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Design of Linear Antenna Arrays with Low Side Lobes Level Using Symbiotic Organisms Search

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Abstract—In this paper, low sidelobe radiation pattern (i.e., pencil-beam pattern) synthesis problem is formulated for symmetric linear antenna arrays. Different array parameters (feed current amplitudes, feed current phase, and array elements positions) are considered as the optimizing variables. The newly proposed evolutionary algorithm, Symbiotic Organisms Search (SOS), is employed to solve such a pattern optimization problem. The design objective is to obtain radiation patterns with very low interference in the entire sidelobes region. In this context, SOS is used to minimize the maximum sidelobe level (SLL) and impose nulls at specific angles for isotropic linear antenna arrays by optimizing different array parameters (position, amplitude, and phase). The obtained results show the effectiveness of SOS algorithm compared to other well-known optimization methods, like Particle Swarm Optimization (PSO), Biogeography-based optimization (BBO), Genetic Algorithm (GA), Firefly Algorithm (FA), and Taguchi method. Unlike other optimization methods, SOS is free of tuning parameters; one just has to set the value of the population size and the number of iterations. Moreover, SOS is robust and is characterized by relatively fast convergence and ease of implementation.

1. INTRODUCTION

Needless to say, antennas, in general, and antenna arrays, in specific, play important roles in modern wireless applications [1]. Designing antenna arrays with desired radiation pattern has been a subject of very much interest in the literature. Several well-known evolutionary optimization techniques; such as particle swarm optimization (PSO), Taguchi optimization, genetic algorithm (GA), central force optimization (CFO), differential evolution (DE), biogeography-based optimization (BBO), and firefly algorithm (FA); have been used in the synthesis of antenna arrays [2–13].

Symbiotic Organisms Search (SOS) is a newly proposed evolutionary global optimization method which was recently proposed in [14] to solve optimization problems. SOS is inspired by the symbiotic interaction strategies between different organisms in an ecosystem. Symbiosis describes the interaction between different species living together. The three main types of symbiotic relationships are: mutualism, commensalism, and parasitism. The first relationship, mutualism, happens when both organisms benefit from interacting with each other. An example of this relationship is the interaction between bees and flowers. The second type, commensalism, occurs when one species benefits from the interaction, while the other does not gain or lose anything. An example of this type is the relationship between remora fish and sharks. The third type, parasitism, occurs when the relationship benefits one species while the other species is harmed. An example of parasitism is the interaction between the plasmodium parasites and humans. SOS algorithm simulates such interactions through simple mathematical models which can be used in optimization problems [14]. Unlike other optimization techniques, for its implementation, SOS is free from any tuning parameters; it requires only common controlling parameters like population size (number of organisms) and maximum number of iterations.

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In [14], SOS has been successfully applied on the minimization of several complex mathematical benchmark functions and structural engineering design problems. The obtained results proved the SOS validity as a valuable optimization technique compared to other already developed optimization techniques. Here, SOS is applied to the design of linear antenna arrays with the goals of having low sidelobes, in addition to imposing nulls in certain directions. The optimized parameters will be the elements positions, the excitation amplitudes, and the excitation phases.

The rest of this paper is organized as follows: In Section 2, SOS is briefly described. In Section 3, the geometry and array factor for the linear antenna array are presented. Then, in Section 4, the fitness function and numerical results are presented. Finally, the paper is concluded in Section 5.

2. SOS ALGORITHM

SOS algorithm starts with a randomly generated initial population of organisms which is called the ecosystem. The number of generated organisms N will be called as the population size. Thus, the ecosystem is a matrix of N rows and D columns, where D is the dimension of the problem (i.e., the number of design variables). An individual (organism) $X_i\,(i = 1, \ldots, N)$ within the population (ecosystem) is a real-valued vector with D elements which represents a single possible solution to a particular optimization problem. Each organism X_i of the ecosystem (i.e., each row in the ecosystem matrix) is associated with a certain fitness function value which imitates the degree of adaptation to the desired objective. The new solutions are generated by simulating the three symbiotic interactions, mentioned above, between two organisms in the ecosystem. Each organism in the ecosystem randomly interacts with another organism through all these three phases and this process of interaction is repeated until a specific termination criterion is fulfilled. The details of operation of these three phases of symbiotic interaction are described below.

In each iteration (till the maximum number of iterations is reached), every organism $X_i\,(i = 1, \ldots, N)$ goes through the following three phases.

2.1. Mutualism Phase

In this phase, another organism X_j is randomly selected to "mutually" interact with X_i. Then, X_i and X_j are updated according to the following expressions [14]:

$$X_{i(new)} = X_{i(old)} + rand(0,1) * [X_{best} - (Mutual\_Vector) * (BF_1)] \quad (1)$$

$$X_{j(new)} = X_{j(old)} + rand(0,1) * [X_{best} - (Mutual\_Vector) * (BF_2)] \quad (2)$$

where the *Mutual_Vector* is computed as follows: $Mutual\_Vector = (X_i + X_j)/2$.

In the above equations, X_{best} is the best organism (that is the one that resulted in the minimum value of the fitness function), and $rand(0,1)$ is a random number in the range $[0,1]$. BF_1 and BF_2 are called benefit factors which are randomly determined as either 1 or 2. They represent the level of benefit between the organisms as the organisms may partially or fully benefit from such an interaction. At the end of this phase, the new organisms are accepted if they give better (that is less) fitness function values than their pre-interaction fitness values. All the accepted ones are kept and become the input to the next phase; the commensalism phase.

2.2. Commensalism Phase

Similar to the mutualism phase, an organism X_j is randomly selected to interact with X_i. However, in this phase, X_i tries to benefit from the interaction, while X_j itself is not affected, whether positively or negatively. The new X_i is calculated using the following formula [14]:

$$X_{i(new)} = X_{i(old)} + rand(-1,1) * (X_{best} - X_j) \quad (3)$$

The term $(X_{best} - X_j)$ reflects the benefit provided by X_j to X_i to increase its degree of adaptation (to the highest degree represented by X_{best}) such that it can better survive in the ecosystem. As in the first phase, the new organism $X_{i(new)}$ is accepted if it results in a better fitness function value. If not, then X_i stays the same, which means that it didn't benefit from such an interaction with X_j.

2.3. Parasitism Phase

In this last phase, a new vector called "*Parasite_Vector*" is created by mutating X_i in a random dimension using a random number. Then, an organism X_j is randomly selected to serve as a host to the parasite vector. The fitness function for both vectors is evaluated. If the parasite vector has a better fitness, then X_j is killed and its position will be taken over by the parasite vector. On the other hand, if X_j has a better fitness value, then it will be immune from the parasite vector, and will not be affected by its existence. In this case, the parasite vector disappears from the ecosystem.

The Pseudo-code of the SOS algorithm can be summarized as follows [15]:

Define objective function $f(x), x = (x_1, x_2, \ldots, x_D)$% D is dimension of the problem
An ecosystem of N organisms (solutions) is randomly created %N is the population size
While ($t <$ *Max. number of iterations*)
For $i = 1 : N$
Find the best organism X_{best} in the ecosystem
% *Mutualism Phase*
Randomly select one organism X_j, where $X_j \neq X_i$
Determine mutual relationship vector (*Mutual_Vector*) and benefit factors (BF_1 and BF_2)
Modify X_i and X_j according to (1) and (2)
If new organisms give better fitness value, then update them in the ecosystem
% *Commensalism Phase*
Randomly select one organism X_j, where $X_j \neq X_i$
Modify organism X_i according to (3)
If the modified organism gives better fitness value, then update it in the ecosystem
% *Parasitism Phase*
Generate *Parasite_Vector* from organism X_i
Randomly select one organism X_j, where $X_j \neq X_i$
If *Parasite_Vector* gives better fitness value than X_j, then replace it with *Parasite_Vector*
end for
end while
The global best solution is saved as the optimal solution

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3. LAA GEOMETRY AND ARRAY FACTOR

Figure 1 shows the geometry of a symmetric linear antenna array (LAA) which consists of isotropic antenna elements distributed along the x-axis. If the number of elements is odd $(2N + 1)$, as shown in Figure 1(a), there will be an element at the origin, while in the case of an even number of elements, Figure 1(b), there is no element at the origin. Thus, the array factor (in the xy-plane) of such a LAA can be written as follows [1]:

$$AF(\emptyset) = I_o \exp(j\varphi_o) + \sum_{\substack{n=-N \\ n\neq 0}}^{N} I_n \exp\left(j\left[kx_n \cos(\emptyset) + \varphi_n\right]\right) \quad \textit{for } (2N+1) \textit{ elements} \tag{4}$$

$$AF(\emptyset) = \sum_{\substack{n=-N \\ n\neq 0}}^{N} I_n \exp\left(j\left[kx_n \cos(\emptyset) + \varphi_n\right]\right) \quad \textit{for } (2N) \textit{ elements} \tag{5}$$

where k is the wave number ($k = 2\pi/\lambda$), and I_n, φ_n, and x_n are, respectively, the excitation amplitude, phase, and location of the nth element. Furthermore, $x_n = \sum_{i=1}^{n} d_i$, where d_i denotes the ith inter-element spacing. In this paper, LAA's with $x_{-n} = -x_n$, $I_{-n} = I_n$ and $\varphi_{-n} = -\varphi_n$ are considered, and thus, the array factor can be written as follows:

$$AF(\emptyset) = I_o \exp(j\varphi_o) + 2\sum_{n=1}^{N} I_n \cos\left[kx_n \cos(\emptyset) + \varphi_n\right] \quad \textit{for } (2N+1) \textit{ elements} \tag{6}$$

$$AF(\emptyset) = 2\sum_{n=1}^{N} I_n \cos\left[kx_n \cos(\emptyset) + \varphi_n\right] \quad \textit{for } (2N) \textit{ elements} \tag{7}$$

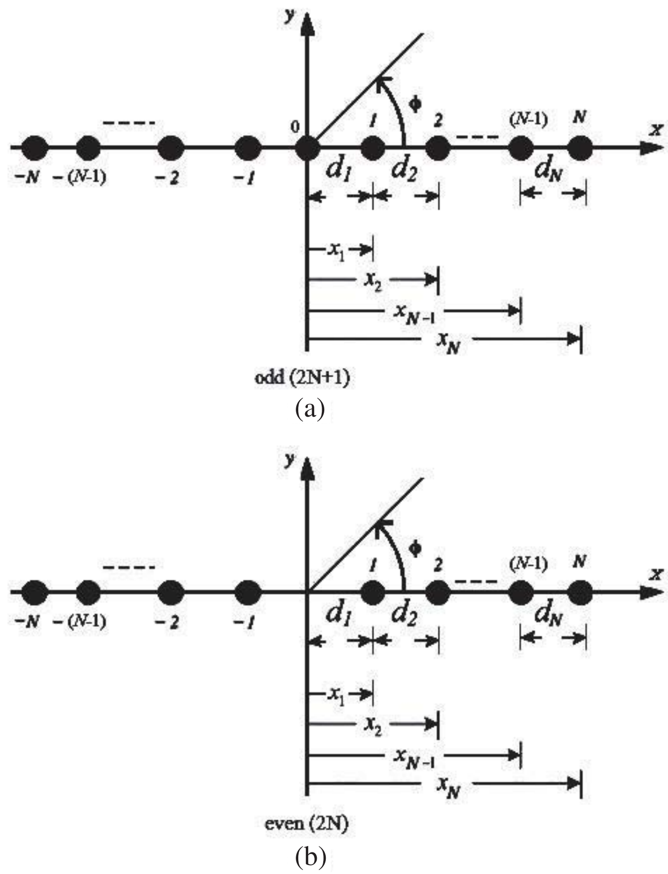

Figure 1. (a) Geometry of the $2N+1$ elements symmetric LAA. (b) Geometry of the $2N$ elements symmetric LAA.

It can be concluded that the array factor is a function of I_n, φ_n, and x_n. In the following sections, the SOS technique will be used to optimize these parameters to minimize the side lobes level which in effect reduces the interference in the side lobes region.

4. FITNESS FUNCTION AND NUMERICAL RESULTS

In order to minimize the maximum side lobe level (SLL), the following fitness function is used:

$$\text{Minimize} \quad fitness = \max\left\{20\log_{10}\left|\frac{AF(\varnothing)}{AF(\varnothing_d)}\right|\right\} \qquad (8)$$
$$\text{subject to} \quad \varnothing \in [0, \varnothing_S]$$

where $[0, \varnothing_S]$ is the side lobes region which depends on the number of elements. Here, it is chosen as [0, 76°], [0, 80°], [0, 84.25°], [0, 83°], [0, 86.8°] and [0, 87°] for 10, 16, 20, 24, 37 and 40 elements LAA, respectively. $\varnothing_d$ is the angle in the direction of the major beam, which is chosen to be 90° (i.e., broadside LAA), except in Section 4.3 where a scanned LAA is considered.

4.1. Optimizing the Element Excitation Amplitudes (I_n)

To optimize the amplitudes, φ_n and x_n are fixed to be those corresponding to the uniform array, i.e., $\varphi_n = 0$ and the spacing between adjacent elements equal to $\lambda/2$. Thus the array factor becomes:

$$AF(\varnothing) = I_o + 2\sum_{n=1}^{N} I_n \cos\left[n\pi\cos(\varnothing)\right] \quad for\ (2N+1)\ elements \qquad (9)$$

$$AF\left(\varnothing\right) = 2\sum_{n=1}^{N} I_n \cos\left[\left(n-0.5\right)\pi\cos\left(\varnothing\right)\right] \quad for\ \left(2N\right)\ elements \tag{10}$$

The excitation currents amplitudes are assumed to be within the range [0, 1]. Different cases of linear arrays have been optimized using the SOS technique. Here, 3 examples are presented only. In addition, the solutions obtained using other techniques will be included for comparison purposes.

4.1.1. Example 1: 10 Elements LAA

Using the equation of the fitness function associated with the array factor for 10 elements LAA, the SOS code is run for 20 independent times. Table 1 shows the best optimum amplitudes obtained using the SOS as compared to those obtained using other optimization techniques, namely, Biogeography-based optimization (BBO) [3], particle swarm optimization (PSO) [16] and Taguchi method [11]. Figure 2 shows the radiation pattern obtained by the SOS results along with the patterns obtained using the other optimization methods results. The results of SOS are very much similar to those obtained using BBO. However, as indicated before, SOS has the advantage of being free of tuning parameters, while one has to choose appropriate values for several tuning parameters in PSO and BBO.

Table 1. Optimum amplitude values found by SOS for the 10 elements LAA in comparison with other optimization techniques.

	I_1	I_2	I_3	I_4	I_5	**Max SLL (dB)**
SOS	1.0000	0.8985	0.7189	0.5017	0.3856	−25.28
BBO [3]	1.0000	0.8988	0.7189	0.5025	0.3862	−25.21
PSO [16]	1.0000	0.9010	0.7255	0.5120	0.4088	−24.62
Taguchi [11]	1.0000	0.8999	0.7228	0.5077	0.3994	−24.87
Uniform	1.0000	1.0000	1.0000	1.0000	1.0000	−12.97

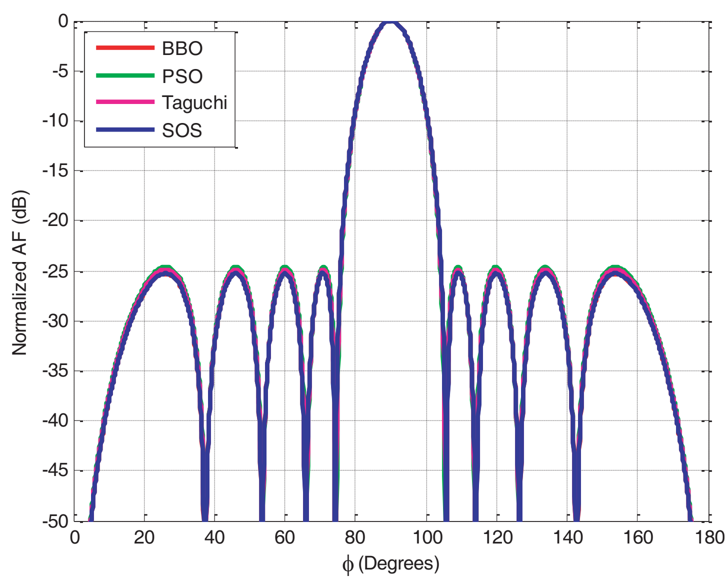

Figure 2. Radiation pattern of SOS-optimized 10 elements LAA compared to other optimization methods.

Table 2 shows some statistics of the SOS results obtained in the 20 independent runs. It can be noticed that SOS is more robust than BBO since it has a much lower standard deviation (SD). The optimal maximum SLLs for the 20 trials are shown in Figure 3. A Laptop with "Intel Core i7 CPU M 620 @ 2.67 GHz" and "4 GB RAM" was used for simulating the SOS code, and the simulation time

Table 2. Performance of SOS algorithm for 10 elements LAA in 20 runs.

	BBO [3]	SOS
Best SLL (dB)	−25.2100	−25.2791
Worst SLL (dB)	−24.0763	−25.1842
Mean (dB)	−24.9704	−25.2645
Standard deviation (SD) (dB)	0.2596	0.0216

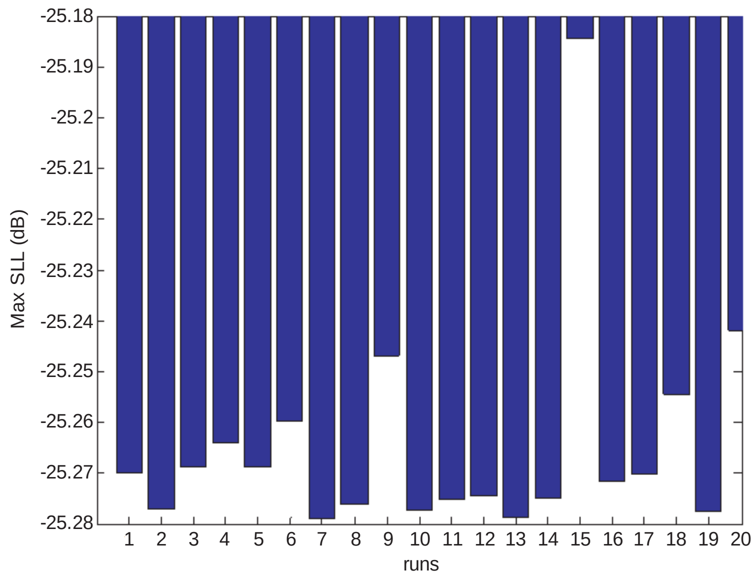

Figure 3. The maximum SLL obtained by SOS in 20 independent trials.

was only 6 seconds for each run with a population size of 50 and number of iterations of 150. Figure 4 shows the convergence plot for this example where it can be noticed that good convergence is fulfilled within only 50 iterations.

4.1.2. Example 2: 16 Elements LAA

In this example, a 16-element LAA is optimized using SOS method (population size = 50, number of iterations = 150). The best results are listed in Table 3. Figure 5 shows the radiation pattern obtained by SOS compared to other methods. The maximum SLL obtained using SOS is −33.39 dB, which is very close to the value obtained by BBO and somewhat better than that obtained using the PSO and Taguchi methods. Table 4 and Figure 6 show the consistency of SOS algorithm and the optimal maximum SLLs for 20 trials, respectively. Again, SOS has a smaller standard deviation than BBO. Figure 7 shows the convergence plot for this example, where it can be seen that 50 iterations are enough to get an acceptable solution.

4.1.3. Example 3: 24 Elements LAA

The optimized amplitudes obtained for 24 elements array are tabulated in Table 5. Figure 8 shows the radiation pattern for the optimized results. The maximum SLL obtained using SOS technique (population size = 50, number of iterations = 150) is −39.37 dB which is better than that obtained using BBO, PSO, and Taguchi methods. In this example, it is clearly seen that SOS outperforms the methods included in Table 5.

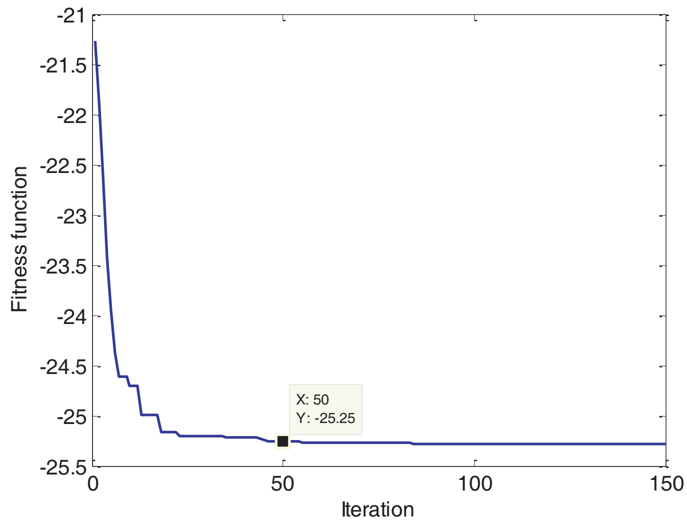

Figure 4. Convergence plot for the SOS-optimized 10 elements LAA.

Table 3. Optimum amplitude values found by SOS for the 16 elements LAA in comparison with other optimization techniques.

	I_1	I_2	I_3	I_4	I_5	I_6	I_7	I_8	**Max SLL (dB)**
SOS	1.000	0.9466	0.8475	0.7137	0.5624	0.4094	0.2697	0.2088	−33.39
BBO [3]	1.000	0.9402	0.8487	0.7104	0.5596	0.4115	0.2697	0.2035	−33.06
PSO [16]	1.000	0.9521	0.8605	0.7372	0.5940	0.4465	0.3079	0.2724	−30.63
Taguchi [11]	1.000	0.9500	0.8575	0.7317	0.5861	0.4381	0.2988	0.2552	−31.21
Uniform	1.000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	−13.15

Table 4. Performance of SOS algorithm for 16 elements LAA in 20 trials.

	BBO [16]	SOS
Best SLL (dB)	−33.0600	−33.3914
Worst SLL (dB)	−29.5565	−32.9152
Mean (dB)	−32.0106	−33.3418
SD (dB)	0.8103	0.1055

4.2. Scanned LAA

Here, a scanned LAA is considered, as opposed to broadside arrays considered in the previous examples. Scanned arrays have the advantage that the major beam can be directed at an arbitrary direction which is useful in mobile and cellular communications. Scanning the major beam can be easily accomplished by adding a progressive phase shift in the current feeding the antennas. Thus, for an N-element array (with an inter-element distance of $\lambda/2$) lying along the x-axis, the array factor can be written as follows [1]:

$$AF(\varnothing) = \sum_{n=1}^{N} I_n \exp\left(j\pi(n-1)\left[\cos(\varnothing) - \cos(\varnothing_d)\right]\right) \tag{11}$$

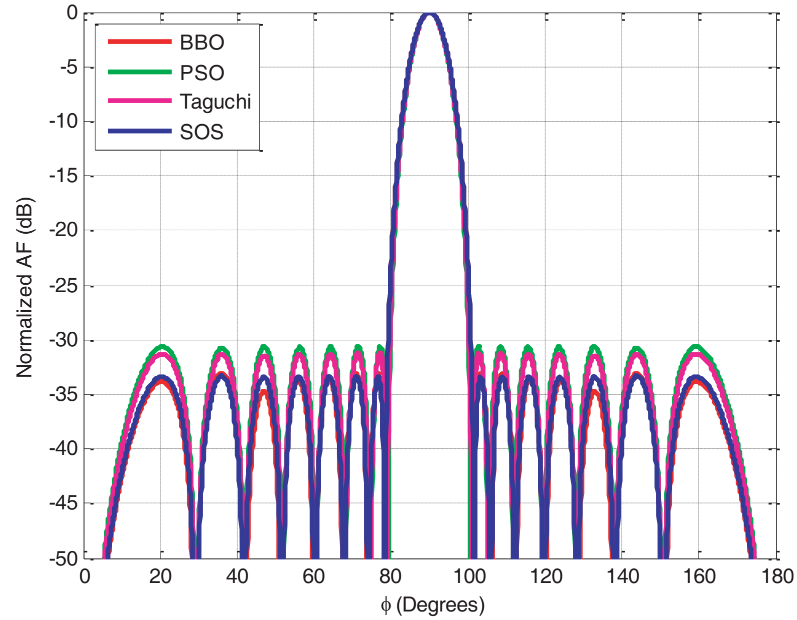

Figure 5. Radiation patterns for the results in Table 3.

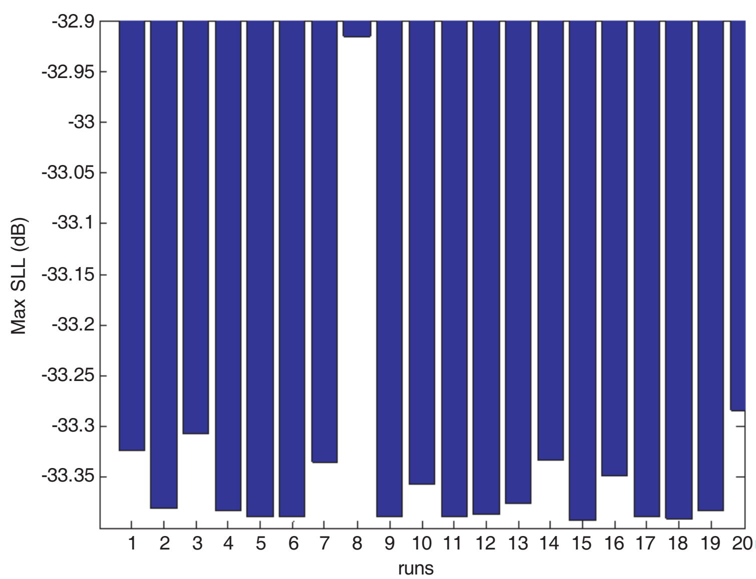

Figure 6. The maximum SLL obtained by SOS in 20 independent trials.

where $\O_d$ is the angle at which the major lobe is oriented.

Three different scanned arrays are considered: ($N = 20$, $\O_d = 30°$), ($N = 26$, $\O_d = 45°$), and ($N = 30$, $\O_d = 60°$). For each scanned array, the SOS code is run 10 independent times with population size = 20, and number of iterations = 250. Table 6 shows the best obtained SOS results out of these 10 independent runs. Table 7 shows a comparison between SOS results and those obtained using Firefly Algorithm (FA) [9]. Statistically speaking, SOS results are slightly better than FA ones. Figures 9–11 show the array factor obtained from the SOS results as compared to the array factor obtained using FA. Both SOS and FA give almost the same array factor. However, SOS has the advantage of being free of tuning parameters, as opposed to FA which requires the tuning of 4 parameters [9].

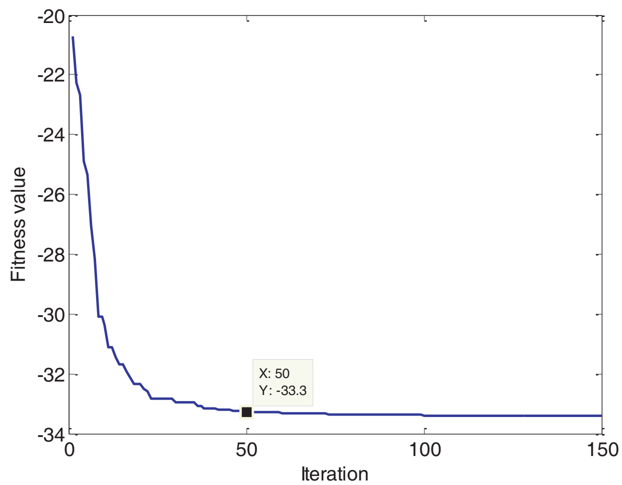

Figure 7. Convergence plot for the 16 elements LAA Example.

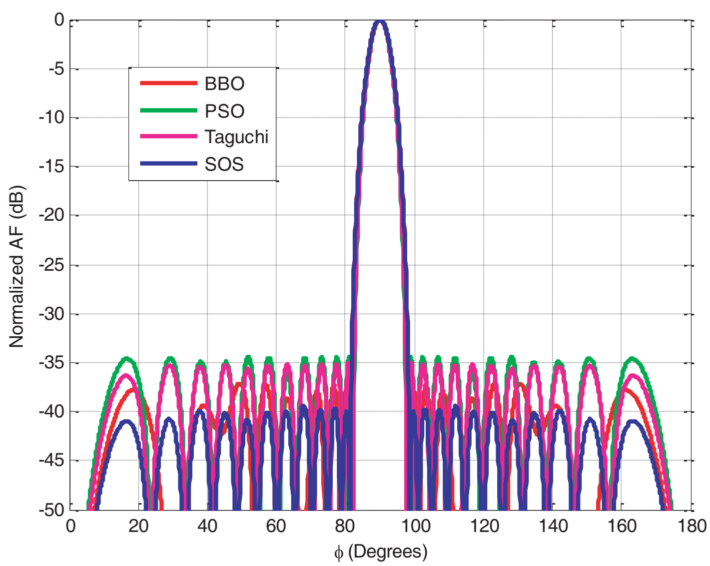

Figure 8. Radiation pattern of the 24 elements LAA results in Table 5.

4.3. Optimizing the Elements Positions (x_n)

In order to optimize the elements positions in the LAA by the SOS, the elements amplitudes and elements phases are fixed as $I_n = 1$ and $\varphi_n = 0$. In this case, the array factor becomes:

$$AF(\emptyset) = 1 + 2\sum_{n=1}^{N} \cos\left[kx_n \cos(\emptyset)\right] \quad for\ (2N+1)\ elements \tag{12}$$

$$AF(\emptyset) = 2\sum_{n=1}^{N} \cos\left[kx_n \cos(\emptyset)\right] \quad for\ (2N)\ elements \tag{13}$$

As an example, a 37-element LAA is optimized by SOS (population size = 50, number of iterations = 100) with constrained inter-element spacing ($d_i \geq 0.5\lambda$) and aperture size (21.996λ) similar to [18].

Table 5. Optimum amplitude values found by SOS for the 24 elements LAA example.

	$I_1, I_2, \ldots, I_{12}$	Max SLL (dB)
SOS	1.0000 , 0.9699, 0.9143, 0.8387, 0.7420, 0.6368, 0.5273, 0.4145, 0.3149, 0.2243, 0.1515, 0.1236	−39.37
BBO [17]	0.9796, 1.0000, 0.9011, 0.8581, 0.7375, 0.6103, 0.5205, 0.4463, 0.3016, 0.2236, 0.1495, 0.0957	−37.14
PSO [16]	1.0000, 0.9712, 0.9226, 0.8591, 0.7812, 0.6807, 0.5751, 0.4768, 0.3793, 0.2878, 0.2020, 0.2167	−34.46
Taguchi [11]	1.0000, 0.9731, 0.9283, 0.8585, 0.7745, 0.6758, 0.5772, 0.4686, 0.3719, 0.2764, 0.1995, 0.2026	−35.02
Uniform	1.0000, 1.0000, 1.0000, 1.0000, 1.0000, 1.0000, 1.0000, 1.0000, 1.0000, 1.0000, 1.0000, 1.0000	−13.22

Table 6. Optimum feeding current amplitudes found by SOS for three different scanned LAAs.

	Feeding current amplitudes ($I_1 \ldots I_N$)	Max SLL (dB)
$N = 20$, $\varnothing_d = 30°$	1.0000 0.2762 0.4499 0.3040 0.3787 0.6113 0.5305 0.5042 0.5554 0.6113 0.4950 0.4909 0.5940 0.4393 0.3429 0.5587 0.4266 0.3142 0.4099 0.9092	−15.64
$N = 26$, $\varnothing_d = 45°$	1.0000 0.2314 0.4243 0.4349 0.3933 0.4423 0.4890 0.3892 0.5260 0.5470 0.3889 0.8891 0.4148 0.5557 0.4317 0.7241 0.4748 0.3302 0.7278 0.5896 0.2174 0.5061 0.1908 0.4341 0.6199 0.9584	−16.18
$N = 30$, $\varnothing_d = 60°$	1.0000 0.9219 0.4011 0.1512 0.6258 0.0149 0.7433 0.5357 0.4412 0.8182 0.3055 0.5388 0.8813 0.5962 0.4734 0.8110 0.3965 0.6665 0.3149 0.7865 0.6591 0.4047 0.3755 0.5224 0.5257 0.5935 0.2734 0.3698 0.6766 0.9982	−15.93

Table 7. Performance of SOS algorithm for scanned arrays in comparison with FA results.

	SOS			FA [9]		
	$N = 20$	$N = 26$	$N = 30$	$N = 20$	$N = 26$	$N = 30$
Best SLL (dB)	−15.64	16.18	−15.93	−15.59	−15.61	−15.97
Mean (dB)	−15.45	−16.04	−15.849	−15.385	−15.437	−15.823
SD (dB)	0.1038	0.093	0.047	0.1332	0.1184	0.0686

Therefore, the positions of the outermost elements $x_{\pm 18}$ are fixed at $\pm 10.998\lambda$, and the positions of the other 17-elements are optimized. This simplifies the array factor to be as follows:

$$AF(\varnothing) = 1 + 2\left\{\sum\nolimits_{n=1}^{17} \cos\left[kx_n \cos(\varnothing)\right] + \cos\left[21.996\pi \cos(\varnothing)\right]\right\} \quad (14)$$

Table 8 contains the inter-element distances obtained using the SOS while Figure 12 shows the obtained array factor. The maximum side lobe levels obtained using the SOS, BBO, self adaptive hybrid differential evolution (SHDE) [19], modified genetic algorithm (MGA) [18] and analytical approach (AA) methods [20] are −20.9377 dB, −20.8086 dB, −21.0922 dB, −20.4869 dB, and −19.3743 dB, respectively.

Table 8. Optimum inter-element distances (d_i) (in terms of wavelength) found by SOS for the 37-elements LAA in comparison with other optimization techniques.

	$\boldsymbol{d_1, d_2, \ldots, d_{18}}(\lambda)$	**Max SLL (dB)**
SOS	0.5, 0.5, 0.5001, 0.5001, 0.5, 0.5, 0.5, 0.5, 0.5007, 0.5504, 0.525, 0.5829, 0.7419, 0.7627, 0.8235, 1.0, 0.9996, 0.511	−20.9377
BBO [17]	0.5, 0.5, 0.5, 0.5, 0.5, 0.5, 0.5, 0.50386, 0.5, 0.59865, 0.5, 0.5, 0.7686, 0.79479, 0.9, 0.9, 0.97342, 0.5587	−20.8086
SHDE [19]	0.5, 0.5. 0.5, 0.5, 0.5, 0.5, 0.5, 0.5, 0.5, 0.5, 0.6003, 0.5749, 0.6143, 0.8405, 0.7014, 1.3131, 0.8102, 0.5433	−21.0922
MGA [18]	0.5024, 0.5, 0.5, 0.5008, 0.5003, 0.5001, 0.5045, 0.5703, 0.5369, 0.5194, 0.5868, 0.5765, 0.7737, 0.7045, 1.0065, 0.8806, 0.8293, 0.5054	−20.4869
AA [20]	0.5, 0.5, 0.5, 0.5, 0.5, 0.5, 0.5, 0.5, 0.589, 0.633, 0.664, 0.687, 0.707, 0.722, 0.735, 0.746, 0.754, 0.761	−19.3743

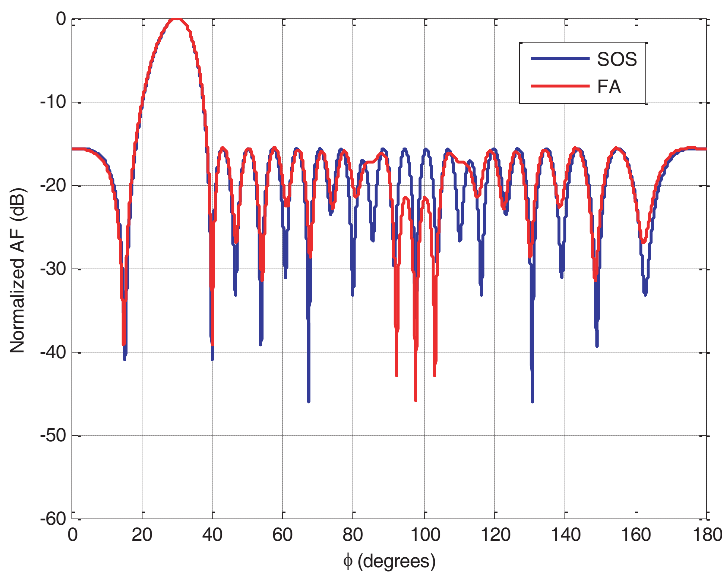

Figure 9. Radiation pattern of the 20 elements scanned LAA.

SOS does very well in this example as it gives a maximum SLL that is comparable to that obtained using other powerful techniques. Figure 13 shows the convergence plot for this example, where it can be seen that the solution converges to its optimum value within only 50 iterations. The above SOS result was the best one obtained from 10 independent runs. The results of these 10 runs have a maximum value of −20.86 dB, mean value of −20.91 dB, and standard deviation of 0.03 dB. Figure 14 shows a bar graph of these results.

4.4. Optimizing the Elements Phases (φ_n)

As in the previous sections, in order to optimize the phases of the elements, the other parameters have to be fixed. The amplitudes are set to unity and the spacing between adjacent elements is set to 0.5λ.

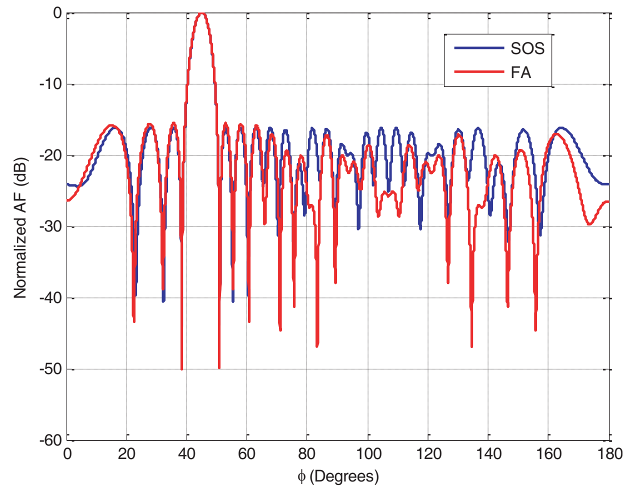

Figure 10. Radiation pattern of the 26 elements scanned LAA.

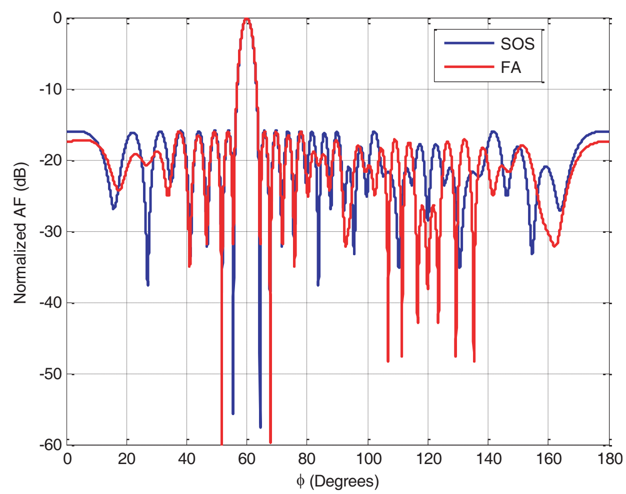

Figure 11. Radiation pattern of the 30 elements scanned LAA.

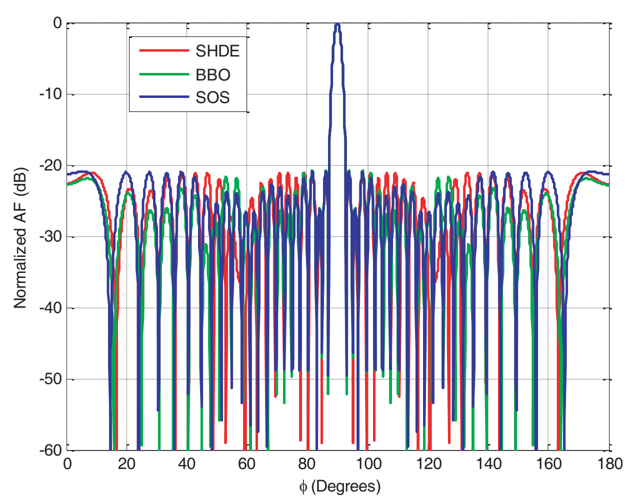

Figure 12. Radiation pattern of 37-elements LAA optimized with respect to positions.

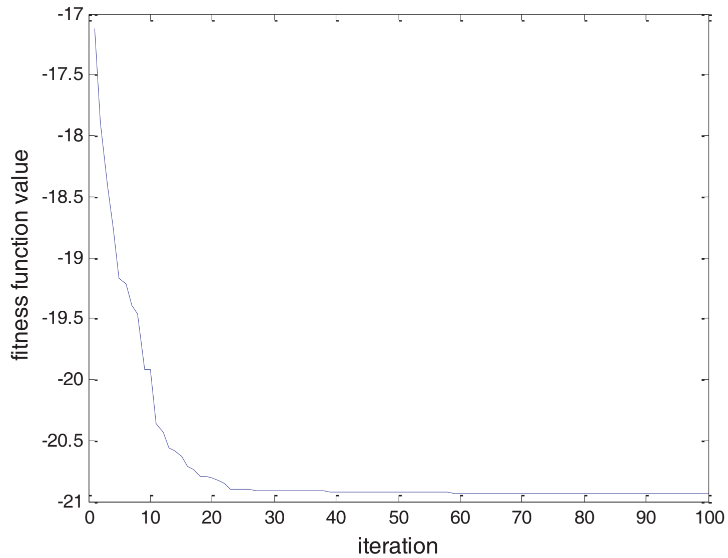

Figure 13. Convergence plot for the 37-elements LAA example.

Table 9. Optimum phase values found by SOS for the 40-elements LAA.

	$\boldsymbol{\varphi_1, \varphi_2, \ldots, \varphi_{20}}$ (degrees)	**Max SLL (dB)**
SOS	28.3636, 25.0046, 22.2290, 31.1901, 23.7626, 17.3337, 15.5147, 39.0199, 18.1678, 7.8822, 1.8298, 60.0022, 0, 0.0146, 0.0161, 148.3908, 45.0096, 56.1693, 61.9867, 2.1350	−18.02
BBO [17]	90.4185, 90.5331, 97.2825, 90.2466, 88.384, 97.1507, 90.0002, 90.3497, 97.2596, 85.9950, 75.0002, 115.5026, 71.8604, 0.3610, 122.9166, 97.0247, 178.8087, 83.3081, 83.9670, 79.2057	−17.96
GA [17]	69.7175, 68.4570, 72.3187, 63.5582, 53.3699, 51.9283, 66.1537, 36.5971, 50.4650, 38.3526, 75.1950, 15.6011, 91.3810, 39.8412, 83.9670, 171.8873, 32.3028, 28.6863, 57.2958, 73.1724	−17.39
Uniform	0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0	−13.24

The phases of the elements are assumed to be symmetric as:

$$\varphi_n = \varphi_{-n} \qquad n = 1, 2, 3, \ldots, N \tag{15}$$

where φ_n is the phase of the nth element. Thus, the array factor can be written as follows:

$$AF(\emptyset) = \exp(j\varphi_o) + 2\sum_{n=1}^{N} \exp(j\varphi_n)\cos[n\pi\cos(\emptyset)] \quad for\ (2N+1)\ elements \tag{16}$$

$$AF(\emptyset) = 2\sum_{n=1}^{N} \exp(j\varphi_n)\cos[(n-0.5)\pi\cos(\emptyset)] \quad for\ (2N)\ elements \tag{17}$$

4.4.1. SLL Reduction of a 40 Elements LAA

Table 9 and Figure 15 show the optimum phases and the radiation pattern for 40 elements LAA optimized by SOS (population size = 200, number of iterations = 300). The excitation phases are assumed to be within the range $[0, \pi]$. The maximum SLL for the optimized array using SOS is -18.02 dB which is very close to that obtained using BBO. Figure 16 shows that good convergence is

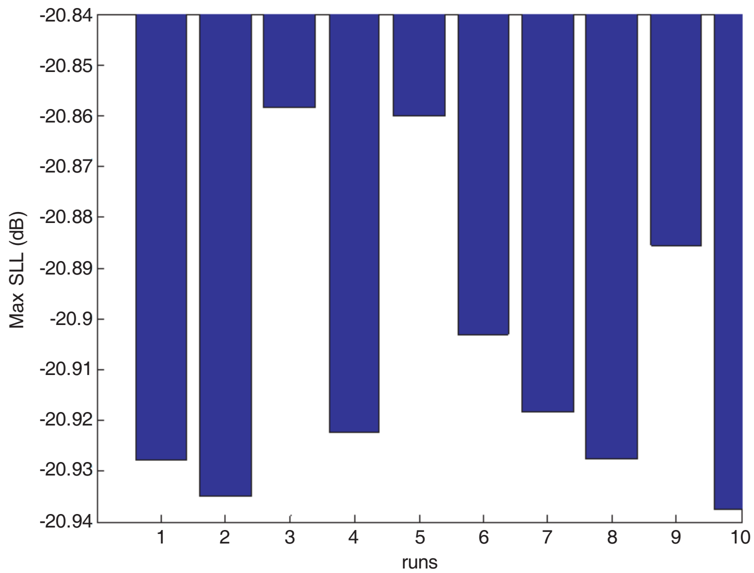

Figure 14. The maximum SLL obtained by SOS in 10 independent trials for the 37-elements LAA.

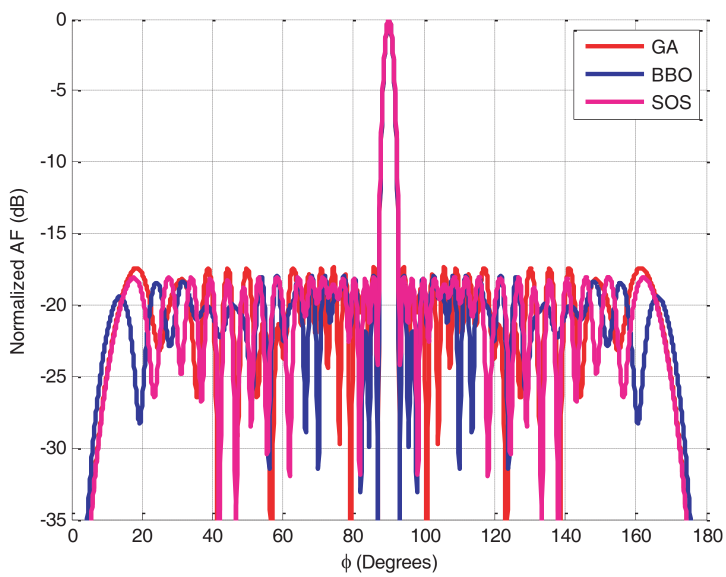

Figure 15. Radiation patterns for the results in Table 9.

obtained within 150 iterations. It is worth mentioning that each run took around 5.5 minutes using the Core i7 Laptop mentioned before.

4.4.2. Minimizing Side Lobes Level and Nulls Control

In order to impose nulls at specific angles in addition to reducing the maximum SLL by optimizing the phases of the array elements; the fitness function is modified to become:

$$fitness = K_1 f_{SL}(\emptyset) + K_2 f_{NS}(\emptyset) \tag{18}$$

$$f_{SL}(\emptyset) = \max\left\{20\log_{10}\left|\frac{AF(\emptyset)}{AF(\emptyset_d)}\right|\right\} \tag{19}$$

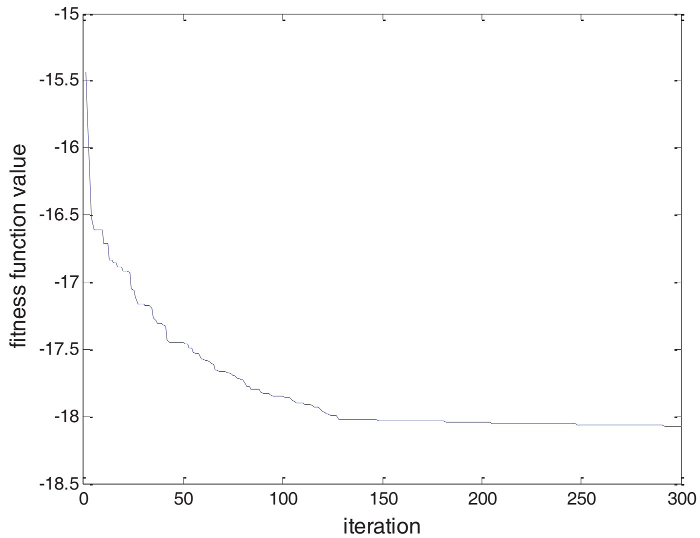

Figure 16. Convergence plot for the 40 elements LAA optimized with respect to phases.

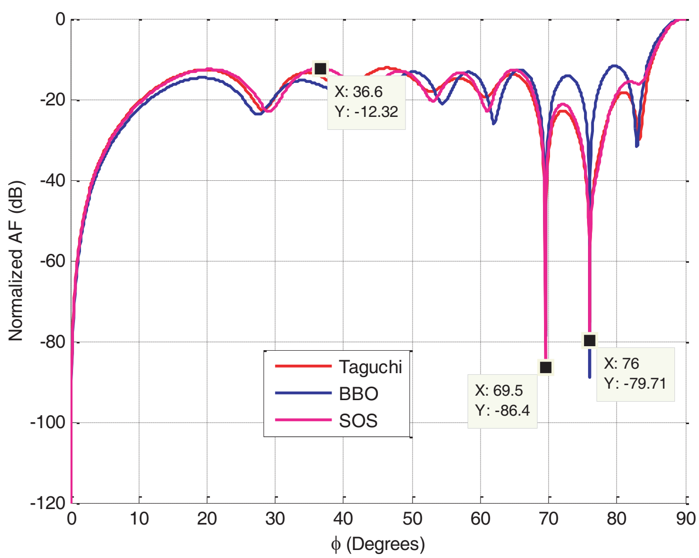

Figure 17. Radiation patterns for the data in Table 10.

$$f_{NS}(\text{Ø}) = \sum\nolimits_k \left\{ 20\log_{10} \left| \frac{AF(\text{Ø}_{k-null})}{AF(\text{Ø}_d)} \right| \right\} \tag{20}$$

where K_1 and K_2 are weights. $f_{SL}(\text{Ø})$ is the fitness function in the side lobes region; $f_{NS}(\text{Ø})$ is the fitness function in the direction of the nulls. Thus, the goal is to achieve nulls at specific angles (k of them) besides reducing the level of the maximum SLL. Here, the excitation phases are assumed to be within the range $[-\pi, \pi]$. Several examples of uni-directional and bi-directional null steering have been optimized using SOS. For brevity purposes, only one example is given here. Bidirectional null steering is applied on a 20 elements LAA. Specifically, a 20 elements LAA with nulls at 69.5° and 76° and minimum side lobes level is designed. The optimum values of the phases (in degrees) are shown in Table 10. SOS (population size = 170, number of iterations = 660, $K_1 = 1$, $K_2 = 0.25$) obtained a first null value of -86.4 dB, a second null value of -79.71 dB, and a maximum SLL of -12.32 dB. Figure 17 shows the radiation patterns for the results in Table 10. Again, SOS proves to be a robust optimization method that can easily compete with other techniques.

Table 10. Optimum phase values for the 20-element LAA with nulls at 69.5° and 76°.

	$\varphi_1, \varphi_2, \ldots, \varphi_{10}$ (degrees)	Max SLL (dB)	1st null value (dB)	2nd null value (dB)
SOS	−18.8852, −22.8728, −28.5132, −11.2643, 0.5386, 3.5521, 14.2509, −82.2554, 63.5413, 6.3598	−12.32	−86.4	−79.71
BBO [17]	63.9765, 57.2958, 54.5530, 57.2035, 52.4440, 56.9595, 57.0070, −3.4791, 57.2958, 175.8465	−11.77	−78.89	−88.90
Taguchi [11]	46.6069, 26.7026, 33.1780, 38.4783, 42.2764, 53.5864, 43.3624, -34.757, 112.3258, 33.9447	−12.27	−77.26	−75.22

5. CONCLUSIONS

For the first time, SOS is used in the synthesis of antenna arrays. It was mainly applied to the design of linear antenna arrays with low side lobes level. Three cases of linear array design have been considered; amplitudes optimization, positions optimization and phases optimization. It was found that the SOS is a robust, fast converging algorithm, and its results are as good as those obtained using other optimization methods. More importantly, SOS has the advantage of being free of tuning parameters.

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