Paper

Performance Comparison of Optimization Methods for Flat-Top Sector Beamforming in a Cellular Network

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Abstract — The flat-top radiation pattern is necessary to form an appropriate beam in a sectored cellular network and to provide users with best quality services. The flat-top pattern offers sufficient power and allows to minimize spillover of signal to adjacent sectors. The flat-top sector beam pattern is relied upon in sectored cellular networks, in multiple-input multiple-output (MIMO) systems and ensures a nearly constant gain in the desired cellular sector. This paper presents a comparison of such optimization techniques as real-coded genetic algorithm (RGA) and particle swarm optimization (PSO), used in cellular networks in order to achieve optimum flat-top sector patterns. The individual parameters of flat-top sector beams, such as cellular coverage, ripples in the flat-top beam, spillover of radiation to the adjacent sectors and side lobe level (SLL) are investigated through optimization performed for 40° and 60° sectors. These parameters are used to compare the performance of the optimized RGA and PSO algorithms. Overall, PSO outperforms the RGA algorithm.

Keywords — flat-top sector beam, particle swarm optimization, real-coded genetic algorithm

1. Introduction

In cellular communication, a radio communication link is established between two users via a base station. The high-speed multimedia communication network consists of a number of cells covering the serviced area. Channel capacity, interference level, data rate and numerous security features are some of the issues that are of great significance for any cellular network. In order to enhance channel capacity and security, each cell is divided into a number of sectors. Each sector is serviced by a dedicated directional antenna. Unfortunately, these directional antennas radiate non-uniformly over the terrain. Therefore, in a cellular communication system, it is necessary to install antenna systems that are capable of generating the desired radiation patterns with almost constant power levels available to all users.

The flat-top radiation pattern is necessary to form a derived beam in a sectored cellular network and, hence, to provide the best quality of service to the users [1]–[3] and to assure lower spillover of signal to the neighboring sectors. It is found that the classical methods are easy to implement, but suffer from several drawbacks [4]–[5]. All the known methods have limitations regarding their coverage area, the formation of ripples on the flat-top or the spillover of the beam to adjacent cells. These drawbacks can be minimized by deploying specific optimization methods.

2. Related Work

In [6], differential evolution (DE) is used to generate an optimally shaped beam pattern with multiple constraints. In cellular networks, in order to enhance network capacity and to ensure better spectral efficiency, cells are divided into a number of angular sectors. For the purpose of forming a sector beam with reduced SLL level, the zero forcing algorithm is used in [7]. For the design of the reflect-array aerial type with a flat-top beam for a remote sensing satellite system, the genetic algorithm (GA) is used in [8]. The formation of a flat-top pattern using a dipole array is reported in [9], using GA, and its performance is compared with results simulated with the use of high frequency structure simulator (HFSS) software.

Despite the large number of reports available in the literature concerned with the generation of flat-top beams using array synthesis and optimization methods, comparisons of performance of specific optimization methods are not available. Therefore, the aim of this work is to use specific optimization techniques, such as RGA and PSO, to generate a flat-top sector beam of a phased array antenna which covers the desired sector and is characterized by low ripples and reduced SLL. In addition, in both RGA and binary genetic algorithms (BGA), the phase-only optimization and amplitude-only optimization are considered for flat-top beam generation, and their performance is compared. Performance related to the maximum SLL, half power beam width (HPBW), maximum ripple formation in the beam pattern, cellular area coverage and spillover of the beam to the neighboring sectors is compared with that of the generated flat-top beams using RGA and PSO. RGA and PSO optimization methods provide good results in terms of flat-top beam generation, but the computation times encountered are very long compared to the classical approach. PSO is characterized by better performance in terms of flat-top sector beam generation. In MIMO, different types of beam patterns of antenna arrays are required [10], with an antenna array for flat-top cellular sector beam being one of them.

3. Description of Optimization Methods

3.1. Real Coded Genetic Algorithm (RGA)

GA is an evolutionary optimization technique and a stochastic method, searching for the global minimum by following the principles of genetics and natural selection. GA deals simultaneously with a large number of variables for global optimization. It is a stochastic method and any variable, whether discrete or continuous, may be used directly in the optimization process. The parameters considered include genes, chromosomes, population sizes, crossovers, selection, and mutations of the biological world. BGA changes the variables into an encoded binary string, while RGA works with continuous valued variables to optimize the cost function, although both algorithms follow the same principles of genetic recombination and natural selection [11]. RGA requires an adjustment of different operator or parameter values. Once all applicable conditions are satisfied, RGA needs fewer iterations to reach the optimum value and provide the best result.

The real coded genetic algorithm operates based on a real value parameter. Chromosomes are formed by groups of random (0 to 1) valued genes and a set of such chromosomes constitutes the initial population [12]. After evaluating the cost of each chromosome from this population, 50% best valued chromosomes are kept for the natural selection process and the rest is discarded. These selected parent chromosomes create offspring by combing the weighted portions of both parents. Weight b is calculated using a random number r and cross over operator μ, as [11], [12]:

$$\begin{aligned} b &= (2r)^{\frac{1}{1+\mu}} && \text{if } r > 0.5 \\ b &= \left(\frac{1-r}{2}\right)^{\frac{1}{1+\mu}} && \text{otherwise} \end{aligned} . \tag{1}$$

The newly generated offspring are:

$$\begin{aligned} \text{Offspring1} &= \frac{(1+b)\ \text{parent}_1 + (1-b)\ \text{parent}_2}{2} \\ \text{Offspring2} &= \frac{(1-b)\ \text{parent}_1 + (1+b)\ \text{parent}_2}{2} \end{aligned} . \tag{2}$$

Mutation is performed on some randomly selected chromosomes to continue the search in a diversified direction, according to the probability of mutation. If η is the mutation operator, then mutation weight p is:

$$\begin{aligned} p &= (2r)^{\frac{1}{1+\eta}} - 1 && \text{if } r \leqslant 0.5 \\ p &= 1 - (2-2r)^{\frac{1}{1+\eta}} && \text{otherwise} \end{aligned} . \tag{3}$$

3.2. Particle Swarm Optimization (PSO)

PSO is another evolutionary algorithm which has evolved from the behavior of animals which do not have a leader in their population or swarm (e.g. bird flocks). The PSO algorithm (search technique) is used to identify the best settings or parameters required to achieve a desired objective [13]. In the PSO approach, each single solution in the search space of an objective function is commonly known as a bird or a particle, and the set of random particles is the initial swarm. Each particle resides at a position within the search space, the fitness of each particle represents the quality of its position. Particles may evaluate their actual positions using the function to be optimized. The randomly generated solutions or swarms propagate in the design space, over a number of iterations, towards the optimal solution. The velocity of each particle is updated by its own best position solution found so far, with the best particle (*pbest*), the best solution that has been found so far by its neighbors (*lbest*) and another best value that is tracked by the particle swarm optimizer, obtained until now by any particle – global best (*gbest*). The swarm converges towards the optimal position by updating its information at every iteration and by checking the termination conditions.

Each particle is characterized by position vector $x_i(t)$ and velocity vector $v_i(t)$. Individual knowledge of the *pbest* particle, its own best-so-far position and social knowledge *gbest* is the *pbest* value in the swarm. In PSO, the velocity update equation is [13]:

$$\begin{aligned} v_i(t+1) \ = \ & w \cdot v_i(t) + c_1 \cdot \text{rand} \cdot [\mathit{pbest} - x_i(t)] \\ & + c_2 \cdot \text{rand} \cdot [\mathit{gbest} - x_i(t)], \end{aligned} \tag{4}$$

and the position update equation is:

$$x_i(t+1) = x_i(t) + v_i(t+1), \tag{5}$$

where i is the number of iterations, v_i is particle velocity at i-th iteration, x_i is the current particle position or solution, w is the inertia weight factor, a random number between $(0, 1)$. c_1, c_2 are the learning factors or constriction factors, such as: c_1 (known as a cognitive parameter) and c_2 (known as a social parameter) are acceleration factors that guarantee the convergence and improve its velocity. Usually, $c_1 + c_2 = 4$. A particle updates its velocity and position using the procedures described above, at every iteration toward the best solution.

4. Simulation Study

For simulation purposes, MATLAB has been used to generate an optimized flat-top cellular sector pattern, while RGA and PSO have been used as optimization tools. The ordinary sector beam, the desired flat-top sector beam and a typical optimized flat-top sector beam in a cellular network are shown in Fig. 1.

The flat-top pattern is characterized by three parameters: SLL, ripple and transition width. If one of them decreased, the others will increase. The techniques relied upon for shaping these patterns focus mostly on controlling the amplitude or phase of the current feeding each antenna element. In this paper, RGA and PSO are used for the generation of optimized flat-top patterns.

A linear antenna array with an element spacing value of d is shown in Fig. 2.

In the case of amplitude-only optimization, common amplitude distribution with a fixed phase of 0° or 180° for the desired sector beam pattern is considered. For the phase-only synthesis, the excitation phase distribution of the antenna array varies within the range of $0° \leqslant \varphi \leqslant 180°$ to achieve a flat-top beam through optimization. For an array of isotropic N an-

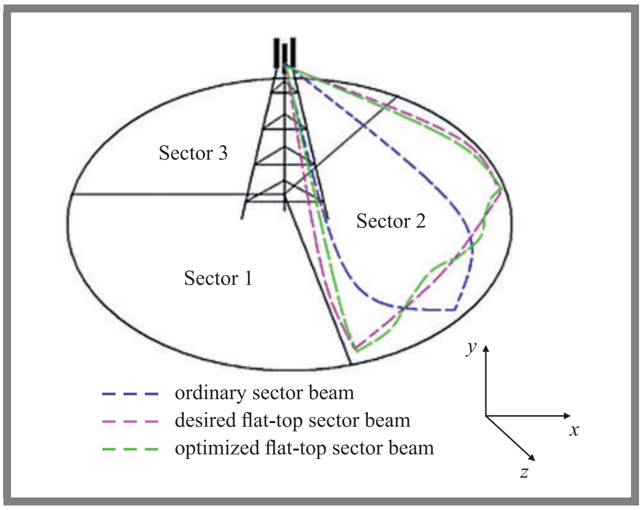

Fig. 1. Flat-top sector beam in a cellular network.

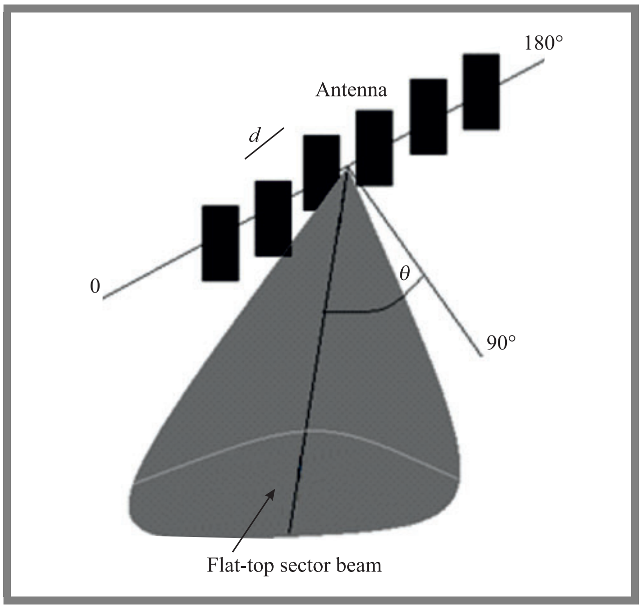

Fig. 2. Linear antenna array with a flat-top sector beam.

tennas with the inter-element distance of d along the y-axis, the array factor $\mathrm{AF}(\theta)$ in the principal y-z plane is [14], [15]:

$$\mathrm{AF}(\theta) = \sum_{n=1}^{N} a_n \mathrm{e}^{\mathrm{j}\varphi_n} \mathrm{e}^{\mathrm{j}(n-1)kd\sin\theta}, \quad (6)$$

where $k = 2\frac{\pi}{\lambda}$, n is the number of elements, λ is the wavelength, a_n and φ_n are the current amplitude and phase of the n-th antenna element, θ is the polar angle measured from the broadside direction (as shown in Fig. 2). The cost function needed to achieve the desired flat-top array pattern is expressed as:

$$\mathrm{Cost} = [\mathrm{AF}_d(\theta_{\mathrm{sec}}) - \mathrm{AF}(\theta_{\mathrm{sec}})]2 + [\mathrm{SLL}_d - \mathrm{SLL}_{\mathrm{max}}]^2, \quad (7)$$

where θ_{sec} is the angular sector region of the beam pattern, $\mathrm{AF}_d(\theta_{\mathrm{sec}})$ is the desired pattern, $\mathrm{AF}(\theta_{\mathrm{sec}})$ is the observed pattern, SLL_d is the desired SLL and $\mathrm{SLL}_{\mathrm{max}}$ is the maximum SLL of the observed pattern. $\mathrm{AF}(\theta_{\mathrm{sec}})$ is the normalized array factor of the observed pattern within the beam range θ_{sec} and for the sector beam range of θ_{sec}, $\mathrm{AF}_d(\theta_{\mathrm{sec}}) = 1$. Here, the goal is to minimize the cost function and to generate a flat-top beam which covers the desired sector area with a minimum SLL value.

4.1. Assumptions for Simulation Tests

In this simulation, the antennas in the array are assumed to be of the isotropic variety and are distributed linearly and uniformly. The various parameters considered in the simulation for RGA- and PSO-based optimization are as follows. For amplitude-only optimization with RGA, the crossover rate $= 0.7$, the crossover operator $\mu = 20$, the mutation rate $= 0.15$, the mutation operator $\eta = 20$, the population size $= 600$ and the number of iterations $= 1000$. For phase-only optimization with RGA, the crossover rate $= 0.6$, the crossover operator $\mu = 20$, the mutation rate $= 0.2$, the mutation operator $\eta = 20$, the population size $= 600$ and the number of iterations $= 1000$. For amplitude-only and phase-only optimizations using PSO, cognitive $c_1 = 1$, the social parameter $c_2 = 3$, the constriction factor $c = 1$, the inertia weight $W = 0$ to 1, the swarm size $= 600$ and the number of iterations $= 1000$. In RGA, single point crossover and roulette wheel selection are used.

4.2. Flat-top Beamforming by Amplitude-only Optimization Using RGA

Non-linear amplitude optimization is used to identify the distribution of the excitation current amplitude of the individual elements in order to achieve the desired flat-top pattern. In this section, RGA is used as the optimization tool, with Eq. (7) being the cost function used to determine the optimum excitation amplitude distribution of the array. A uniform linear array (ULA) of $N = 11$ elements is considered, with the inter-element spacing of $d = \lambda/2$, with all elements having the same phase to radiate in the broadside direction (90°). The desired patterns are 40° and 60° sector flat-top beams

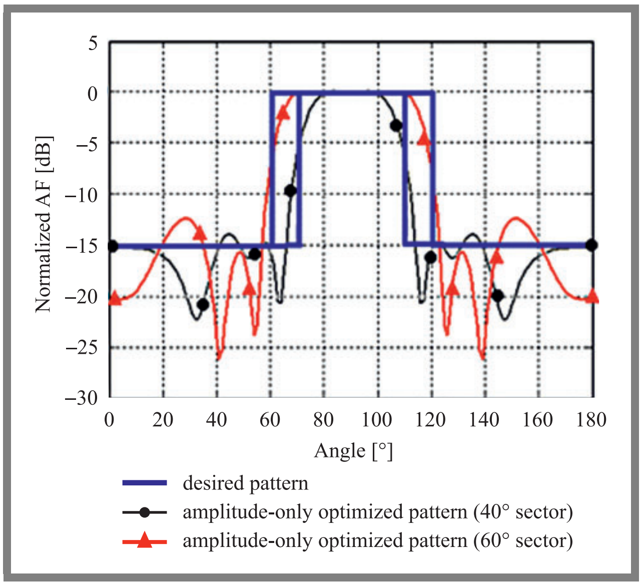

Fig. 3. 40° and 60° flat-top sector beams achieved by an amplitude-only RGA optimized array ($N = 11$).

having a maximum SLL of −15 dB. To generate such a desired pattern using the given array, Eqs. (6) and (7) are used to obtain the minimum value of the cost. The RGA-optimized simulated patterns generated using MATLAB are shown in Fig. 3 for a 40° sector and for a 60° sector, with broadside patterns for 11-element antenna arrays ($N = 11$).

For a 20-element array with $d = \lambda/2$, the excitation amplitude is optimized using RGA. The simulated radiation patterns and the desired patterns are plotted in Fig. 4.

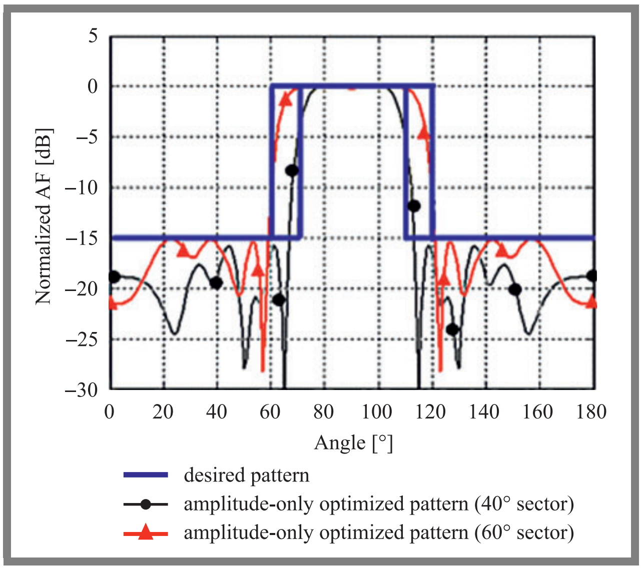

Fig. 4. 40° and 60° flat-top sector beams achieved by an amplitude-only RGA optimized array ($N = 20$).

The variations of RGA-optimized cost values with the number of iterations corresponding to Fig. 3 and Fig. 4 are plotted in Fig. 5.

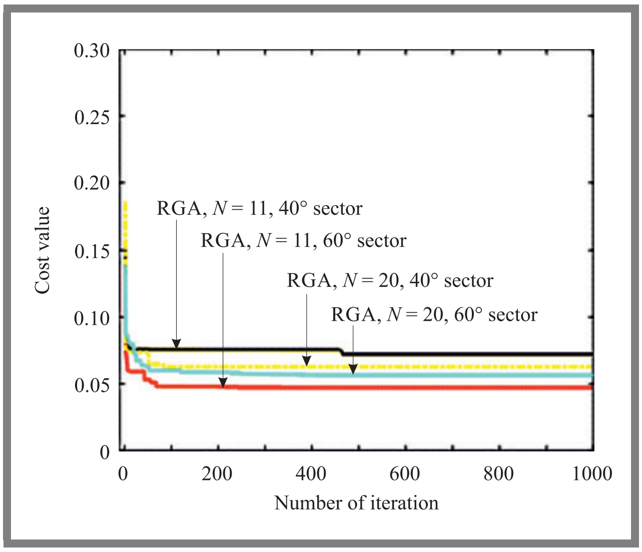

Fig. 5. Cost values for RGA amplitude-only optimized arrays.

In RGA optimized flat-top patterns in all the above cases (Fig. 3 and Fig. 4) the flat-top ripple disappears, but spillover to the neighbor sectors increases. In Fig. 3 optimized patterns do not satisfy the desired maximum SLL criteria, but in Fig. 4 the optimized patterns satisfy the desired maximum SLL criteria.

4.3. Flat-top Beamforming by Amplitude-only Optimization Using PSO

In this section, PSO is used to obtain the optimum excitation current amplitude distribution of the individual elements to achieve the desired flat-top pattern. PSO is a continuous algorithm, beginning with a real random number, but it is simple to implement, as it does not possess the evolutionary operator. Equation (7) is the cost function used to determine the optimum excitation amplitude distribution of the array. A uniform linear array (ULA) of $N = 11$ elements is considered, having the inter-element spacing of $d = \lambda/2$. All elements have the same phase to radiate in the broadside direction (90°). The desired patterns area 40° and 60° sector flat-top

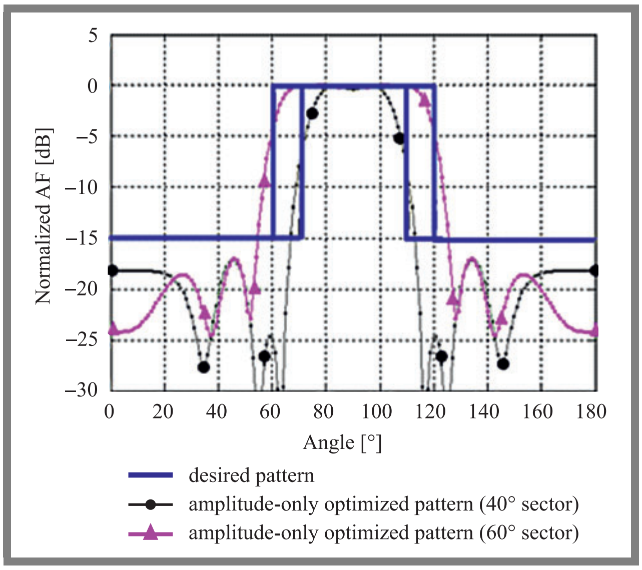

Fig. 6. 40° and 60° flat-top sector beams by amplitude-only PSO optimized array ($N = 11$).

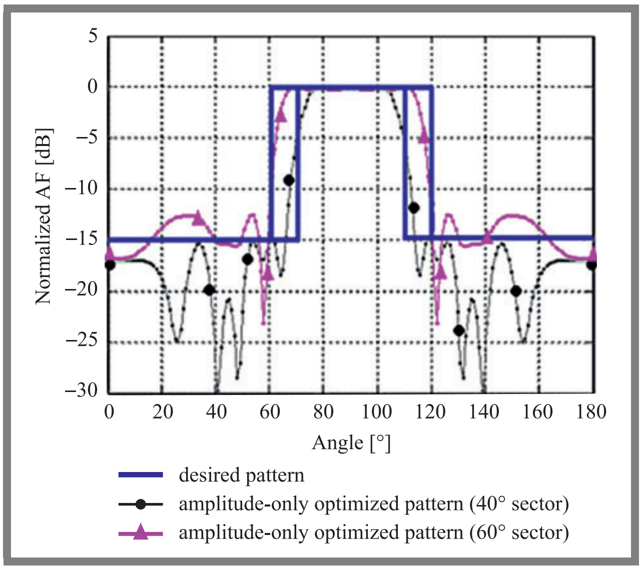

Fig. 7. 40° and 60° flat-top sector beams by amplitude-only PSO optimized array ($N = 20$).

beam generation having a maximum SLL of -15 dB. To generate such desired pattern using the given array, Eqs. (6) and (7) are used to obtain the minimum value of the cost function.

The simulated radiation pattern using PSO for the amplitude optimized array of 11 elements ($N = 11$) for 40° and 60° sector beam patterns are presented in Fig. 6.

The 40° and 60° flat-top sector beams by amplitude-only PSO optimized array for $N = 20$ are shown in Fig. 7.

The variation of PSO optimized cost values with number of iteration corresponding to Figs. 6 and 7 are plotted in Fig. 8.

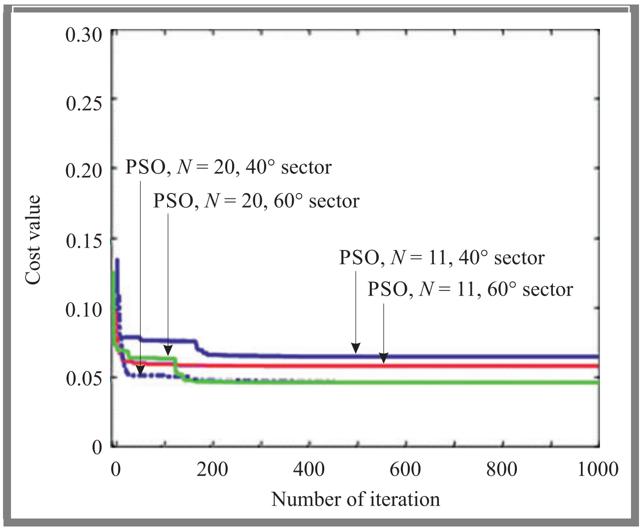

Fig. 8. Cost values for PSO amplitude-only optimized arrays.

4.4. Flat-top Beamforming by Phase-only Optimization Using RGA and PSO

In phase-only synthesis, design of an antenna array for generation of sector pattern is based on finding a common phase distribution of the array elements when the feeding current amplitude is fixed and equal value for all elements. Phase distribution can be determined by optimization of excitation current phase. RGA is applied to determine the phase distribution of each element in the array to generate a sector flat top beam pattern. Here, two ULAs of $N = 11$ and $N = 20$ are considered, which are placed along y-axis with half-wavelength array spacing. The desired pattern is a 60° sector flat top beam and SLL is -15 dB. Now a different approach is considered to generate such a desired radiation pattern using the given array by controlling the phase of excitation current while keeping a fixed excitation current amplitude. To determine the phase distribution of the array, phase-only optimization is performed using RGA on Eqs. (6) and (7) to identify the best pattern which will produce the desired pattern. Results for the phase-only RGA-optimized flat-top beam and the phase-only PSO-optimized flat-top beam are compared in Figs. 9 and 10.

The variations in RGA- and PSO-optimized cost values, observed with the increasing number of iterations corresponding to Figs. 9 and 10, are plotted in Fig. 11.

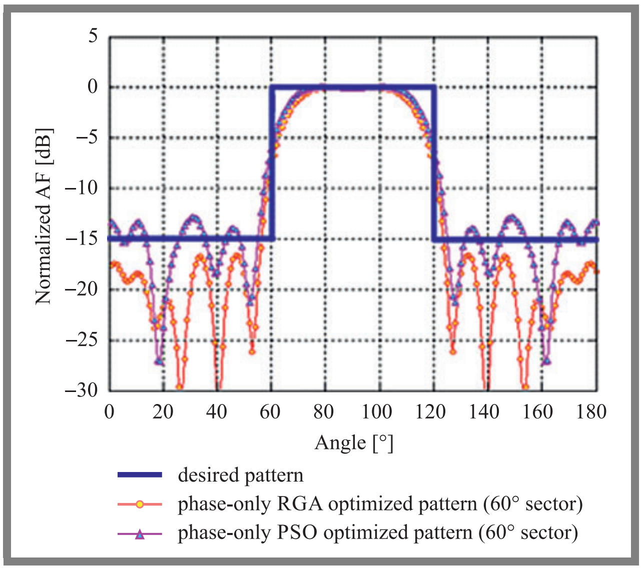

Fig. 9. 60° sector beam achieved by phase-only RGA and PSO optimized arrays ($N = 11$).

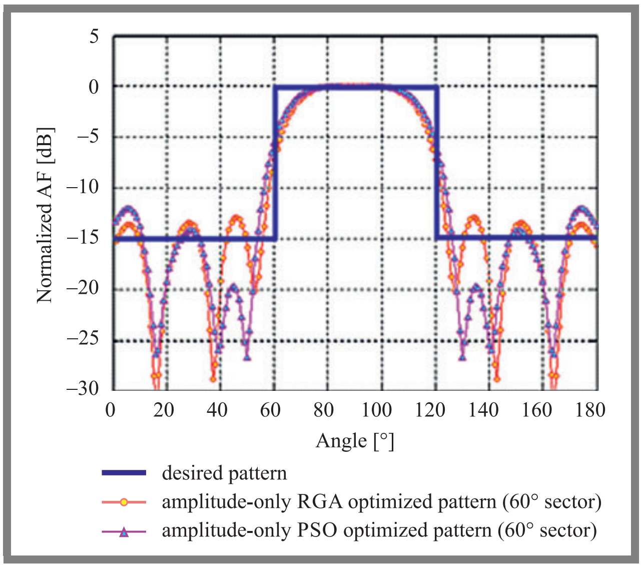

Fig. 10. 60° sector beam achieved by phase-only RGA and PSO optimized arrays ($N = 20$).

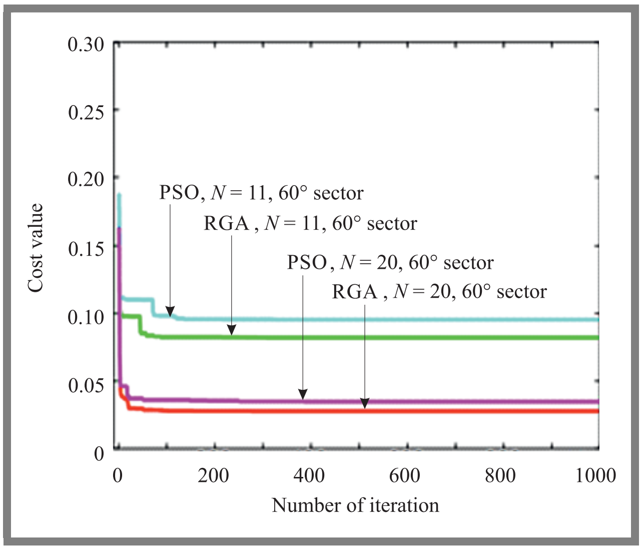

Fig. 11. Cost values for RGA and PSO phase-only optimized arrays.

Tab. 1. Phase-only optimization weights for flat-top beam formation using RGA and PSO.

Antenna elements	Sector area	Weights (RGA) phase-only	Weights (PSO) phase-only
$N = 11$	40°	1.88	1.50
		−1.75	−1.15
		1.53	2.50
		−1.76	−1.25
		1.14	2.05
		−1.24	−1.10
		1.38	2.40
		−1.07	−0.85
		1.65	1.31
		−1.36	0.53
		1.73	2.10
$N = 20$	60°	0.32	1.03
		2.98	−3.19
		−1.15	−0.64
		2.59	2.62
		−0.62	−0.55
		1.46	2.15
		0.94	0.14
		2.99	2.73
		0.96	−1.51
		−2.98	−2.76
		−0.61	−0.21
		2.99	−3.12
		0.24	−1.25
		−2.76	−2.97
		0.58	−0.36
		2.95	2.02
		−1.36	−1.87
		−1.69	−1.05
		−0.75	1.03
		0.59	−1.95

Tab. 2. Amplitude-only optimization weights for flat-top beam formation using RGA and PSO.

Antenna elements	Sector area	Weights (RGA) phase-only	Weights (PSO) phase-only
$N = 11$	40°	−0.15	−0.17
		−0.21	−0.19
		0.03	0.11
		0.35	0.37
		0.85	0.77
		0.91	0.90
		0.77	0.68
		0.45	0.28
		0.01	0.11
		0.30	−0.17
		0.20	0.04
	60°	0.60	0.38
		0.95	0.81
		0.70	0.72
		0.04	0.12
		−0.30	−0.30
		−0.08	−0.14
		0.05	0.14
		0.20	0.12
		−0.15	−0.15
		0.00	0.02
		0.01	0.03
$N = 20$	40°	0.01	0.02
		0.02	0.09
		−0.10	−0.11
		0.01	0.03
		0.03	0.02
		−0.15	−0.13
		−0.23	−0.22
		0.02	0.04
		0.35	0.37
		0.75	0.68
		0.95	0.92
		0.78	0.95
		0.40	0.41
		0.01	0.02
		−0.30	−0.31
		0.01	−0.05
		0.04	0.06
		0.17	0.15
		0.08	0.09
		−0.08	−0.11
	60°	0.06	0.01
		0.07	0.09
		−0.06	−0.11
		0.05	0.09
		0.09	0.10
		0.07	0.09
		−0.29	−0.36
		0.16	0.18
		0.65	0.75
		0.99	0.97
		0.79	0.85
		0.04	0.04
		−0.25	−0.26
		−0.12	−0.12
		0.08	0.09
		0.05	0.07
		−0.09	−0.10
		−0.08	−0.08
		0.03	0.04
		−0.03	0.02

In the case of amplitude weight optimization, the excitation phase of each element is kept the same and the initial population is made up of random values whose maximum and minimum levels are restricted by the corresponding maximum and minimum values considered in the simulation. The other array synthesis method uses the phase-only optimization technique in which the excitation phase varies and amplitude is fixed at the unity level for all the elements.

The values of phase-only optimization weights using RGA and PSO are presented in Tab. 1.

The values of amplitude-only optimization weights using RGA and PSO are presented in Tab. 2.

5. Performance Comparison

The best cost values (the cost value at 1,000 iterations) for RGA and PSO optimizations are compared in Table 3.

Two ULAs with $N = 11$ and $N = 20$ are considered for synthesis purposes. Various outcomes of amplitude-only and phase-only optimized radiation patterns are presented in Tab. 4.

Tab. 3. Best cost values for RGA and PSO optimizations.

Optimization methods	Parameters	Best cost value	Computation time
RGA amplitude-only	$N = 11, 40°$	0.074	937.7 s
	$N = 11, 60°$	0.048	
	$N = 20, 40°$	0.068	1846.3 s
	$N = 20, 60°$	0.058	
PSO amplitude-only	$N = 11, 40°$	0.068	734.9 s
	$N = 11, 60°$	0.060	
	$N = 20, 40°$	0.048	1491.1s
	$N = 20, 60°$	0.047	
RGA phase-only	$N = 11, 60°$	0.080	899.2 s
	$N = 20, 60°$	0.030	1763.6 s
PSO phase-only	$N = 11, 60°$	0.092	719.4 s
	$N = 20, 60°$	0.035	1483.3 s

6. Conclusion

While generating the desired flat-top sector radiation pattern by using the RGA optimization technique, a large population size and a large number of iterations are required in order to reach an acceptable value. Both RGA and PSO optimizations show better performance in flat-top sector beam formation in cellular networks, but the performance of PSO is better than that of RGA-based optimization. The deployment of PSO for flat-top beam generation is easier than in the case of RGA, and the computation time is also lower in PSO than in RGA. The performance of PSO is better than that of RGA if the flat-top sector beam is generated with the use of a large array. Application of these methods in multiple-beam arrays for flat-top sector beam formation in cellular networks may be the focal point of future studies.

Tab. 4. Performance comparison of amplitude-only and phase-only optimized array using RGA and PSO for a flat-top 60° sector.

Antenna elements	Parameters	Desired pattern	RGA amplitude-only optimized	PSO amplitude-only optimized	RGA phase-only optimized	PSO phase-only optimized
$N = 11$	Max. SLL [dB]	-15	-12.75	-17.18	-16.45	-13.83
	HPBW [°]	60	52	54	51	52
	Max. ripple [dB]	0.0	0.0	0.03	0.0	0.03
$N = 20$	Max SLL [dB]	-15	-14	-13.76	-13.87	-12.52
	HPBW [°]	60	53	56	50	52
	Max. ripple [dB]	0.0	0	0.04	0	0.04

Tab. 5. Performance of optimization methods used for flat-top beam formation in a cellular network.

Parameter	Amplitude-only optimization		Phase-only optimization	
	RGA	PSO	RGA	PSO
Implementation for flat-top beam generation	More difficult	Less effort	More difficult	Less effort
Ripple of flat-top beam	Almost zero	Very low but not almost zero like RGA	Almost zero	Very low but not almost zero like RGA
Coverage of desired sector by HPBW	Not good	Better than RGA	Not good	Better than RGA
Spillover of beam to the neighboring sectors (beyond coverage area and below -10 dB level)	Lesser than PSO	Low	Lesser than PSO	Low
Performance for a large array	Good	Better than RGA	Good	Better than RGA
Performance for a small array	Good	Good	Good	Good
Simulation time	High	Low	High	Low

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