Synthesis of Planar Thinned Arrays by Means of an Innovative Analytical-Stochastic Approach

M. Salucci, G. Gottardi, N. Anselmi, and G. Oliveri

Abstract

In this work, an innovative approach is proposed to design planar thinned phased arrays. The proposed methodology exploits the integration of analytical strategies and a global optimization technique in order to solve the limitations of current almost difference sets (*ADS*s)-based methods. Towards this end, a customization of the optimization operators is performed in order to exploit the *a-priori* information provided by *ADS* sequences and guide the optimization performed by a Genetic Algorithm (*GA*). Some numerical results are shown in order to validate the proposed *ADSGA* approach for the thinning of planar arrays.

1 Problem Definition

1.1 Problem I - PSL Minimization in Array Synthesis

In order to determine an optimal thinned configuration starting from the (usually) sub-optimal ADS arrangement with a given aperture size N_{ADS} and thinning factor ν_{ADS}, let us formulate the following constrained optimization problem

$$Min\,(F\{\rho\}) = \frac{max_{(u,v)\notin R_m^2}\left\{|S(u,v)|^2\right\}}{|S(0,0)|^2} \tag{1}$$

subject to $K = K_{ADS}$, $N_x = N_{x-ADS}$ and $N_y = N_{y-ADS}$, to be solved through ADSGA.

In such a case, the GA fitness function is defined as the PSL of the array while the constraints force the array to kept its descriptive parameters (i.e., original dimension, $N_x = N_{x-ADS}$ and $N_y = N_{y-ADS}$, and thinning, $\nu = \nu_{ADS}$).

1.2 Problem II - PSL Minimization in Array Synthesis

a)

In order to determine an optimal thinned configuration starting from the (usually) sub-optimal ADS arrangement with a given aperture size N_{ADS} and thinning factor ν_{ADS}, let us formulate the following constrained optimization problem

$$Min\,(F\{\rho\}) = \frac{max_{(u,v)\notin R_m^2}\left\{|S(u,v)|^2\right\}}{|S(0,0)|^2}$$

subject to $K = K_{ADS}$, $N_x \neq N_{x-ADS}$ and $N_y \neq N_{y-ADS}$ to be solved through ADSGA.

In such a case, the GA fitness function is defined as the PSL of the array while the constraints force the array to kept its descriptive parameters (i.e., original thinning factor ν_{ADS}).

b)

In order to determine an optimal thinned configuration starting from the (usually) sub-optimal ADS arrangement with a given aperture size N_{ADS} and thinning factor ν_{ADS}, let us formulate the following constrained optimization problem

$$Min\,(F\{\rho\}) = \frac{max_{(u,v)\notin R_m^2}\left\{|S(u,v)|^2\right\}}{|S(0,0)|^2}$$

subject to $K \neq K_{ADS}$ ($K > K_{ADS}$) and $N_x \neq N_{x-ADS}$ and $N_y \neq N_{y-ADS}$ ($N > N_{x-ADS}$ and $N_y > N_{y-ADS}$) to be solved through ADSGA.

In such a case, the GA fitness function is defined as the PSL of the array while the constraints force the array to kept its descriptive parameters.

1.3 Problem III - Definition of a General Purpose ADS Construction Technique for Array Synthesis

With reference to the potential limitation outlined in the Introduction, the aim is now to and the explicit forms of ADS s sequences (i.e., binary sequences with a three-level auto-correlation function) for arbitrary values of N . Towards this end, let us denote with $L\{\rho\}$ and $R\{\rho\}$ the number of levels of the auto-correlation function $\xi(\tau)$ of a trial solution ρ and the number of τ values for which $\xi(\tau)$ differ from . Then, the search for admissible (but not available in ADS repositories) ADS sequences is recast as the solution of the following problem

$$Min\,(F\{\rho\}) = \alpha\,[L\{\rho\} - 3] + \beta R\{\rho\}$$

subject to $N_x \neq N_{x-ADS}$ and $N_y \neq N_{y-ADS}$. The ADSGA within the *auto-correlation space* instead of in the *pattern space*, while the constraints are still on the set of parameters defining the ADS as well as the corresponding array arrangement.

2 General Definitions and Settings

Optimization Algorithm

We used the following optimization algorithm:

- Binary Coded Genetic Algorithm (GA)
  - Crossover Probability: $CP = 0.9$
  - Mutation Probability: $MP = 0.01$
  - Initialization:
    * Random: $P(bit = 0) = P(bit = 1) = 0.5$ (Random-GA Approach)
    * with Planar ADS (Hybrid-GA Approach)

Main Parameters

- Element Spacing: $d = \lambda/2$

The 2D array configuration is loaded into a single1D binary array (chromosome of the GA). The algorithm performs the optimization in the same manner of linear arrays.

3 Problem I - PSL Minimization in Array Synthesis

In order to determine an optimal thinned configuration starting from the (usually) sub-optimal ADS arrangement with a given aperture size N_{ADS} and thinning factor ν_{ADS}, let us formulate the following constrained optimization problem

$$Min\left(F\{\rho\}\right) = \frac{max_{(u,v)\notin R_m^2}\left\{\left|S(u,v)\right|^2\right\}}{\left|S(0,0)\right|^2}$$

subject to $K = K_{ADS}$ and $N = N_{ADS}$ to be solved through ADSGA.

In such a case, the GA fitness function is defined as the PSL of the array while the constraints force the array to kept its descriptive parameters (i.e., original dimension, $N = N_{ADS}$, and thinning, $\nu = \nu_{ADS}$).

- PSL: Kopilovich
  - Initialization: Random vs Hybrid
  - Fitness: PSL and Thinning

$$\Psi(i) = \frac{\alpha}{PSL^i_{Kopilovich}} + \beta\nu^i$$

where i is associated to the i-th trial solution.

RESULTS: $P = 7$, $Q = 7$, $K_{ADS} = 25$

Setting Parameters of Algorithms

GA Parameters

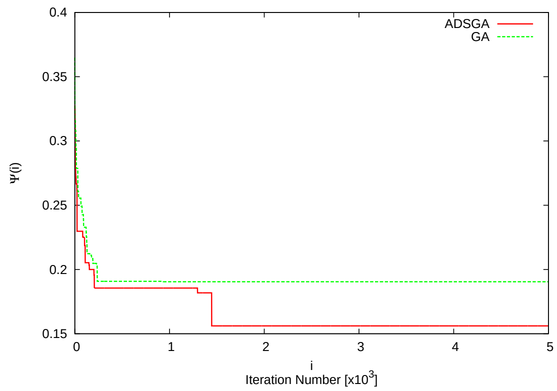
- Chromosome Dimension $C = 49\, bits$
- Population Dimension $S = 20$
- Max Iteration number $K_{max} = 5000$

FFT Parameters

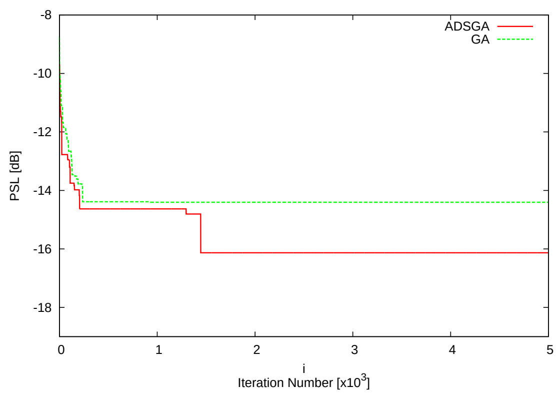
- $FFT\ Theta = 128$
- $FFT\ Phi = 128$

Array Parameters

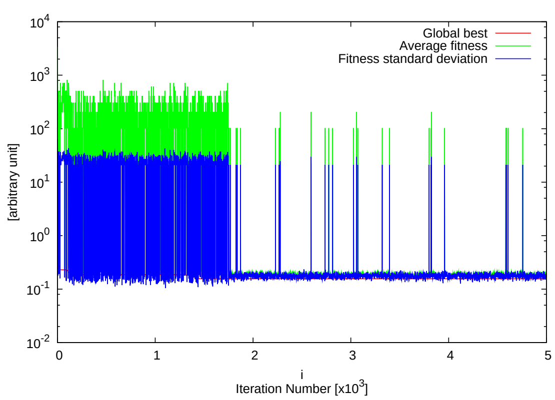
- Number of total cells $N = 49$
- Dimension X: 7
- Dimension Y: 7



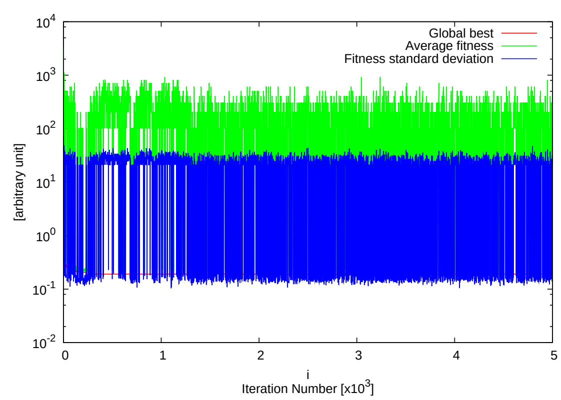
(*a*)



(*b*)



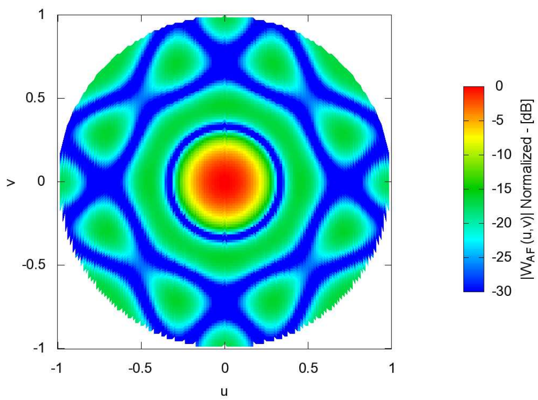
(*c*)



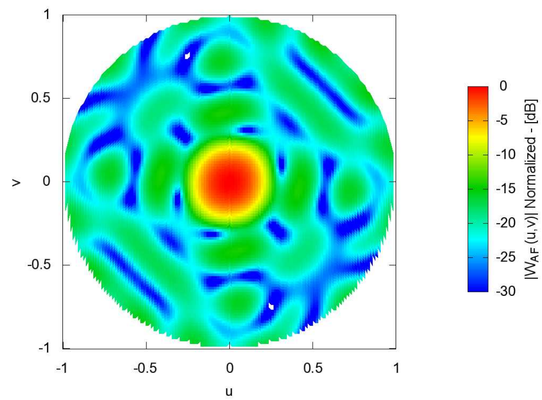
(*d*)

Figure 1.

Figure 1: ADSGA approach (*c*), GA approach (*d*)



(a)



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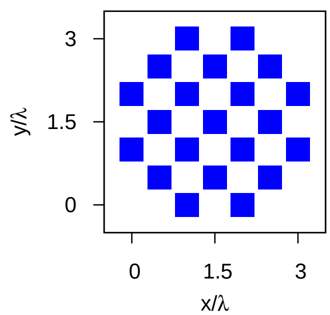

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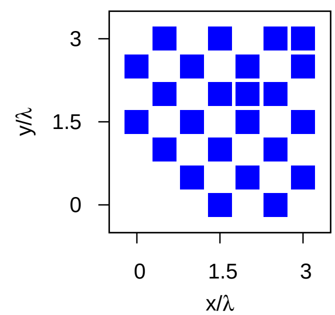


(d)

Figure 2.

Figure 2: ADSGA approach (a)-(c), GA approach (b)-(d)

RESULTS: $P = 11$, $Q = 11$, $K_{ADS} = 61$

Setting Parameters of Algorithms

GA Parameters

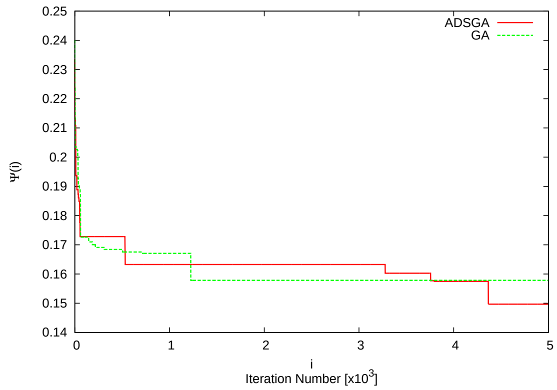
- Chromosome Dimension $C = 121\, bits$
- Population Dimension $S = 30$
- Max Iteration number $K_{max} = 5000$

FFT Parameters

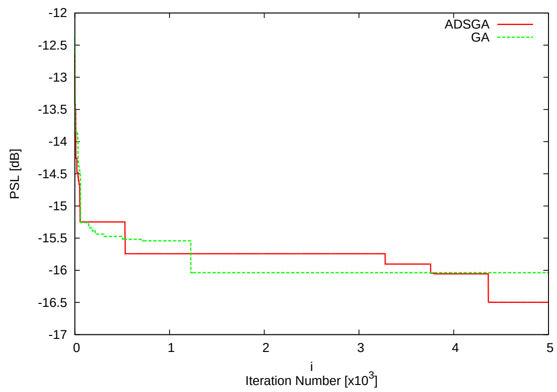
- $FFT\, Theta = 128$
- $FFT\, Phi = 128$

Array Parameters

- Number of total cells $N = 121$
- Dimension X: 11
- Dimension Y: 11



(a)



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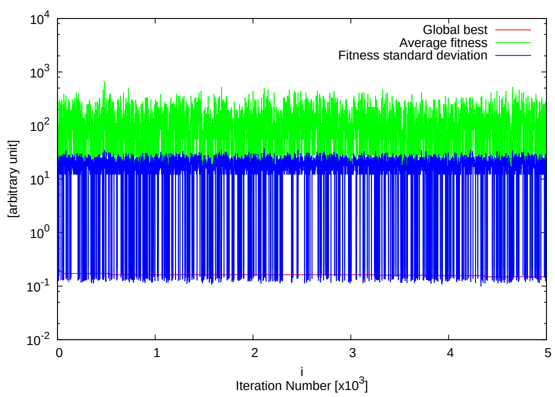

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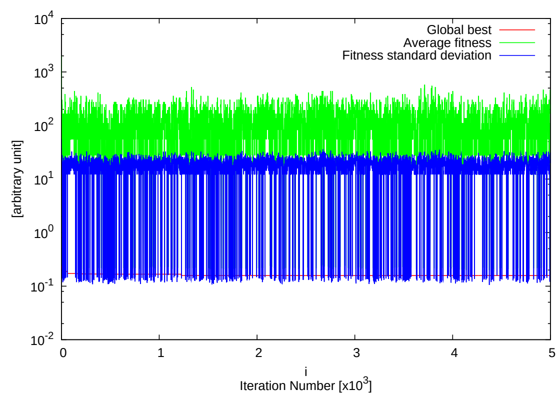


(d)

Figure 3.

Figure 3: ADSGA approach (c), GA approach (d)

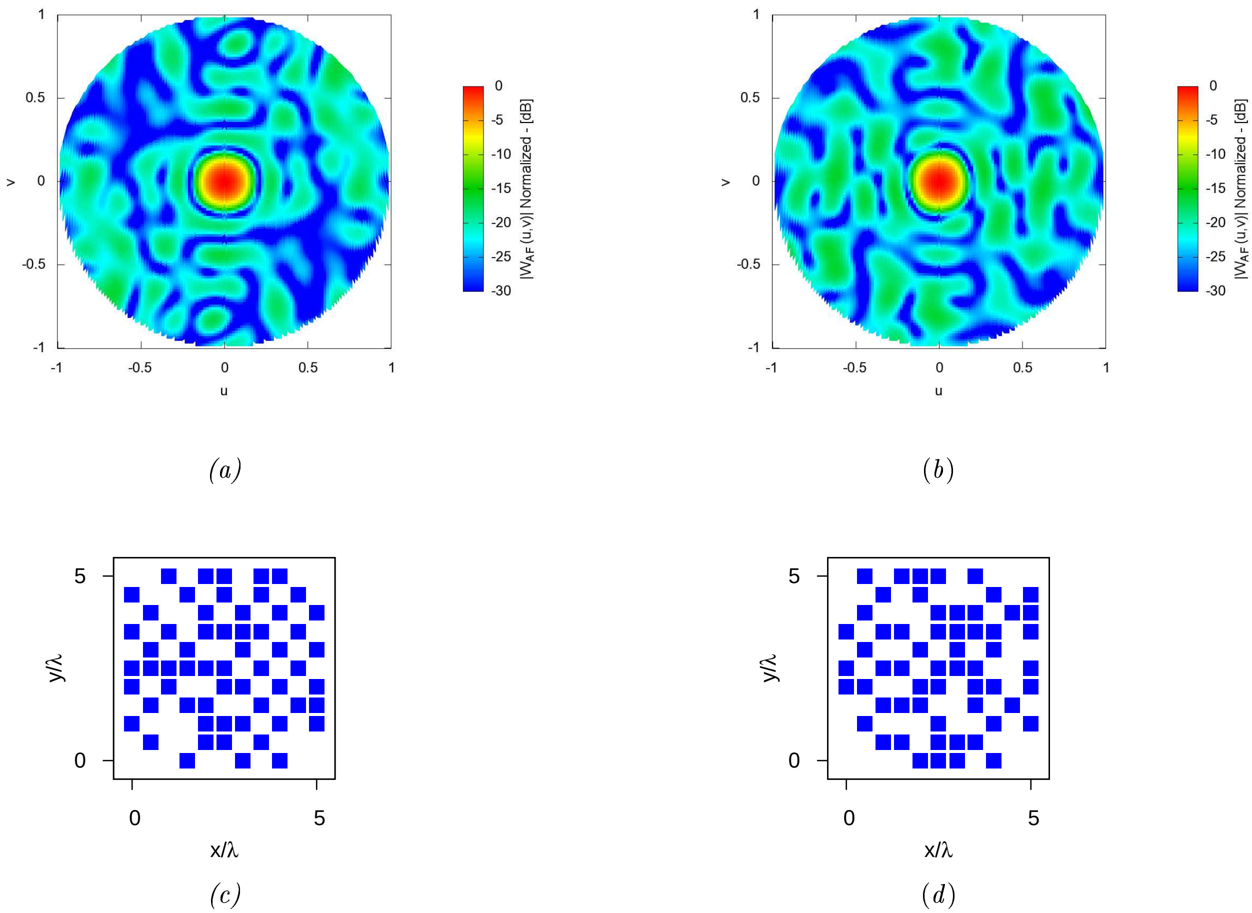


Figure 4.

Figure 4: ADSGA approach (a)-(c), GA approach (b)-(d)

RESULTS: $P = 17$, $Q = 17$, $K_{ADS} = 145$

Setting Parameters of Algorithms

GA Parameters

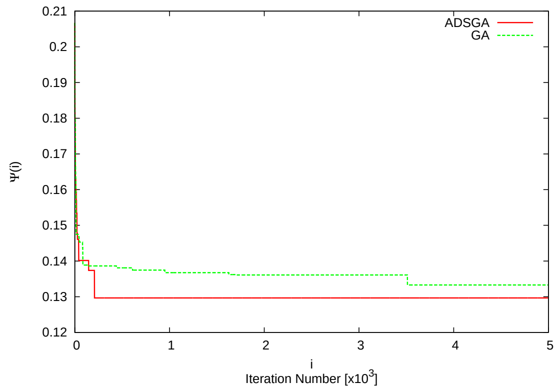
- Chromosome Dimension $C = 289\, bits$
- Population Dimension $S = 40$
- Max Iteration number $K_{max} = 5000$

FFT Parameters

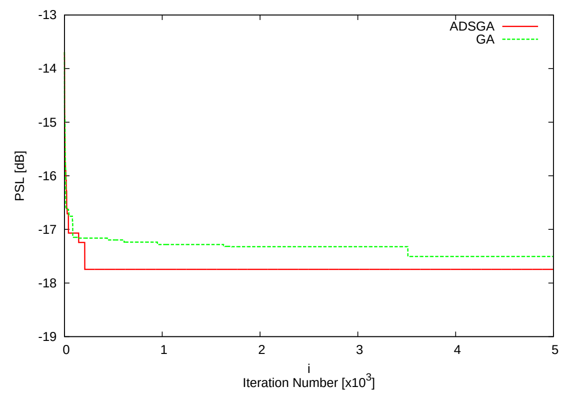
- $FFT\ Theta = 256$
- $FFT\ Phi = 256$

Array Parameters

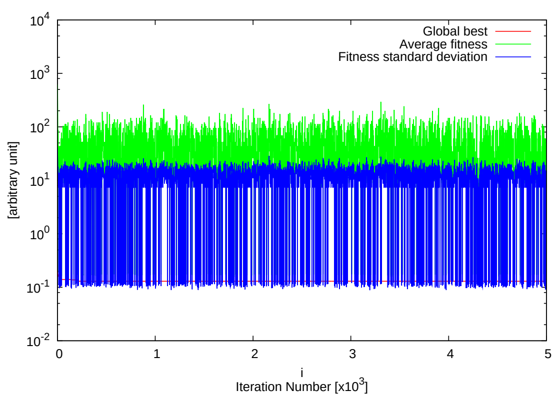
- Number of total cells $N = 289$
- Dimension X: 17
- Dimension Y: 17



(a)



(b)



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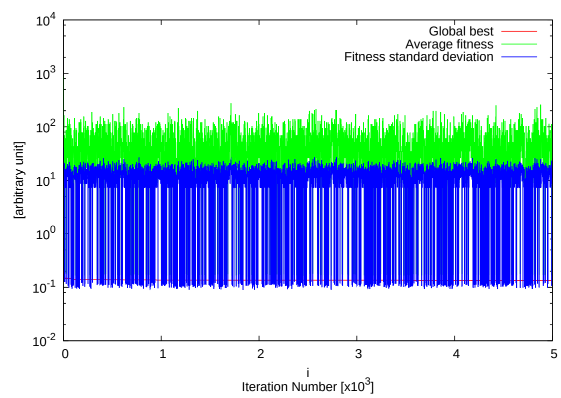

(d)

Figure 5.

Figure 5: ADSGA approach (c), GA approach (d)

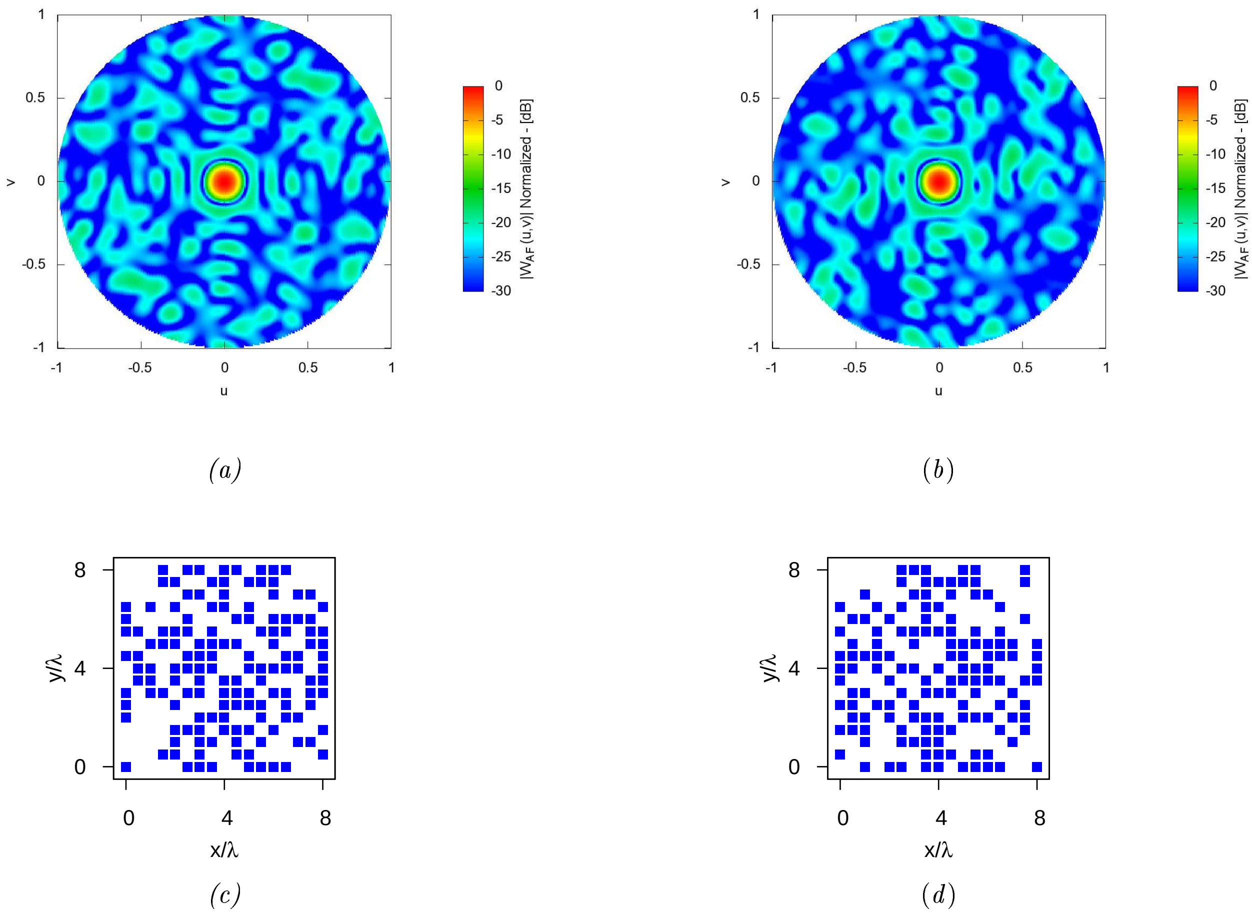

Figure 6.

Figure 6: ADSGA approach (a)-(c), GA approach (b)-(d)

3.1 Summary

		$ADSGA$	GA	$ADSGA$	GA	$ADSGA$	GA
$P = Q$		$\nu[\%]$	$\nu[\%]$	$PSL[dB]$	$PSL[dB]$	$BW\ (U_m = V_m)$	$BW\ (U_m = V_m)$
7		0.428	0.489	−16.13	−14.40	0.2857	0.2857
11		0.496	0.487	−16.50	−16.03	0.1818	0.1818
17		0.480	0.494	−17.74	−17.50	0.1176	0.1176

Table I

References

[1] P. Rocca, M. Benedetti, M. Donelli, D. Franceschini, and A. Massa, “Evolutionary optimization as applied to inverse problems,” Inverse Problems, vol. 25, pp. 1-41, Dec. 2009.

[2] P. Rocca, G. Oliveri, and A. Massa, “Differential Evolution as applied to electromagnetics,” *IEEE Antennas Propag. Mag.*, vol. 53, no. 1, pp. 38-49, Feb. 2011.

[3] M. Salucci, G. Gottardi, N. Anselmi, and G. Oliveri, “Planar thinned array design by hybrid analytical-stochastic optimization,” *IET Microwaves, Antennas & Propagation*, vol. 11, no. 13, pp. 1841-1845, Oct. 2017.

[4] G. Oliveri, M. Donelli, and A. Massa, “Genetically-designed arbitrary length almost difference sets,” *Electronics Letters*, vol. 5, no. 23, pp. 1182-1183, Nov. 2009.

[5] N. Anselmi, P. Rocca, M. Salucci, and A. Massa, “Irregular phased array tiling by means of analytic schemata-driven optimization,” *IEEE Transactions on Antennas and Propagation*, vol. 65, no. 9, pp. 4495-4510, September 2017.

[6] N. Anselmi, P. Rocca, M. Salucci, and A. Massa, “Optimization of excitation tolerances for robust beamforming in linear arrays,” *IET Microwaves, Antennas & Propagation*, vol. 10, no. 2, pp. 208-214, 2016.

[7] P. Rocca, M. Donelli, G. Oliveri, F. Viani, and A. Massa, “Reconfigurable sum-difference pattern by means of parasitic elements for forward-looking monopulse radar,” *IET Radar, Sonar & Navigation*, vol 7, no. 7, pp. 747-754, 2013.

[8] T. Moriyama, L. Poli, and P. Rocca, "Adaptive nulling in thinned planar arrays through genetic algorithms," *IEICE Electronics Express*, vol. 11, no. 21, pp. 1-9, Sep. 2014.

[9] L. Poli, P. Rocca, M. Salucci, and A. Massa, “Reconfigurable thinning for the adaptive control of linear arrays,” *IEEE Transactions on Antennas and Propagation*, vol. 61, no. 10, pp. 5068-5077, Oct. 2013.

[10] P. Rocca, L. Poli, G. Oliveri, and A. Massa, “Adaptive nulling in time-varying scenarios through time-modulated linear arrays,” *IEEE Antennas Wireless Propag. Lett.*, vol. 11, pp. 101-104, 2012.

[11] P. Rocca, G. Oliveri, R. J. Mailloux, and A. Massa, “Unconventional phased array architectures and design methodologies - A review,” *Proceedings of the IEEE*, vol. 104, no. 3, pp. 544-560, March 2016.

[12] L. Poli, P. Rocca, G. Oliveri, and A. Massa, “Failure correction in time-modulated linear arrays,” *IET Radar, Sonar & Navigation*, vol. 8, no. 3, pp. 195-201, 2014.

[13] G. Oliveri, M. Salucci, and A. Massa, “Synthesis of modular contiguously clustered linear arrays through a sparseness-regularized solver,” *IEEE Transactions on Antennas and Propagation*, vol. 64, no. 10, pp. 4277-4287, Oct. 2016.

[14] P. Rocca, N. Anselmi, and A. Massa "Optimal synthesis of robust beamformer weights exploiting interval analysis and convex optimization," *IEEE Trans. Antennas Propag.*, vol. 62, no. 7, pp. 3603-3612, Jul. 2014.

[15] N. Anselmi, P. Rocca, M. Salucci, and A. Massa, "Optimization of excitation tolerances for robust beamforming in linear arrays," *IET Microwaves, Antennas & Propagation*, vol. 10, no. 2, pp. 208-214, 2016.

[16] T. Moriyama, E. Giarola, M. Salucci, and G. Oliveri, "On the radiation properties of ADS-thinned dipole arrays" *IEICE Electronics Express*, vol. 11, no. 16, pp. 1-10, Aug. 2014.

[17] G. Oliveri, F. Viani, and A. Massa, "Synthesis of linear multi-beam arrays through hierarchical ADS-based interleaving," *IET Microw. Antennas Propag.*, vol. 8, no. 10, pp. 794-808, Jul. 2014.