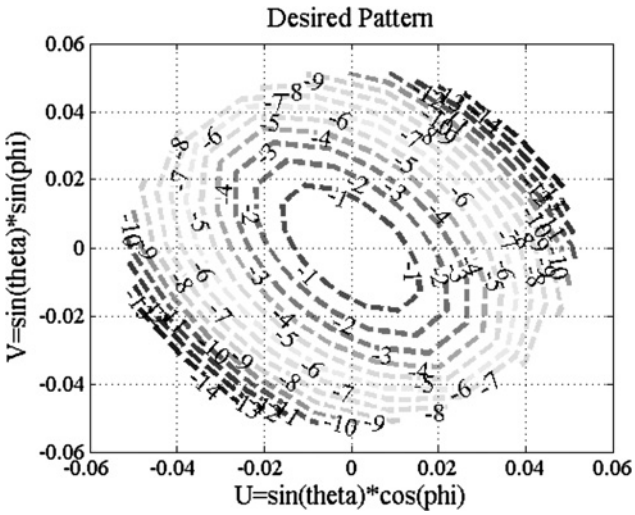

Fig. 9 *Desired rotated elliptical beam in U–V plane for MFRAs*

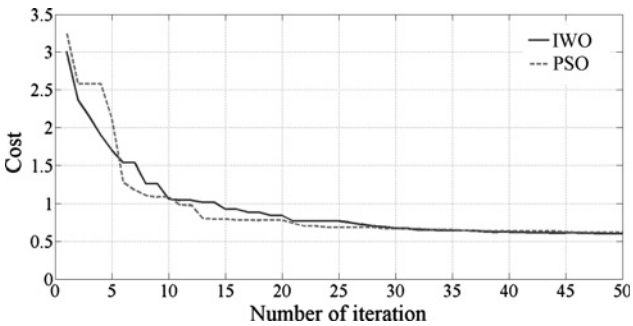

Fig. 10 *Convergence diagram of the IWO and PSO algorithms to synthesise rotated elliptical beam in the U–V plane for MFRAs*

is optimised by the IWO algorithm is shown in Fig. 7. In addition, the results of the PSO algorithm are also shown in Fig. 8. It is clear that the IWO algorithm can provide good predictions, better than PSO in several cases, with a few tuning parameters.

3.2.2 Rotated elliptic: In this section, a rotated elliptical-shaped beam in the $U-V$ plane is considered as the desired radiation pattern, shown in Fig. 9. At first, by using a feed array of 25 elements (5 × 5 configuration) for offset reflector antennas, phase and amplitude with no constraint for array elements is considered. The dimensions of the offset reflector antenna are as follow

$$D_{\mathrm{p}} = 64\lambda, \quad D = 23\lambda, \quad F = 16\lambda, \quad H = 9\lambda$$

$$\Psi_U = 2\tan^{-1}((D+H)/2F) = 90$$

$$\Psi_L = 2\tan^{-1}(H/2F) = 31$$

$$\Psi_C = 2\tan^{-1}((D/2+H)/2F) = 65$$

$$\Psi_B = (\Psi_U + \Psi_L)/2 = 60.5$$

The IWO parameters are set as presented in Table 1 (the only difference is the dimension, $d = 50$). The radiation pattern of the multi-feed offset reflector antennas by amplitude and phase excitation with no constraint are optimised by the IWO algorithm. The convergence diagram of the IWO and PSO algorithms is shown in Fig. 10. Moreover, the results of the radiation patterns in the $U-V$ plane for the rotated elliptic by the IWO algorithm are shown in Fig. 11. As seen, the IWO algorithm can provide a good convergence during finite iterations. This simple IWO algorithm has a few tuning parameters such as σ_{ini}, σ_{final}, $\mathrm{Seed}_{\mathrm{min}}$, $\mathrm{Seed}_{\mathrm{max}}$

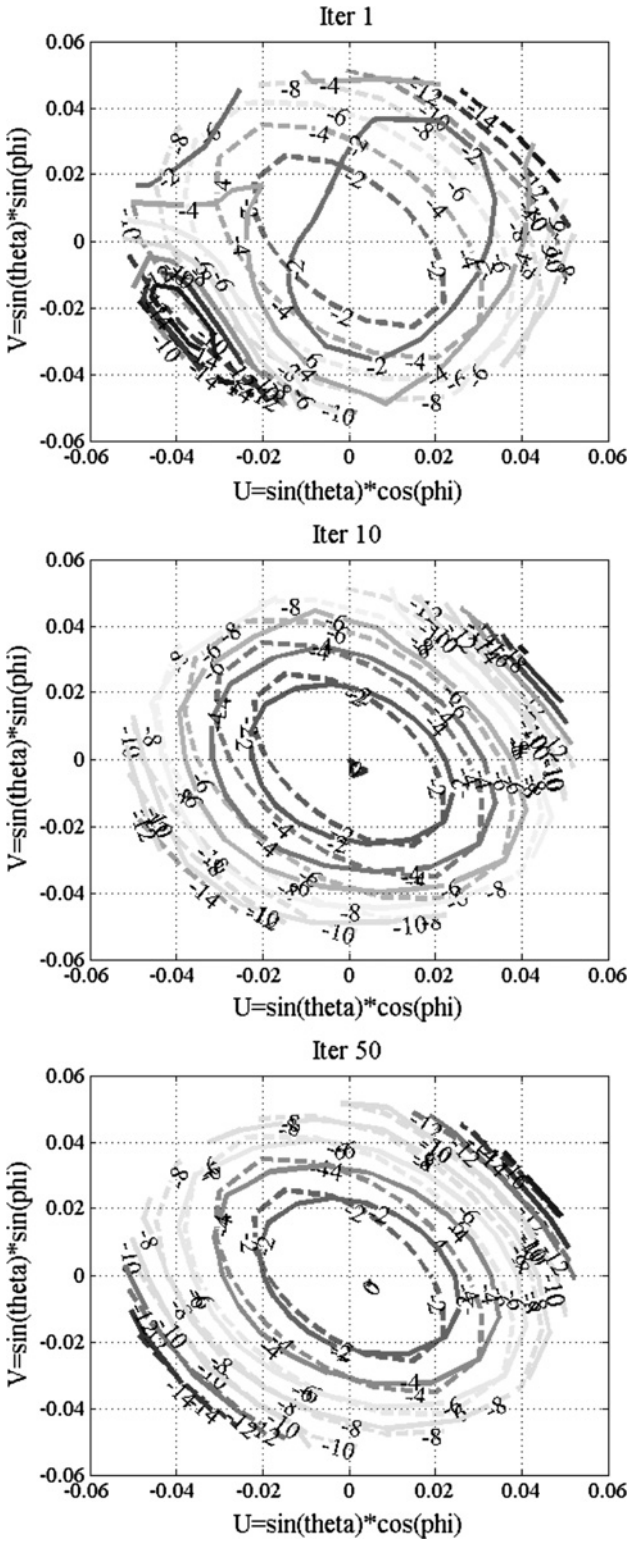

Fig. 11 *Simulation results of the IWO algorithm to synthesise the rotated elliptical contour beam of MFRAs by amplitude and phase synthesis with no constraints (solid lines are the provided pattern and dashed lines are the desired pattern)*

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and n. In other words, complex radiation patterns can be obtained easily by the IWO algorithm.

4 Conclusion

We have used the IWO algorithm as a novel evolutionary algorithm in electromagnetic problems. Different radiation patterns, namely the cosecant squared and contoured beam, have been optimised in several MFRA configurations. Symmetric and offset parabolic reflector antennas, which are illuminated by an array of conical horn antennas with λ spacing, have been considered for different reflector structures. By using PO to analyse the diffraction of reflectors and the RMS method to compute the error values in each iteration, the desired patterns are optimised.

The IWO algorithm shows very robust usage for different configurations in shaped beam antenna designs. This algorithm also shows a high degree of stability with different boundary conditions and is a good candidate for different electromagnetic problems. The results of the IWO are comparable with the PSO algorithm in different situations which shows that by tuning the IWO parameters, better predictions can be obtained.

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6 References

1 Gonzalez-Valdes, B., Martinez-Lorenzo, J.A., Rappaport, C., Pino, A.G.: 'Generating contoured beams with single-shaped reflectors using a iterative field-matrix approach', *IEEE Antennas Wirel. Propag. Lett.*, 2008, **7**, pp. 697–700

2 Hay, S.G.: 'Application of the PTD to cross-polarization prediction in shaped-reflector antenna'. IEEE AP-S Int. Symp. Digest, California, 1995, vol. 2, pp. 1174–1177

3 Duan, D.W., Rahmat-Samii, Y.: 'A generalized diffraction synthesis technique for high performance reflector antennas', *IEEE Trans. Antennas Propag.*, 1995, **43**, (1), pp. 27–40

4 Bhattacharyya, A.K.: 'Projection matrix method for shaped beam synthesis in phased arrays and reflectors', *IEEE Trans. Antennas Propag.*, 2007, **55**, (3), pp. 675–683

5 Lier, E., Cherrette, A.: 'A comparison between reflector and active array satellite antennas with contour beams'. IEEE AP-S Int. Symp. Digest, California, 1995, vol. 1, pp. 124–127

6 Botha, E., McNamara, D.A.: 'A contoured beam synthesis technique for planar antenna arrays with quadrantal and centro-symmetry', *IEEE Trans. Antennas Propag.*, 1993, **41**, (9), pp. 1222–1231

7 Vipiana, F., Vecchi, G., Sabbadini, M.: 'A multiresolution approach to contoured-beam antennas', *IEEE Trans. Antennas Propag.*, 2007, **55**, (3), pp. 684–697

8 Chou, H.T., Hsaio, Y.T., Pathak, P.H., Nepa, P., Janpugdee, P.: 'A fast DFT planar array synthesis tool for generating contourd beams', *IEEE Antennas Wirel. Propag. Lett.*, 2004, **3**, pp. 287–290

9 Bird, T.S.: 'Contoured-beam synthesis for array-fed reflector antennas by field correlation', *IEE Proc. Microw. Opt. Antennas*, 1982, **129**, (6), pp. 293–298

10 Duan, D.W., Rahmat-Samii, Y.: 'Reflector/feed(s) synthesis challenges for satellite contour beam applications'. IEEE AP-S Int. Symp., Illinois, 1992, vol. 1, pp. 297–300

11 Ramanujam, P., Law, P.H.: 'Shaped reflector and multi-feed paraboloid – a comparison'. IEEE AP-S Int. Symp., Florida, 1999, vol. 2, pp. 1136–1139

12 Richie, J.E., Kritikos, H.N.: 'Linear program synthesis for direct broadcast satellite phased array', *IEEE Trans. Antennas Propag.*, 1988, **36**, (3), pp. 345–348

13 Skolnik, M.I., Nemhauser, G., Sherman, J.W.: 'Dynamic programming applied to unequally spaced arrays', *IEEE Trans. Antennas Propag.*, 1964, **12**, (1), pp. 35–43

14 Perini, J.: 'Note on antenna pattern synthesis using numerical iterative methods', *IEEE Trans. Antennas Propag.*, 1971, **19**, (2), pp. 284–286

15 Haupt, R.L.: 'Thinned arrays using genetic algorithms', *IEEE Trans. Antennas Propag.*, 1994, **42**, (7), pp. 993–999

16 Jin, N., Rahmat-Samii, Y.: 'Advances in particle swarm optimization for antenna designs real-number, binary, single-objective and multiobjective implementations', *IEEE Trans. Antennas Propag.*, 2007, **55**, (3), pp. 556–567

17 Bayraktar, Z., Werner, D.H., Werner, P.L.: 'Miniature meander-line dipole antenna arrays, designed via an orthogonal-array-initialized hybrid particle-swarm optimizer', *IEEE Antennas Propag. Mag.*, 2011, **53**, (3), pp. 42–59

18 Xu, S., Rahmat-Samii, Y.: 'Boundary conditions in particle swarm optimization revisited', *IEEE Trans. Antennas Propag.*, 2007, **52**, (3), pp. 760–765

19 Mehrabian, A.R., Lucas, C.: 'A novel numerical optimization algorithm inspired from weed colonization', *Ecol. Inf.*, 2006, **1**, (4), pp. 355–366

20 Sedighy, S.H., Mallahzadeh, A.R., Soleimani, M., Rashed-Mohassel, J.: 'Optimization of printed yagiantenna using invasive weed optimization (IWO)', *IEEE Antennas Wirel. Propag. Lett.*, 2010, **9**, pp. 1275–1278

21 Karimkashi, S., Kishk, A.A.: 'Invasive weed optimization and its features in electromagnetics', *IEEE Trans. Antennas Propag.*, 2010, **58**, (4), pp. 1269–1278

22 Roy, G.G., Das, S., Chakraborty, P., Suganthan, P.N.: 'Design of non-uniform circular antenna arrays using a modified invasive weed optimization algorithm', *IEEE Trans. Antennas Propag.*, 2011, **59**, (1), pp. 110–118

23 Foudazi, A., Mallahzadeh, A.R., Samadi Taheri, M.M.: 'Pattern synthesis for multi-feed reflector antenna using iwo algorithm'. Sixth European Conf. Antennas Propagation, Prague, March 2012, pp. 1–5

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