Optimization of the Shape of Non-Planar Electronically Scanned Arrays for IFF Applications via Multi-Objective Invasive Weed Optimization Algorithm

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Abstract **─** The identify friend or foe antenna is a complement to many radar antennas which allows the discrimination between friendly and hostile targets by receiving identification data. Such antenna must synthesize both a sum and a difference pattern in azimuth to allow target discrimination and must point to the target being inquired, either by mechanical or electronic scanning in azimuth. In this paper, to attain optimal electronic scanning, an array of antennas lying on a generic planar curve is considered. A multi-objective optimization based on the invasive weed optimization algorithm is then applied to the shape of such curve, aimed at maximizing performances. Whereas a conventional linear array of 6 elements can effectively scan ±30°, with respect to broadside, the proposed array, notwithstanding the same number of elements and overall length, can scan ±45° and still synthesize effective sum and difference patterns.

Index Terms **─** Antenna arrays, conformal arrays, IFF antenna, optimization, phased arrays.

I. INTRODUCTION

The identify friend or foe (IFF) system integrates military radar antenna. It allows the discrimination between friendly and hostile targets by receiving identification data. IFF systems relies on their own antenna, placed in proximity of the radar antenna [1]. IFF antennas are almost as old as radar itself and their design is a long running engineering problem [2]. Current IFF standard, Mark XII, states a transmitting frequency centered at 1030 MHz and a receiving frequency centered at 1090 MHz. Hence frequency much lower than those currently used on radars. Yet, the IFF antenna must have azimuth angular discrimination characteristics comparable to those of the matching radar and should not be larger than the radar antenna itself. These conflicting requirements are addressed by designing IFF antennas capable of generating at the same time a sum (Σ) pattern for communication and a difference (Δ) pattern for target discrimination in a framework similar to that of monopulse radars [2-4]. The IFF is commonly a linear array, seldom a planar array, of few elements which can of course be implemented on a flat surface [5,6] or made conformal to a curved surface [7].

If the radar is to be an electronically steering active array antenna, as it is the current state-of-the art, then also the IFF antenna should be electronically steerable in both sum and difference patterns, with steering performance comparable to that of the main antenna.

If the IFF antenna is to be of the same size of the main antenna, being requested to work at a much lower frequency, then its number of elements will be much smaller, and scanning capabilities would be impaired with respect to the main antenna [8]. In this contribution, a compact IFF array with few elements to keep its width minimal is designed, via a stochastic optimization procedure, to achieve maximum scanning capabilities.

Optimization is made on the curve, contained in the *xy*, horizontal, plane, on which radiating elements are placed and a multi-objective strategy is applied to the pattern as steering is performed on the *xy*-plane (azimuth) cut. The basic idea is that the array is not conformal to any given surface due to mechanical reasons but is rather of a shape designed so as to maximize scanning capabilities.

In this paper preliminary results are presented, attained on an ideal array comprising non-interacting elements with weakly directive patterns, optimized via an in-house multi-objective (MO) implementation of the invasive weed optimization (IWO) algorithm [9-10]. IWO has been chosen among many competing algorithms for its good performances in electromagnetic problems, both antenna ones [11-14] and circuit ones [15-16]. Its extension to MO is simple, as per any population based stochastic optimization method, as explained in [17]. In the present paper radiating elements are considered ideal sources, implementation with patch antennas and full wave simulations will be matter of future studies.

The paper is organized as follows: the following Section II describes the problem set up; Section III presents the optimization method; Section IV the optimization results. Finally, Section V draws some

Submitted On: January 10, 2020
Accepted On: March 26, 2020

conclusions.

II. ARRAY GEOMETRY AND OPTIMIZATION VARIABLES

The reference for the analysis is a Cartesian reference with a vertical *z*-axis. Due to the IFF application only azimuth patterns will be considered, that is *xy* cuts of the radiation solid. The coordinate considered is θ, measuring the angular distance between the *x*-axis and the direction of observation.

The problem geometry is sketched in Fig. 1: a spline, defined by $N+2$ control points, the first (0,0) and last $(L,0)$, being fixed, is used as a baseline on which to deploy radiating elements. The internal N control points (x_i,y_i) with $0<x_1<\ldots<x_i<\ldots<x_N<L$ are evenly spaced in x, while their coordinates $0<y_i<y_{\max}$ are the variables for the optimization procedure.

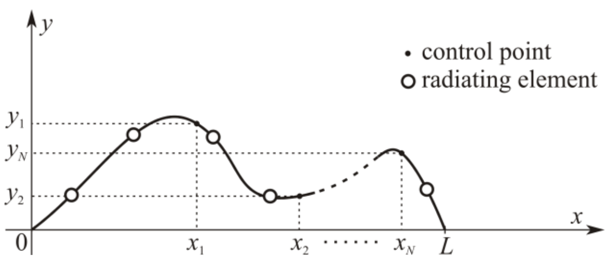

Fig. 1. A spline in the (x,y) plane defined by $N+2$ control points and on which M radiating elements are uniformly spaced.

On the spline M equally spaced radiating elements are deployed. Since the spline length varies as the control points (x_i,y_i) are moved, physical feasibility constraints are enforced, i.e., the number of elements M is chosen so that the straight array along the segment of length L is realizable. That is, elements are further than half wavelength from each other in the straight array. Then, since any possible spline is longer than L, the spline-based array is realizable. First and last elements are placed at a distance from the end of the spline equal to half the inter element distance. This to ensure that, when this design will be used in practice, finite dimension patch antennas will have room within the spline.

Element pattern is assumed as either a cardioid or a cosine, both being a good approximation of a patch antenna pattern at least in the upper half-space:

$$P(\theta)=\begin{cases}\cos^n\left(\theta-\theta^{(b)}\right) & \text{if } \cos\left(\theta-\theta^{(b)}\right)>0 \\ 0 & \text{otherwise}\end{cases} \quad \text{cosine pattern}$$

$$P(\theta)=\frac{\cos\left(\theta-\theta^{(b)}\right)+1}{2} \quad \text{cardioid pattern} \quad .(1)$$

Being $\theta^{(b)}$ the boresight direction (maximum radiation) of the pattern.

When elements are deployer onto the spline, the boresight direction $\theta_i^{(b)}$ of the generic element i is set perpendicular to the spline as it is the standard in a conformal array (Fig. 2). By comparing boresight direction $\theta_i^{(b)}$ with the desired scan angle θ_0 it is possible to switch off an element that would not contribute significantly to the pattern. In the following if $\left|\theta_0-\theta_i^{(b)}\right|>\theta_{\max}$ then, element i is turned off, being $\theta_{\max}$ among the optimization parameters (Fig. 2).

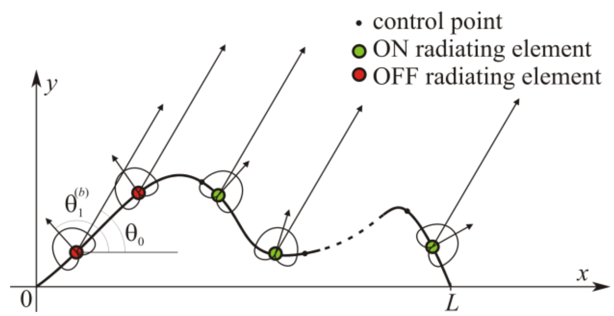

Fig. 2. On/off array elements selected on the basis of the beam steering. Angle θ is measured from x axis.

III. IWO ALGORITHM AND OPTIMIZATION SET-UP

The IWO algorithm searches for the best cost value by mimicking the behavior of invasive weed in a crop field. In its MO version (MO-IWO [14]) P weed seeds are randomly scattered on the problem parameters domain, from each seed grows a plant, plants are then ranked according to a non-dominating sorting [17] on the basis of the various cost functions evaluated at their position. Plants in excess are discarded.

Plants ranking higher in the sorting are considered as growing in an area rich of resources and hence produce more seeds than plants with worse cost values. The number of seeds each plant can produce vary from 1 to M_s.

Newly produced seeds are then spread around the plant location according to a normal (Gaussian) distribution of standard deviation σ, and give rise to new plants in the population. σ is decreased at each iteration so as to refine solution. Basic algorithm details can be found in [9], where single objective IWO is discussed. Figure 3 shows the flow chart for the MO-IWO here implemented. Both the MO-IWO algorithm and the evaluation of the array costs detailed in the following have been implemented by the authors in Matlab.

For the present case $N=3$ inner control points are chosen. The x_i are equally spaced in the $[0, L]$ interval, and symmetry is enforced, i.e., $y_1=y_3$. Optimization variables are hence only two: y_1 and y_2, with the additional choice of parameter $y_{\max}=L$.

Optimization parameters are then $\theta_{max}=\pi/3$, M=6, $L=2\lambda$, being λ the free-space wavelength. Patterns are cosine type, with n=1 (see eq. (1)).

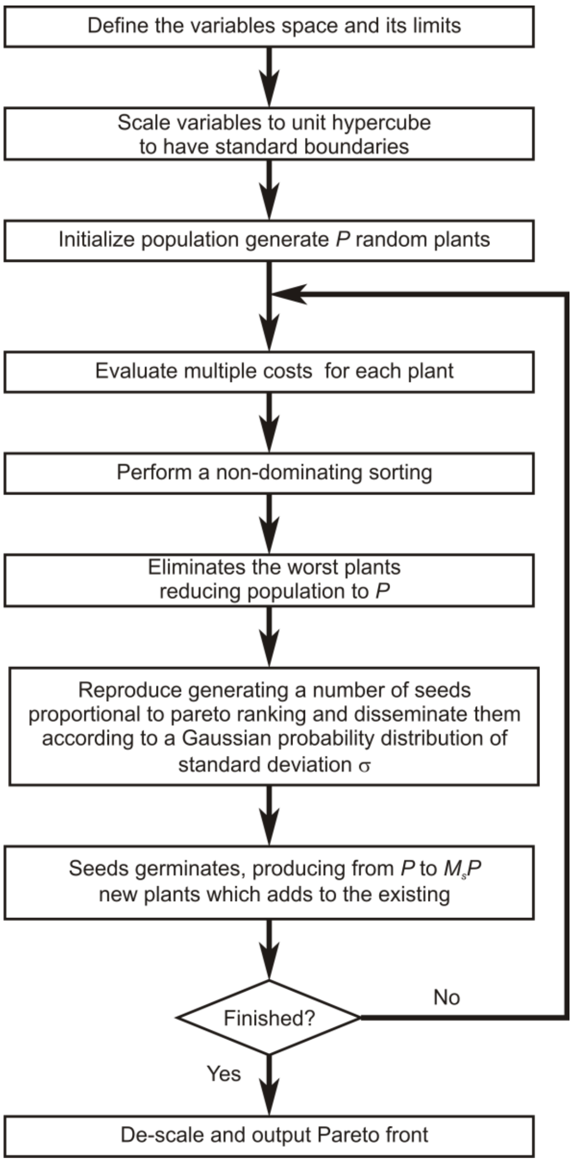

Fig. 3. MO-IWO Algorithm flowchart.

Costs are defined in terms of the following pattern quality parameters (Fig. 4):

- θ_0 – desired scan angle; on the basis of this angle theoretical phases for the elements are computed;
- θ_Σ – scan angle effectively synthesized with theoretical phases on sum pattern (Σ); this will differ from θ_0, in general, due to the fact that element boresight directions are not aligned;
- θ_Δ – scan angle effectively synthesized with theoretical phases on difference pattern (Δ);
- θ_{e-} – left crossing angle between sum and difference patterns;
- θ_{e+} – right crossing angle between sum and difference patterns;
- ND – null depth, difference between normalized sum pattern maximum and normalized difference pattern minimum (computed in linear scale, not dB, i.e., in the [0,1] range).

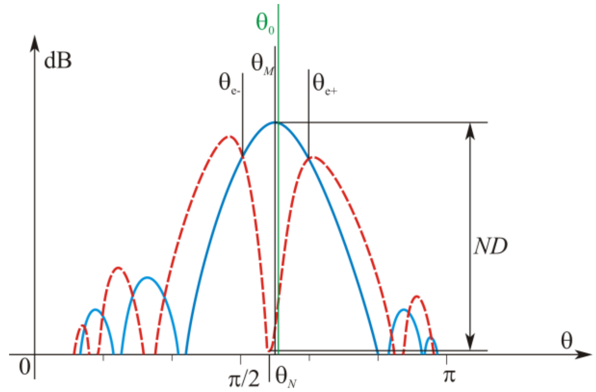

Fig. 4. Sum (blue, solid) and difference (red, dashed) and pattern parameters described in the text.

Based on these 6 quality factors, 5 costs are defined as the maximum values over the scan angle range of the following quantities:

$$c_1 = \max_{\theta_0\in[\theta_-,\theta_+]} (ND), \quad (2)$$

$$c_2 = \max_{\theta_0\in[\theta_-,\theta_+]} \left(\left|\theta_\Sigma - \theta_\Delta\right|\right), \quad (3)$$

$$c_3 = \max_{\theta_0\in[\theta_-,\theta_+]} \left(\theta_{e+} - \theta_{e-}\right), \quad (4)$$

$$c_4 = \max_{\theta_0\in[\theta_-,\theta_+]} \left(\left|\theta_{e+} - \theta_\Sigma\right|, \left|\theta_{e-} - \theta_\Sigma\right|\right), \quad (5)$$

$$c_5 = \max_{\theta_0\in[\theta_-,\theta_+]} \left(\left|\theta_{e+} - \theta_\Delta\right|, \left|\theta_{e-} - \theta_\Delta\right|\right). \quad (6)$$

Being $[\theta_-, \theta_+]$ the desired scan interval with respect to broadside. In our analysis $\pm 45°$, that is, being the broadside direction $\theta = 90°$: $\theta_- = 45°$, $\theta_+ = 135$.

A sixth cost, c_6, is given by the maximum y value of the spline, hence it accounts for the antenna overall size.

All costs ought to be minimized: Minimization of (2) leads to the deepest, hence sharper, null. Minimization of (3) leads to the best alignment between the sum maximum and the difference null. Minimization of (4); leads to the smallest effective angle, that is the smallest beamwidth for the sum/difference beam pair, which is a crucial parameter for target discrimination. Minimization of (5) and (6) leads to maximum symmetry between the effective angle and the maximum/null directions.

The IWO algorithm is run with P=25, M_s=3 for 200 generations. Standard deviation σ starts at 0.1 and linearly decreases to 0.001, at generation 200. Figure 5 shows the number of elements on the Pareto set. Note that if all 25 plants are in the Pareto set, then each produces 3 seeds and the total number of plants, after ranking and before elimination of the worst, sums up to 100. If plants on the Pareto set must be discarded the crowding distance is employed to select those to discard [17]. At the end of the optimization procedure, a Pareto set containing 25 solutions is obtained. Run time over a relatively old i5-4590S PC with 16Gb ram was about 1h, with most of the time dedicated to the determination of the pattern quality parameters.

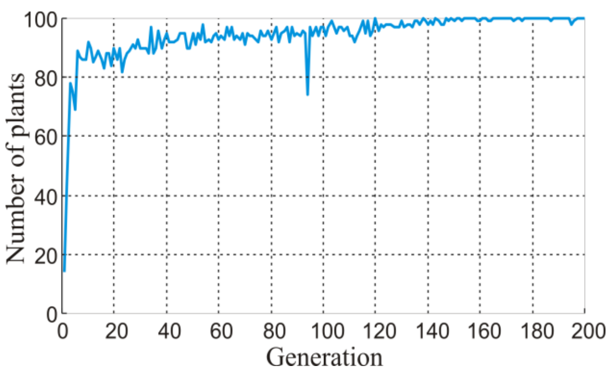

Fig. 5. Number of plants on the Pareto set as a function of generation.

IV. OPTIMIZATION RESULTS

The optimization run returned a Pareto set of 25 elements. A Pareto set is a set of non-dominated solutions in Pareto sense, that is, optimal solutions on which a trade-off must be done *a posteriori* [17]. Figure 6 shows six 2D projections of the 6D cost space. It is apparent how many different performances are attained. The chosen solution for showing patterns in detail in the following is number 24, highlighted by the green bullets in Fig. 6. Such a solution shows excellent cost values for the first four costs, an acceptable behavior on the fifth, and quite poor values for the sixth cost. Since c_6 is bound to spline height, this means that the spline extends significantly in the y direction, but space occupation requirement is here considered less important than electromagnetic behavior.

The spline defining the optimal array chosen among the ones in the final Pareto set is defined by the control points reported in Table 1 and the shape sketched in Fig. 7. It is somewhat surprising at first that the array is not convex but a mix of convex and concave, the middle point being lower in y than the surrounding ones.

Table 1: Spline control points

	0	1	2	3	4
x	0	0.5	1	1.5	2
y	0	0.880	0.275	0.880	0

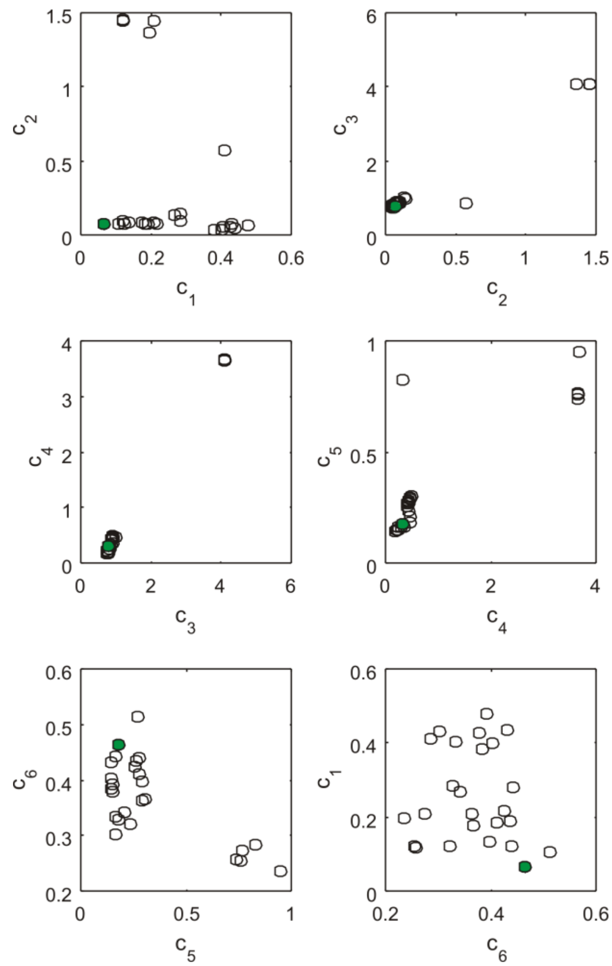

Fig. 6. 2D cuts of the 6D cost space showing the attained pareto set. Empty circles: all solutions; filled bullet: solution selected. Costs are linear (c_1), in radians (c_2 to c_5) or wavelengths (c_6).

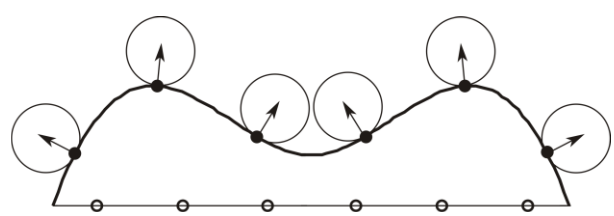

Fig. 7. Optimized geometry (bullets) with element factors and boresight directions highlighted, and equivalent linear array (empty circles).

This is indeed explained by the need of having a wide baseline for the array elements also while scanning. The optimized spline allows to have from 6 to 4 elements contributing to radiation for any scan angle, but, when four only are used, they may not be contiguous, especially at angles far from boresight, so effectively realizing a larger baseline countering the baseline reduction due to scanning.

Figure 7 shows the optimized geometry and the equivalent linear array of the same baseline and number of elements used for comparison.

Figure 8 shows all the costs, as compared to the ones computed for the linear array with the same baseline. For a clearer understanding, null depth (c_1) is reported in dB as a positive value while all the other costs are reported in degrees.

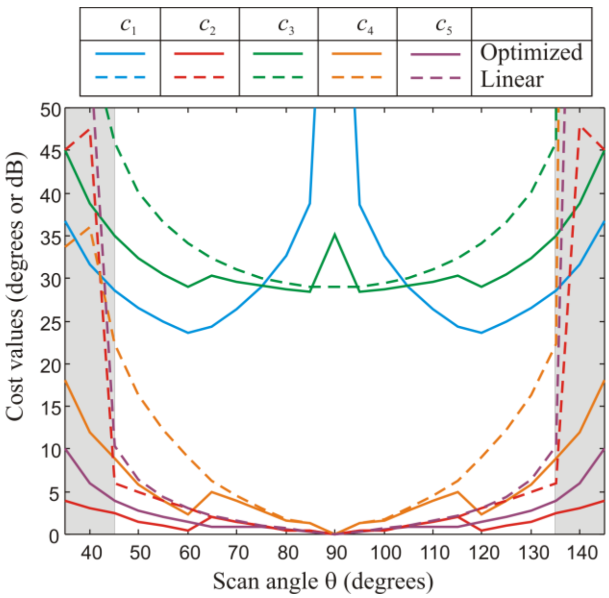

Fig. 8. Comparison between the five costs defined on patterns evaluated over the optimized array and over the corresponding linear array. Costs are in dB for null depth and degrees for the others. C_6 is not shown since it is not angle dependent. Null depth for linear array is always better than 50dB and out of the graph.

It is apparent, as scan angle gets farther from broadside, how the linear array performs steadily worse, while the optimized array has a clear step down in costs when it passes from the configuration with all 6 elements turned on to one of those with just 4 elements on. It is worth noticing that better results could be achieved with amplitude modulation of the elements, but in this work it has been decided to use phase only synthesis so as to attain a simpler implementation of the real antenna in the future.

To have a better understanding of the performance comparison, Fig. 9 reports the sum and difference patterns for three scan angles, namely 45°, 60° and 90° (broadside).

It is clear from the patterns that the linear array is unusable at 45°, the difference pattern never gets higher than the sum pattern on the left of the main beam, meaning that the effective angle cannot even be defined. Furthermore, the maximum and the null happen at quite different angles. On the other hand, the optimized array, even if presenting an asymmetry in the effective angle, has a much better behavior.

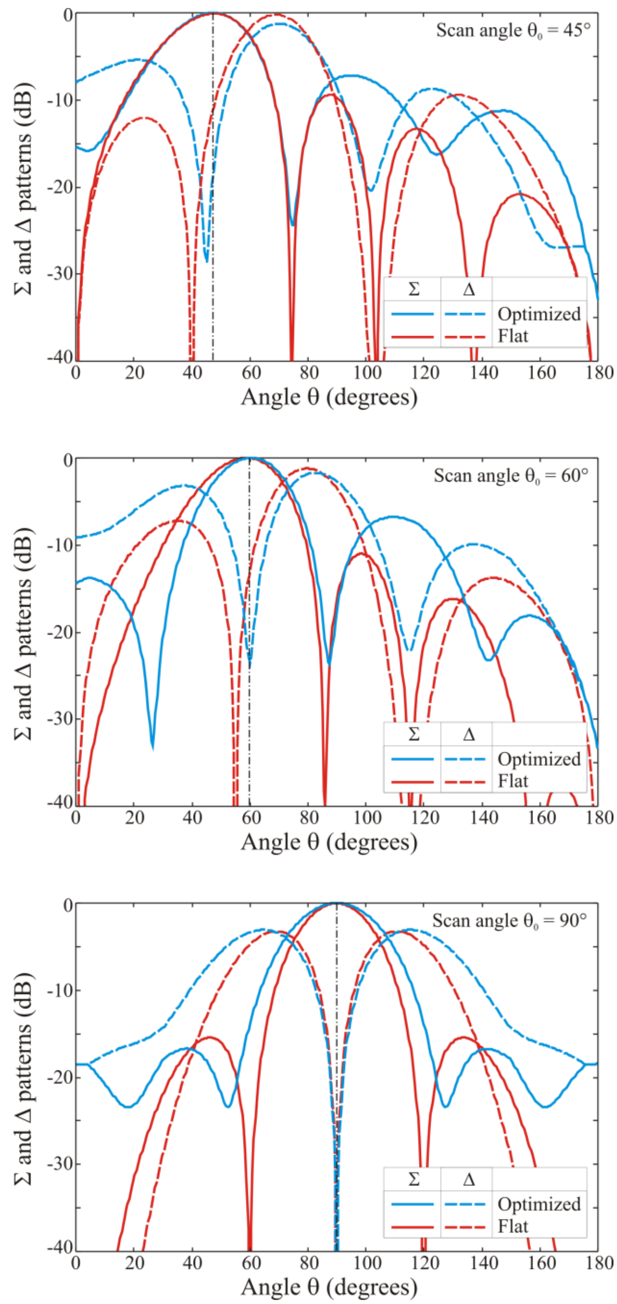

Fig. 9. Patterns for the optimized and linear array a three different scan angles.

The 60° case is less critical and the linear array can be used at that steering, yet the displacement of the null with respect to the maximum is much greater than for the optimized array. The 90° case is of course the best performing for both. It must be noted that, relying on phase only synthesis, the linear array always has a very deep null thanks to the fact that all element have the same orientation and hence perfect cancellation can be achieved. On the optimized array, due to different orientation, perfect cancellation is not attained by simply inverting half of the phases. Better null depth is hence possible via a minor optimization on the phase. This can be done via a further optimization, which also should take into account the real digital phase shifter to be used and hence their finite phase increment step.

V. CONCLUSIONS

By allowing an automatic stochastic MO-IWO optimization on a spline-defined curved array for IFF applications superior scanning performances are attained. Elements are turned on/off on the basis of their boresight direction with respect to scan angle. The convex-concave curve, obtained by optimization, might seem counter-intuitive but *a posteriori* its superior performances can be justified by the increased baseline of the array when scanning. Further studies will be carried out in the future, with full wave simulations on a printed array in this shape to assess its electromagnetic performances also taking into account mutual coupling.

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