Jurnal
Teknologi

Full Paper

MULTI-OBJECTIVES ADAPTIVE ARRAY SYNTHESIS USING SPEEDY-PARTICLE SWARM METHOD

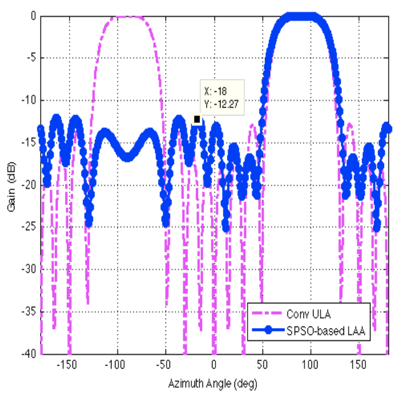
N.N.N.A. Malik*, M. Esa, S.K.S. Yusof, N.M.A. Latiff

Faculty of Electrical Engineering, Universiti Teknologi Malaysia, 81310 UTM Johor Bahru, Johor, Malaysia

Article history
Received
18 May 2015
Received in revised form
9 July 2015
Accepted
24 August 2015

*Corresponding author
noordini@utm.my

Graphical abstract



Abstract

A method of computing the optimum element distance position of multi-objectives adaptive linear antenna arrays (MLAA) is developed by taking several objectives (eg. adaptive capability, beamwidth and minimum sidelobe level (SLL)) into consideration. In this paper, the recently invented algorithm, known as Speedy-Particle Swarm Optimization (SpPSO) algorithm is adopted to optimize the distance between the MLAA elements. Different numerical examples of 8- and 12-element MLAA are presented to validate and illustrate the capability of SpPSO for pattern synthesis with a prescribed adaptive angle, controllable beamwidth and minimum SLL. It was found that by employing SpPSO method, the results provide considerable improvement over the conventional array. It is observed that the maximum normalized SLL of -12.27 dB has been achieved by using SpPSO for 8-element MLAA. The proposed SpPSO-based LAA also able to achieve a beampattern with sufficiently low sidelobes for 12-element MLAA by having maximum SLL of -16.46 dB, a desired wider FNBW of 50° and main beam that is pointing to 20°.

Keywords: Array signal processing, linear array, particle swarm method

Abstrak

Satu kaedah pengiraan kedudukan jarak elemen optimum berbilang objektif tatasusunan antena linear (MLAA) dibangunkan dengan mengambil beberapa objektif (contohnya. keupayaan penyesuaian, beamwidth dan paras cuping sisi (SLL)). Dalam kertas kerja ini, algoritma yang telah dicipta, yang dikenali sebagai Teknik Laju Kerumunan Zarah (SpPSO) algoritma diguna pakai untuk mengoptimumkan jarak antara elemen MLAA. Contoh simulasi yang berbeza 8- dan 12-elemen MLAA dibentangkan untuk mengesahkan dan menggambarkan keupayaan SpPSO bagi sintesis corak dengan sudut yang ditetapkan penyesuaian, lebaralur terkawal dan SLL minimum. Ia telah mendapati bahawa dengan menggunakan kaedah SpPSO, keputusan menunjukkan peningkatan yang besar berbanding tatasusunan konvensional. Adalah diperhatikan bahawa SLL normal maksimum -12.27 dB telah dicapai dengan menggunakan SpPSO bagi 8-elemen MLAA. Cadangan LAA berasaskan SpPSO juga dapat mencapai corak alur dengan sampingan lobus yang cukup rendah untuk 12-elemen MLAA dengan mempunyai SLL maksimum -16.46 dB, FNBW dikehendaki lebih luas sebanyak 50 ° dan rasuk utama yang menunjuk ke 20 °.

Kata kunci: Pelbagai pemprosesan isyarat, tatasusunan linear, teknik kerumunan zarah

1.0 INTRODUCTION

The radiation pattern of a single element is usually relatively wide with low values of directivity and gain. The needs of designing an antenna with a very high gain and directivity is very demanding especially for long distance communication. Antenna array is an assembly of two or more antennas in electrical and geometry configuration. The signals from each of the antenna interfere constructively (add) in the desired direction and interfere destructively (cancel each other) in the remaining angles [1]. Additionally, intelligence can also be introduced to the antenna systems. The main beam of the antenna pattern can be directed towards and focused on the desired direction while minimizing other beams. The interference from other users are reduced by setting a radiation pattern with minimal sidelobe level (SLL). Thus, the antenna structures, especially in array arrangements, have the capability to improve signal quality and provide interference reduction, thereby increasing system coverage and capacity.

Techniques of designing array antenna can be realized by controlling several factors: the geometrical configuration of the array, the amplitude and phase of the current excitations, and the distance position of the individual elements. The methods used for designing antenna arrays can be categorized into two categories (i.e. deterministic and stochastic). The deterministic method, which consists of the analytical and semi-analytical method (i.e. least mean square (LMS) or recursive least square (RLS) algorithms) can be very complex and computationally time consuming.

Nevertheless, stochastic methods have many superior characteristics over deterministic method [2]. These methods include evolutional optimization algorithm such as genetic algorithm (GA) [3], [4], simulated annealing (SA), and particle swarm optimization (PSO) have been aggressively introduced in antenna designs and electromagnetics. The advantages of using these stochastic methods are the capability of dealing with multi-objective optimization within shorter time, and require simple computations. PSO has also been found to work better in certain kind of optimization problems compared to conventional analytical approaches, classical optimizations and other evolutionary optimization techniques. Compared to GA and SA, it is easily implemented as it has smaller number of parameters to be tuned, thus, has least complexity with fewer lines of code [5].

A comparison study has been performed comparing PSO to GA [5]. The literature also reported that PSO has been used in [6] to present a study of adaptive beamforming for arbitrary array by applying the powerful and versatile PSO. Numerical experiments for sidelobe suppression, nulling, null steering and array failure correction have demonstrated that the presented PSO approach is effective for adaptive beamforming. An Improved Particle Swarm Optimization (IPSO) [7] is adopted for the complex synthesis of three-ring Concentric Circular Antenna Arrays (CCAA) with having the objective of maximum Sidelobe Level (SLL) reduction.

An improved PSO (IPSO) is also proposed in order to overcome the drawbacks of standard PSO [8]. The improvements included mechanisms for velocity updating, the exceeding boundary control, the global best perturbation and the simplified quadratic interpolation (SQI) operator. A modified PSO has been investigated by adding integral control and the contractive factor in [9].

The problem described herein is as follows: design 8- and 12-element MLAA (see Figure 1) such that the same amplitude excitation generates a minimum SLL radiation pattern with prescribed adaptive angle and controllable beamwidth, the difference being dependent only upon the element distance of the array. New objective function is introduced to offer better outcomes. The performance of this newly developed SpPSO method is compared with conventional method [1] in terms of the performance result of the radiation pattern. Previous trials to improve the PSO in other numerical examples have been reported in previous work [10], [11].

The remainder of the paper is organized as follows. The optimization model for MLAA is discussed in Section II. The development of a SpPSO engine for array optimization is briefly described in Section III, the optimization results and analysis are presented in Section IV. Section V concludes the paper.

2.0 OPTIMIZATION MODEL FOR MULTI OBJECTIVE ADAPTIVE LINEAR ANTENNA ARRAY

A one-dimensional MLAA is assumed to be positioned along the x-axis. The array factor, *AF* of this MLAA using identical omnidirectional antennas such as in Figure 1 can be expressed as:

$$AF(d_n,\theta) = \sum_{n=1}^{N} I_n \exp(j\kappa d_n \cos\theta + \beta_n) \qquad (1)$$

where κ is the wavenumber and I_n, β_n, θ, and d_n are the excitation amplitude, phase, observation angle, and location of the *n*th element from the reference node at the origin, respectively. The distance, d_n represents $d_1=x_1$; $d_2=d_1+x_2$; $d_3=d_2+x_3$;….$d_N=d_{N-1}+x_N$. Assuming a uniform excitation of amplitude, $I_n=1$ and phase, β_n:

$$\beta_n = -\kappa d_n cos\theta_0 \qquad (2)$$

The progressive phase excitation, β_n for each element in the array is responsible to adapt the main beam of the radiation pattern to the direction given by θ_0. Thus, both equations (1) and (2) can be simplified to:

$$AF(d_n,\theta) = \sum_{n=1}^{N} I_n \exp(j\kappa d_n(\cos\theta - \cos\theta_0)) \quad (3)$$

The maximum value of *AF* is at $\theta = \theta_0$ which is the main lobe of the radiation pattern pointing towards θ_0. The normalized power gain, G_{norm} in *dB* is given by:

$$G_{norm} = 10log_{10}\left(\frac{|AF(d_n,\theta)|^2}{max|AF(d_n,\theta)|^2}\right) \quad (4)$$

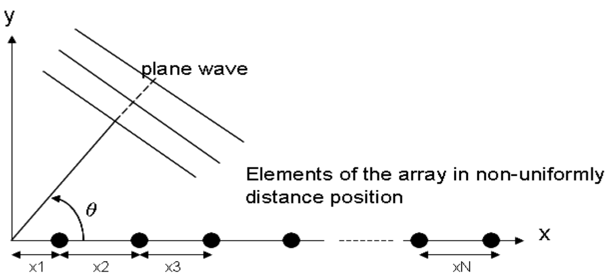


Figure 1 N-element MLAA Geometry

3.0 PROPOSED METHODOLOGY DESCRIPTION

3.1 Speedy-PSO Algorithm (SpPSO)

The SpPSO is developed with the purpose of overcoming problems such as lacking of global search ability and trapping inside local optima from the original PSO. Two main PSO operators, which can be expressed as [12]:

$$v_{sn}(\tau+1) = \omega v_{sn}(\tau) + c_1 r_1[p_s(\tau+1) - x_{sn}(\tau)] + c_2 r_2[g_n(\tau+1) - x_{sn}(\tau)] \quad (5)$$

$$x_{sn}(\tau+1) = x_{sn}(\tau) + v_{sn}(\tau+1) \quad (6)$$

where c_1 and c_2 are acceleration constants, r_1 and r_2 are uniformly distributed numbers in [0,1]. $\tau+1$ and τ refer to the time index of the current and previous iterations. ω is the inertial weight factor. x_{sn}, v_{sn}, p_s and g_n are the position, velocity, the particle's best position and the global position, respectively.

The newly formulated algorithm, SpPSO is expected to successfully solving MLAA problems by optimizing the distances between elements of MLAA. SpPSO is employed to determine the optimum distance location of the MLAA elements; which performs the best within the objective scopes. Some improvements have been adopted in original PSO in order to overcome the weaknesses and to adopt the algorithm in MLAA. The new SpPSO is proposed by adopting two novel mechanisms, i.e. global limit variables restriction and location and velocity reinitialization. The modifications and improvements that have been done in SpPSO are discussed as follows:

3.1.1 Global Limit Variables Restriction

Two sets of global limit variables for lower boundary, *L* and upper boundary, *U* for different position particles, d_{s1} and d_{sn} (n=2,3,…N) is adopted and represented as:

$$L_1 \le d_{s1} < U_1 \quad (7)$$
$$L_N \le d_{sn} < U_N \quad (8)$$

These two limits are applied to restrict d_{s1} and d_{sn} to stay inside the solution space. Additionally, maximum upper limit and minimum lower limit are also assimilated inside this proposed SpPSO, i.e. U_{max} and L_{min}, respectively. These two limits are determined before the computation of the objective function, *of* in order to enhance the diversity of the particle's searching abilities to be more global and freedom. Thus, it is expressed as:

$$d_{s1} = \begin{cases} d_{s1} = L_1 \xrightarrow{yields} of(L_1), & if\ d_{s1} > U_{max} \\ d_{s1} = d_{s1} \xrightarrow{yields} of(d_{s1}), & if\ L_{min} \le d_{s1} < U_{max} \\ d_{s1} = L_1 \xrightarrow{yields} of(L_1), & if\ d_{s1} \le L_{min} \end{cases} \quad (9)$$

and

$$d_{sn} = \begin{cases} d_{sn} = L_N \xrightarrow{yields} of(L_N), & if\ d_{sn} > U_{max} \\ d_{sn} = d_{sn} \xrightarrow{yields} of(d_{sn}), & if\ L_{min} \le d_{sn} < U_{max} \\ d_{sn} = L_N \xrightarrow{yields} of(L_N), & if\ d_{sn} \le L_{min} \end{cases} \quad (10)$$

3.1.2 Location and Velocity Reinitialization

The random numbers of particle position, d_{sn} can be a factor of the particle's tendency to leave the initially defined search space. Therefore, a modification based on the absorbing wall conditions by [13] is implemented in this algorithm. In order to control the movement of particle from flying outside the border of the search space, the velocity, v_{sn} is zeroed whenever the particle, d_{sn} goes over the boundary U_N and L_N. However, the particle, d_{sn} are then pulled back inside the search space by reinitializing it as random numbers, *r* generated from the values of [L_{min},U_{max}]. The objective of this reinitialization of d_{sn} is to prevent the particle from being stucked in local optima scenario where the particle is trapped and inhibited to search for a better solution. By introducing the reinitilization, a more flexible and comprehensive searching can be done by the particle with noted limitations, as expressed by equations below:

$$v_{sn} = \begin{cases} v_{sn} = 0 \rightarrow d_{sn} = r[L_{min}, U_{max}], & if\ d_{sn} > U_N \\ v_{sn} = v_{sn}, & if\ L_N \le d_{sn} < U_N \\ v_{sn} = 0 \rightarrow d_{sn} = r[L_{min}, U_{max}], & if\ d_{sn} \le L_N \end{cases} \quad (11)$$

By using equation (11), the particle movement maybe triggered again so that it has the higher probability to search for the optimum global best. In addition, the particle position is also forced to stay inside the upper boundary, *U* and lower boundary, *L* as denoted by following equations:

$$d_{s1} = \begin{cases} d_{s1} = U_1, & if\ d_{sn} > U_1 \\ d_{s1} = d_{s1}, & if\ L_1 \le d_{sn} < U_1 \\ d_{sn} = L_1, & if\ d_{sn} \le L_1 \end{cases} \quad (12)$$

and

$$d_{sn} = \begin{cases} d_{sn} = U_N, & if\ d_{sn} > U_N \\ d_{sn} = d_{sn}, & if\ L_N \le d_{sn} < U_N \\ d_{sn} = L_N, & if\ d_{sn} \le L_N \end{cases} \quad (13)$$

3.2 Simulation and Optimization Setup of SpPSO

The proposed SpPSO is developed by using Matlab software. The convergence speedness and effectiveness of novel SpPSO algorithm are verified by implementing MLAA with various objectives as follows:

i) Sidelobe level (SLL) suppression
ii) Adaptive first null beamwidth (FNBW)
iii) Adaptive main beam angle
iv) Multi-objectives (i.e. two or more above objectives simultaneously)

SpPSO explores for the optimum particle positions, d_{sn} by aiming at the target objectives where d_{sn} is the optimum inter element position of MLAA, i.e. x_n. These x_n (n=1,2,…N) are optimized and re-located whilst maintaining uniform excitation, i.e. $I_n = 1$ over the array aperture. For the design specifications, the parameters for SpPSO as in Table 1 have been selected.

The optimization task inside SpPSO algorithm is to determine the optimum value of objective function, of_{SLL} as described in Figure 2. Thus, the optimization task is to suppress the SLL, of_{SLL}. These problems can be defined by considering the following equations:

$$of_{SLL}(\theta_{SLL}) = \sum_{SLL_1=1}^{MaxSL} |AF(\theta_{SLL_1})|_{dB} + \sum_{MinSL}^{SLL_2=181} |AF(\theta_{SLL_2})|_{dB} \quad (14)$$

where θ_{SLL1} and θ_{SLL2} are the angles where the SLL is suppressed in the lower band (from $\theta_{SLL1=1}$ to $\theta_{SLL1=MaxSL}$) and in the upper band (from $\theta_{SLL2=MinSL}$ to $\theta_{SLL2=181}$), respectively.

Step 1: Define objective function, *of* and SpPSO parameters
Step 2: Initiate random particles
Step 3: Start iteration
Step 4: Start for each particle
Step 5: Evaluate *of* of each *d* *of*(*d*) (**Restriction**)
Step 6: Set *of*(*pbest*)=*of*(*d*) and *gbest*=*optimum*(*pbest*)
Step 7: Is *of(d)* better than *of*(*pbest*)?. If no, store *pbest* and *d*.If yes, update *pbest* and store *d(pbest)*
Step 8: Is *of(pbest)* better than *of*(*gbest*)? If yes, update *gbest* and store *d(gbest)*. If no, store *gbest* and *d*
Step 9: Update and limit *V* using Eqns (5) and (11) (**Reinitialization**)
Step 10: Update and limit *D* using Eqns (6), (9) and (10) (**Reinitialization**)
Step 11: Repeat for each particle S
Step 12: Repeat for each iteration

Figure 2 Proposed SpPSO

Table 1 List of Parameters and Values used in SpPSO

Number of particles	***S***	**30**
Dimension of particles	*N*	8 and12
Iterations	*It*	500
Range of particles	*D*	0 to 2λo
Upper boundary for d_n	U_N	1.5λo
Lower boundary for d_n	L_N	0.8λo
Upper boundary for d_1	U_1	1.0λo
Lower boundary for d_1	L_1	0.3λo
Maximum upper limit	U_{max}	0.1λo
Minimum lower limit	L_{min}	2.5λo
Velocity	*V*	0 to 0.2
Learning factors	c_1=c_2	2.0

4.0 OPTIMIZATION RESULTS AND ANALYSIS

The capabilities of the formulation method in the previous section are assessed by presenting the computed results of the 8- and 12-element MLAAs. The investigations are performed for an adaptive capability with multiple objectives of suppressing SLL, steering capability and controlled FNBW. The problem described herein is as follows: design 8- and 12-element MLAAs such that the same amplitude excitation generates a radiation beampattern with prescribed objectives, the difference being dependent only upon the element distance of the array. In order to demonstrate the superiority of SpPSO, the performance of SpPSO is evaluated and compared with other synthesis obtained from conventional [1]. The design parameters used in this comparison is similar, which ensures a fair comparison in performance quality. Two cases with different objectives are simulated and validated to show the capabilities of SpPSO in MLAAs.

Case 1: Adaptive main beam angle with SLL suppression

This case addresses the problem of designing MLAA for suppressing SLL during scanning. The array geometry may cause the outer SLL to increase especially when the main beam direction is steered to maximum desired scan angle from the broadside (i.e. 90°). This phenomenon comprises unneeded large side lobes in the visible region with levels, which can be higher and outperformed the first SLL. Table 2 illustrates three different maximum SLL results at three different iterations. It is noted that objective function values have been reduced until 3.482, -82.34 and -321.9 at 50th, 150th and 277th iteration as shown in Figures 3, 5 and 7, respectively. The best performance of SLL is at 277th iteration. It is proven that the proposed SpPSO converges extremely early at 277th iteration with very excellent results as shown in Figure 8.

Figures 4, 6, and 8 show the comparison performances between conventional ULA and SpPSO-based LAA. The figures illustrate that high back lobe exists in ULA at -90° when the antenna is steered to maximum angle, i.e. 90°. At the angle of -90°, this particular back lobe has been minimized approximately to -17 dB at 277th iteration. It is also observed that the maximum normalized SLL of -12.27 dB has been achieved by using SpPSO. SpPSO has efficiently computed the distance between elements, d_n (n = 1, 2,…, N) of MLAA. The optimized element distance, d_n for 8-element SpPSO-based LAA are 0.3, 1.5, 0.78, 0.78, 0.82, 0.78, 0.78 and 0.78. From Table 3 it is noted that the amount of aperture reduction by using SpPSO is 6.53 as compared to conventional ULA which is 8.

Table 2 Iteration values with maximum SLL of 8-element SpPSO-based LAA

Iterations	50	150	277
Objective/Fitness function value	3.482	-82.34	-321.9
Max SLL(dB)	-6.407	-6.304	-12.27

Table 3 Element position of the 8-element SpPSO-based LAA

LAA	**Max SLL (dB)**	**FNBW (°)**	**[d_1,d_2,d_3,….d_8] in λ_o's**	**Aperture ($\sum x_n$) in λ_o's**
ULA	0	80	[1,1,1,1,1,1,1,1]	$\sum$=8.00
SpPSO	-12.27	80	[0.30,1.50,0.78, 0.78,0.82,0.78,0.78,0.78]	$\sum$=6.53

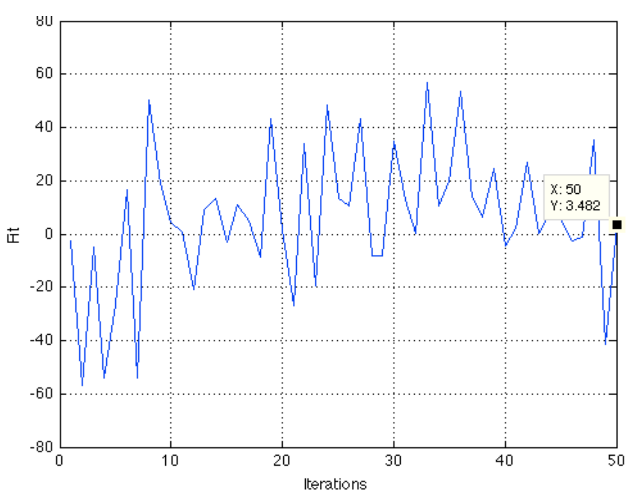


Figure 3 Objective function value at 50th iteration

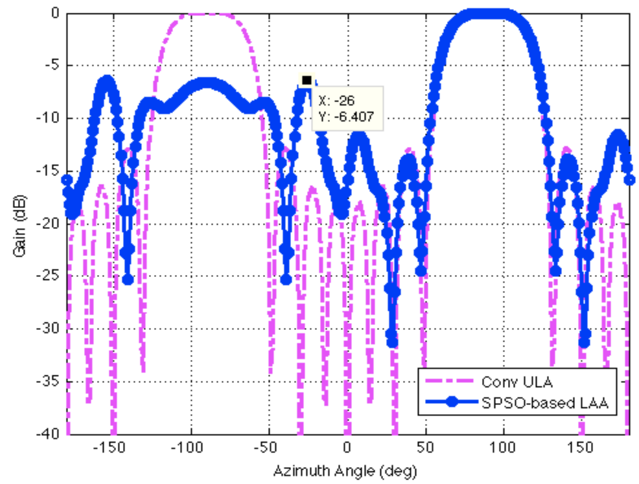


Figure 4 Radiation Beampattern of 8-element SpPSO-based LAA with Desired Multi-objectives at 50th Iteration

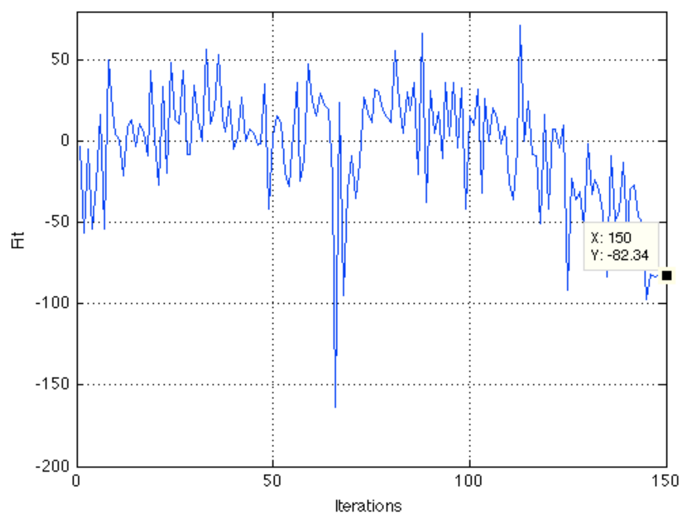


Figure 5 Objective Function value at 150th Iteration

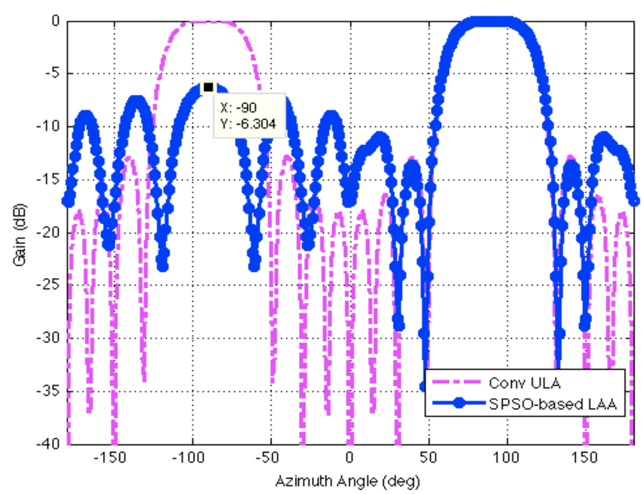


Figure 6 Radiation beampattern of 8-element SpPSO-based LAA with desired multi-objectives at 150th iteration

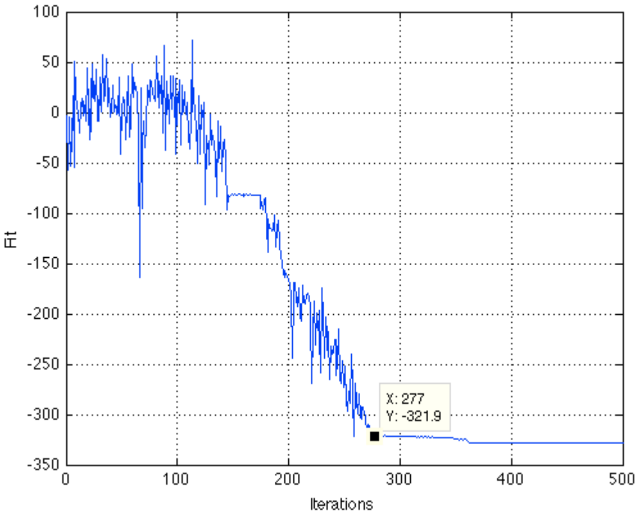


Figure 7 Objective function value at 500th iteration. convergence time at 277th iteration.

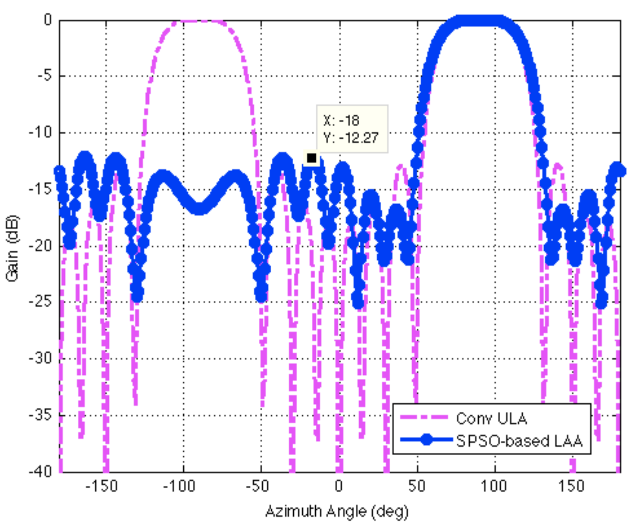


Figure 8 Radiation beampattern of 8-element SpPSO-based LAA with desired multi-objectives. Convergence time at 277th iteration.

Case 2: SLL suppression, adaptive main beam angle with wider FNBW

Next, the main beam of 12-element MLAA is then steered to 20° with a requirement for wider FNBW. Table 4 illustrates the particular objective function values and maximum SLL achieved by SpPSO-based MLAA at iteration of 150, 200, 250 and 400. Both the objective function and maximum SLL values show a decrement from 14.56 to -108.6 and -11.69 dB to -16.46 dB, respectively. Figure 9 illustrates the performance of the radiation beampattern at each iteration which expresses that the particle of the proposed algorithm is searching for the optimum result. The searching evaluation terminates at 350th iteration where the algorithm converges at the optimum minimum result as shown in Figure 10. Table 5 illustrates the element position of 12-element SpPSO-based MLAA as compared to 12-element ULA.

It can be concluded from Figure 11 that the SpPSO-based LAA is able to achieve a beampattern with sufficiently low sidelobes having maximum of -16.46 dB, a desired wider FNBW of 50° and main beam that is pointing to 20°, as compared to the corresponding conventional ULA. It is obviously noted that this newly-proposed SpPSO can satisfies these three conflicts by achieving the optimum radiation beampattern. The SpPSO also proves that it can converge fast as it only consumes 148.26s to converge to the desired multi-objectives result. Table 4 demonstrates the time consuming period for every iteration. Table 5 shows the the optimized element distance, d_n for 12-element SpPSO-based LAA are 0.5, 0.5, 0.5, 0.35, 0.3992, 0.3558, 0.35, 0.35, 0.5, 0.4652, 0.5 and 0.5. It is also noted that the amount of aperture reduction by using SpPSO is 5.27 as compared to conventional ULA which is 12.

Table 4 Iteration values with maximum SLL Of 12-element SpPSO-based LAA

Iterations	150	200	250	400
Objective/Fitness function value	14.56	-10.49	-48,72	-108.6
Max SLL(dB)	-11.69	-11.79	-14.39	-16.46
Time consuming (s)	55.57	74.64	93.66	148.26

Table 5 Element position of the 12-element SpPSO-based LAA

LAA	**Max SLL**	**FNBW (°)**	**[$d_1,d_2,d_3,\ldots,d_8$] in λ_o's**	**Aperture ($\sum x_n$) in λ_o's**
ULA	-13.13	20	[1,1,1,1,1,1,1,1,1,1,1,1]	12.00
SpPSO	-16.46	50	[0.5000,0.5000,0.5000,0.3500,0.3992,0.3558,0.3500,0.3500,0.5000,0.4652,0.5000,0.5000]	5.27

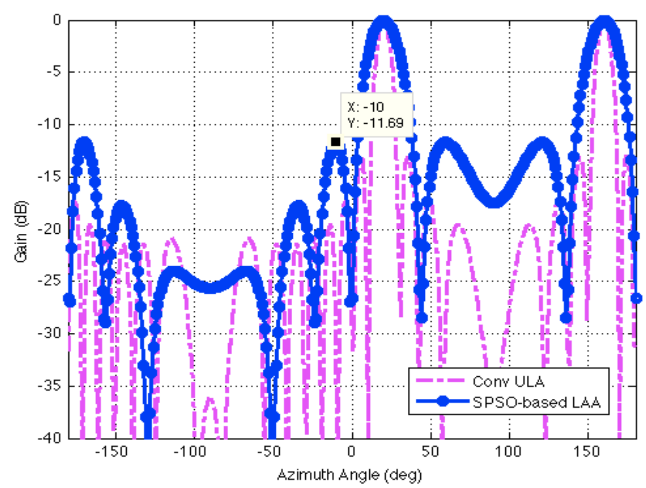


Figure 9 Radiation beampattern of 12-Element SpPSO-based MLAA with desired multi-objectives at 150th iteration.

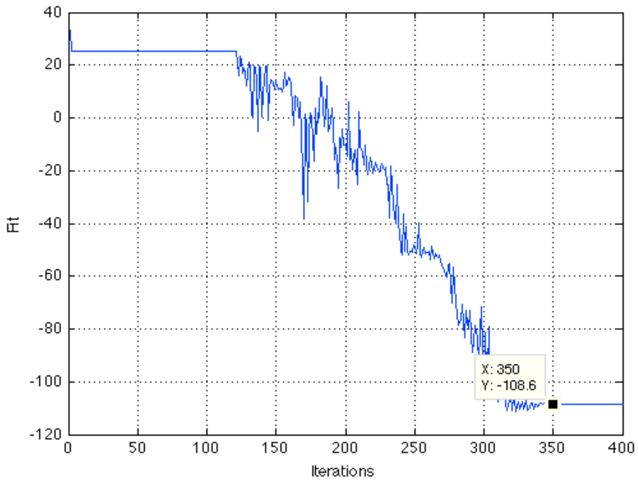


Figure 10 Objective function value at 400th iteration. Convergence time at 350th iteration.

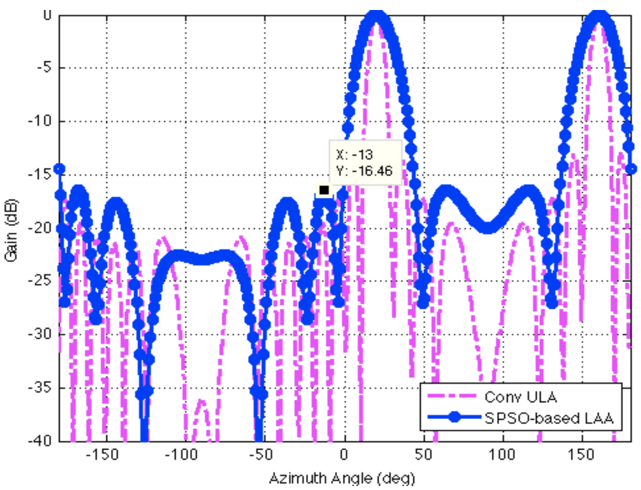


Figure 11 Radiation beampattern of 12-element SpPSO-based MLAA with desired multi-objectives at 350th iteration.

From the simulation results, the efficiency of proposed SpPSO algorithms in order to optimize the design of MLAA with adaptive capability, controllable FNBW and minimum SLL has been shown. As a comparison between the SPSO and the conventional [1], the SpPSO is shown to generate better outcomes with multi-objectives constraints.

4.0 CONCLUSION

A significant feature of the particle swarm optimizer is that the algorithm itself is highly robust yet extremely simple to implement, and it appears to possess good possibilities for many potential applications. This paper illustrates how to model the design of a non-uniform MLAA for multi-objective optimization by implementing newly discovered SpPSO algorithm. The SpPSO is proposed as the solution to optimize the distance spacing between neighbour elements of 8- and 12-element MLAA with adaptive capability, controlled beamwidth and minimum SLL. This method efficiently computes the design of requirements of these antennas to generate radiation pattern with desired properties. The numerical results show that the developed SpPSO algorithm has successfully optimized the distance position of the array elements and demonstrate better performance than those presented in [1].

Acknowledgement

We are grateful for the UTM financial support for Fundamental Research Grant Scheme vote FRGS/2/2013/ICT03/UTM/03/2.

References

[1] Constantine A. Balanis, Antenna Theory: Analysis and Design, 2nd Edition, John Wiley & Sons.
[2] M. Khodier, M. Al-Aqeel. 2009. Linear and Circular Array Optimization: a Study Using Particle Swarm Intelligence. *Progress in Electromagnetics Research B*. 15 : 347-373.
[3] Marco A. Pandro, Carlos A. Brizuela, David H. Covarrubias, 2008. Design Of Electronically Steerable Linear Arrays With Evolutionary Algorithms. Applied Soft Computing 8 (AEU).8 (1).ISSN:1568-4946. *Elsevier Science Publishers B. V*.
[4] Marco A. Pandro, David H. Covarrubias, Carlos A. Brizuela, Francisco R. Marante. 2005. A Multi-Objective Approach In The Linear Antenna Array Design. *Int. J. Electron. Commun*. 59 (4): 205-212.
[5] Boeringer, D. W. and D. H.Werner. 2004. Particle Swarm Optimization Versus Genetic Algorithms For Phased Array Synthesis. *IEEE Trans. Antennas Propagat*. 52: 771-779.
[6] Wei Cui , Yilong Lu. 2015. Adaptive Beamforming For Arbitrary Array By Particle Swarm Optimization. *Computational Emelctromagnetics (ICCEM), 2015 IEEE International Conference*.
[7] Mandal, D. , Kar, R. , Ghoshal, S. 2011.Improved Particle Swarm Optimization based synthesis of Concentric Circular Antenna Array with Non-Isotropic Elements". *Recent Trends in Information Systems (ReTIS), 2011 International Conference*.
[8] W.T.Li, X.W.Shi. 2008. An Improved Particle Swarm Optimization Algorithm for Pattern Synthesis of Phased Arrays. *Progress in Electromagnetic Research*, *PIER*. 82: 319-332.
[9] M. Rattan, M. S. Patterh, and B. S. Sohi. 2008. Design of a Linear Array of Half Wave Parallel Dipoles Using Particle Swarm Optimization. *Progress In Electromagnetics Research M*. 2: 131-139.
[10] Nik Noordini Nik Abd Malik, Mazlina Esa, Sharifah Kamilah Syed Yusof, Jayaseelan Marimuthu. 2009. Suppression of Antenna Sidelobes Using Particle Swarm Optimization.*PIERS Proceedings* : 683-686. August 18-21, Moscow RUSSIA.
[11] Nik Noordini Nik Abd Malik, Mazlina Esa, Sharifah Kamilah Syed Yusof. 2009. Multi-objective Design of Linear Antenna Arrays with Particle Swarm Optimization, *Proceedings of The 2009 International Symposium on Antennas and Propagation (ISAP 2009)*, Oct 20-23 2009, Bangkok Thailand.
[12] Kennedy, J., Eberhart, R. 1995. Particle Swarm Optimization, Neural Networks Proceedings. *IEEE International Conference*. 4: 1942 – 1948.
[13] Zaharis, Z., D. K., Papastergiou, A., Hatzigaidas, A., Lazaridis, P. Spasos, M. 2006. Optimal Design Of A Linear Antenna Array Using Particle Swarm Optimization, *Proc. of the 5th WSEAS Int. Conf. on Data Networks, Communications and Computers*. City: Bucharest (Romania). 69-74.