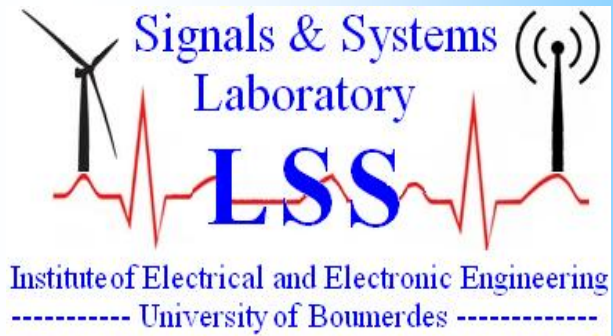


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Concentric Ring Arrays Optimization Using the Spiral Inspired Technique

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Abstract: In this work, concentric ring Arrays (CRA) with non-uniform excitation are investigated, with the objective being to minimize the Sidelobe Level (SLL) for the array and keep the Directivity within an acceptable value. The optimization technique to be used to reach this objective is the spiral inspired optimization technique.. First, the technique is used to minimize the SLL only. Next the array factor is optimized for Directivity only. Then, the excitation is varied for both SLL and Directivity to be optimized. The results show significant improvements with respect to the uniform case, especially for SLL reduction, with different levels of success depending on the employed optimization technique, fitness function, varied parameters, and array size.

Keywords: Concentric ring arrays, optimization, the spiral optimization method, sidelobe level, directivity.

1. INTRODUCTION

Wireless communication has become imperative and essential in our everyday life. An important contribution to the development of this technology is due to the advances in antenna design that made possible the implementation of highly efficient and compact wireless devices. The antenna is one of the most critical components in a communication system. It is the transitional structure between the transmission line and free space through which the electromagnetic waves travel. In other words it is the system that collects and converts the radio waves into electrical signals in receiving mode. The opposite is done when the antenna is used in a transmitter system. The quality of the antenna and its properties affect significantly the overall performance of a wireless communication system. For this reason, engineering has demonstrated great interest for antennas with the objective to adapt the conception to many applications by improving the characteristics of the antennas like Directivity, Sidelobe Level (SLL), and/or physical layout such that it suits the desired application [1-3].

It has been devised that multiple antennas can be combined to co-operate, resulting in an antenna array structure that can achieve a better performance along with a more adjustable radiation pattern that can be modified to meet the specifications thanks to the various geometries the array can take, and to the several possible ways to feed its individual elements. Many array geometries were employed in practice, from simple configurations with a few elements, to the more complex arrays having a large number of elements such as planar and conformal arrays [4-41].

An important class of arrays is the ring array that is used in various applications including mobile communications and radar due to its useful geometry and angular symmetry [11-13]. Another version of this array is the concentric ring Array (CRA) which is the one investigated in this work. It consists of elements arranged in multiple concentric rings that result in an antenna with very low SLL. This antenna can be optimized further as it has been done in several works using a variety of approaches and different optimization techniques [14-31].

In many applications, it is desired to design an antenna with a low SLL in order minimize interference. However, reducing the sidelobes generally results in decreasing Directivity, which is needed to be high in order to increase power efficiency and avoid useless electromagnetic pollution.

Optimization is extensively used in several fields of science and engineering to solve various problems, especially with the advent of modern global non-classical techniques that handle non-differentiable and non-linear complex functions, by exploiting the processing power of the quickly evolving computers. Various optimization techniques have been used in the field of electromagnetism, Genetic Algorithms (GA)[13], Differential Evolution (DE)[20], and Particle Swarm

Optimization (PSO) [12,14], that belong to the class of evolutionary techniques inspired from nature. Other recent techniques have also been employed in antenna design such as the Taguchi method [40-42], which is based on the concept of fractional factorial design, and makes use of Orthogonal Arrays (OAs) that significantly reduce the number of iterations needed in the optimization process. The Galaxy-based Search Algorithm (GbSA) is another recently developed nature-inspired metaheuristic technique that mimics the behavior of spiral galaxies when searching its surroundings [45].

In this work, The spiral optimization method is used to optimize Concentric Ring Arrays to achieve a better performance both in terms of SLL and Directivity, through the use of non-uniform excitation in amplitude and phase of the array elements, Several fitness functions are used with the spiral algorithm to reach the objectives. The results are interesting and can be exploited in communication systems.

2. PROBLEM FORMULATION

The array factor of a uniformly spaced concentric circular array as shown in Fig. 1 is given as:

$$AF(\theta, \varphi) = \sum_{m=1}^M \sum_{n=1}^{N_m} I_{mn} \exp(j[ka_m \sin \theta \cos(\varphi - \varphi_{mn}) + \alpha_{mn}]) \quad (1)$$

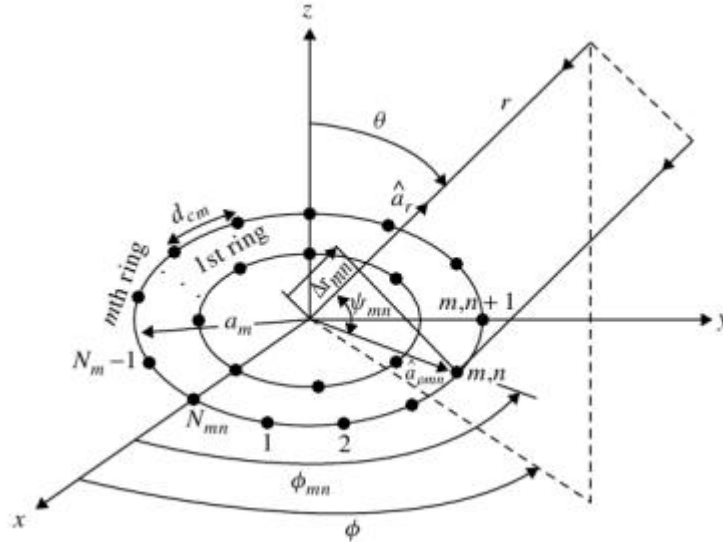


Fig. 1 Geometry of a uniform concentric circular array

Where

$$ka_m = \frac{2\pi}{\lambda} a_m = \sum_{n=1}^{N_m} d_{nm} \quad (2)$$

$$\varphi_{mn} = \frac{2\pi \sum_{i=1}^n d_{em}}{ka_m} = \frac{2\pi(n-1)}{N_m} \quad (3)$$

$$\alpha_{mn} = -ka_m \sin \theta_0 \cos(\varphi_0 - \varphi_{mn}) \quad (4)$$

If the UCCA has a center element, then the array factor is given as:

$$AF(\theta, \varphi) = I_{center} + \sum_{m=1}^M \sum_{n=1}^{N_m} I_{mn} \exp(j[ka_m \sin \theta \cos(\varphi - \varphi_{mn}) + \alpha_{mn}]) \quad (5)$$

The simulated array throughout this part is a three ring array having 6, 12, and 18 elements in the first, second, and third ring respectively. The elements are uniformly spaced along the rings with angular positions given by equation (3). The radii in wavelengths are 0.5, 1, and 1.5. This array geometry ensures an inter-element spacing between two adjacent elements that is greater or approximately equal to half of the wavelength. The array also has a center element. Therefore the array has a total number of 37 elements. The array characteristics are summarized in table 1.

Table 1 Dimensions of the 3-ring UCCA

Ring Number	Ring Radii a_m in wavelengths	Number of elements N_m	φ_{mn} in degrees for $n=1$ to N_m
1	0.55	6	0 60 120 180 240 300
2	1.05	12	0 30 60 90 120 150 180 210 240 270 300 330
3	1.6	18	0 20 40 60 80 100 120 140 160 180 200 220 240 260 280 300 320 340

3. THE SPIRAL INSPIRED OPTIMIZATION TECHNIQUE

Compared with traditional optimization techniques and other global optimizers, the spiral optimization method is easy to implement and very efficient in reaching optimum solutions. Spiral optimization method has been recently developed based the analogy to spiral phenomena [43]. Spiral Dynamics is a theory of human development. Spiral Dynamics argues that human nature is not fixed: humans are able, when forced by life conditions, to adapt to their environment by constructing new, more complex, conceptual models of the world that allow them to handle the new problems [44]. Each new model transcends and includes all previous models. Within the model, individuals and cultures do not fall clearly in any single category (color). Each person/culture embodies a mixture of the value patterns, with varying degrees of intensity in each. Spiral Dynamics claims not to be a linear or hierarchical model although this assertion has been contested. The colors act as reminders for the life conditions and alternate between cool and warm colors as a part of the model [44].

According to Spiral Dynamics, there are infinite stages of progress and regression over time, dependent upon the life circumstances of the person or culture, which are constantly in flux. Attaining higher stages of development is not synonymous with attaining a "better" or "more correct" values system. All stages co-exist in both healthy and unhealthy states, meaning any stage of development can lead to undesirable outcomes with respect to the health of the human and social environment [43].

The spiral phenomena occurring in nature are approximated to logarithmic spirals as in Fig. 1. Examples of natural spiral dynamics include whirling currents, low pressure fronts, nautilus shells and arms of spiral galaxies. Logarithmic spirals discrete processes to generate spirals that can form an effective behaviour in metaheuristics. A two-dimensional algorithm has been first proposed [43], and then, a more generalized n-dimensional version has been recently suggested [44].

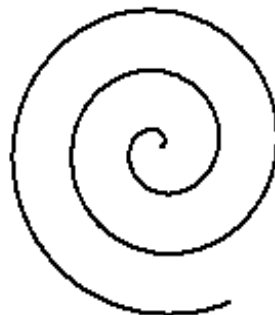


Fig. 1 Logarithmic spiral

Before presenting the n-dimensional spiral optimization algorithm, it is worth understanding the two dimensional optimization model as a basis for the n-dimensional version of the algorithm.

Two-dimensional spiral optimization

Rotating a point in a 2-dimensional orthogonal coordinate system (as shown in fig. 2) in the counter-clockwise direction around the origin by θ can be expressed as:

$$x' = R(\theta)x \tag{6}$$

Where

$$R_2(\theta) = \begin{bmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{bmatrix} \tag{7}$$

Hence, the two dimensional algorithm moves from one point to another as:

$$\begin{bmatrix} x_1(k+1) \\ x_2(k+1) \end{bmatrix} = rR_2(\theta) \begin{bmatrix} x_1(k) \\ x_2(k) \end{bmatrix} \tag{8}$$

Where

θ is the rotation angle around the origin ($0 \leq \theta \leq 2\pi$) and r is the convergence rate of distance between a point and the origin at each k ($0 < r < 1$).

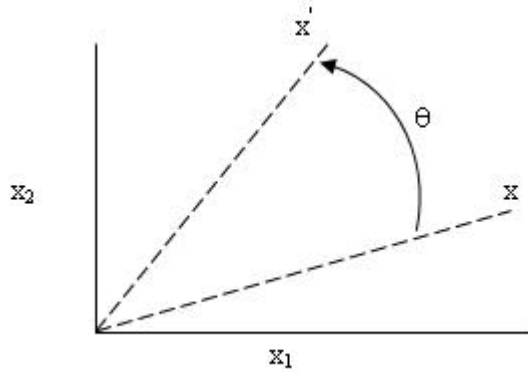


Fig. 2 Rotation in x_1 - x_2 plane

The spiral model presented earlier has a center only at the origin. Hence, it should be extended to have center at an arbitrary point x^* as:

$$x(k+1) = rR_2(\theta)x(k) - (rR_2(\theta) - I_2)x^* \tag{9}$$

This suggests the following optimization algorithm:

- ◆ **Preparation:** select the number of search points $m > 2$, the parameters θ and r and the maximum number of iterations k_{max} .
- ◆ **Initialization:** initialize randomly the points; $x_i(0) \ i=1..m$; in the feasible region and the center x^* as the point with the least fitness value.

- ◆ **Updating x_i :**

$$x_i(k+1) = rR_2(\theta)x_i(k) - (rR_2(\theta) - I_2)x^* \text{ for } i=1\dots m. \tag{10}$$

- ◆ **Updating x^* :** Select x^* as the point with the least fitness function in the updated set of points.
- ◆ **Check for termination criterion:** If $k=k_{max}$ then stop. Otherwise, start a new iteration.

n-dimensional spiral optimization

The extension of the two-dimensional optimization algorithm presented earlier is easy to do as one must understand how rotation in an n-dimensional space is done. Rotation in n-dimension is performed in the same way as the two-dimensional rotation taking two dimensions at a time. This is defined for dimensions i, j as:

4. RESULTS AND DISCUSSIONS

In this work, different strategies are considered. The main purpose is to design arrays that have the least possible sidelobe level and the highest possible directivity.

The treated array in this part is going to be the three ring array described previously. In this first part, three cases with different fitness functions are studied. First, the array is optimized for minimum SLL only. Then the parameters are varied to maximize Directivity only. In the third and last section of this part, both Directivity and SLL are optimized. Throughout these three sections, the varied parameters are excitation amplitude, and excitation phase of the array elements that are allowed to vary from 0 to 1 for the amplitude, and from 0 to 2π for the phase. These two parameters are varied separately.

The constraints on the lower and upper bounds of the amplitude search space are set to 0 and 1, respectively and 0 to 2π for the phase. Additional parameters of the algorithms are given with the obtained results. The programs used are all written in MATLAB. The different fitness functions used at each stage are described further.

The optimization algorithm generates individuals (amplitude excitations and phase perturbations of the antenna elements). The individuals are encoded in a vector of real numbers, that represents the amplitudes, and a vector of real numbers restrained on the range $(0,2\pi)$, that represents the phase perturbations of the antenna elements.

Parameter Variation for SLL Reduction With FNBW Restriction

In this part, the objective is to minimize the SLL while keeping the FNBW (First nulls beamwidth) under a certain given value. This is done to make sure the optimization does not result in an undesired distorted or flattened beam shape, especially since the array contains only three rings, resulting in few sidelobes. The fitness function is written as:

$$F_1 = \alpha \times SLL \tag{11}$$

Where

$$\alpha = 1 \quad \text{If } FNBW < FNBW_d$$

$$\alpha = 0 \quad \text{Otherwise}$$

$FNBW_d$ is the maximum allowed Beamwidth.

It is apparent from the fitness function that arrays resulting in a FNBW that is higher than the desired value are going to be discarded due to the coefficient α .

A. Excitation Amplitude Variation:

The optimization using the spiral algorithm with amplitude variation resulted in a reduction of the SLL to -28.154 dB with a decrease in Directivity to 15.748 dB. The obtained array factor for this simulation is shown in Fig. 4.

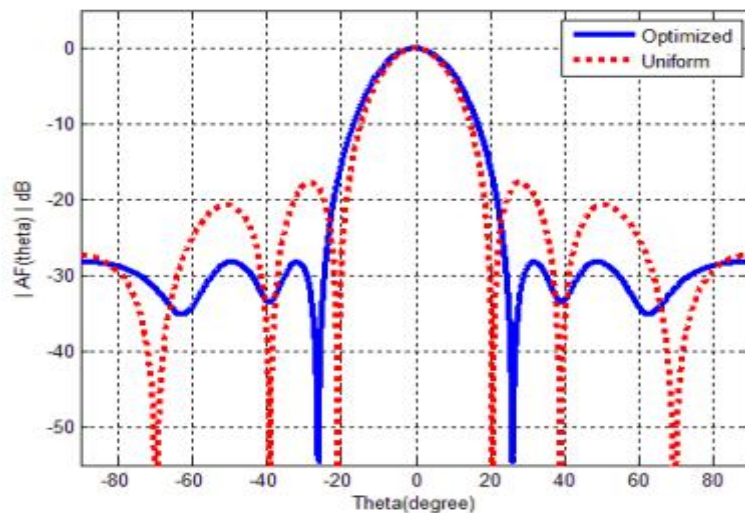


Fig. 4 The array factor optimized array for SLL using amplitude variation

B. Phase Excitation Variation:

Using phase variation this time, the results obtained with the Spiral were better as shown in Fig. 5 with a SLL reduced from -17.685 dB to -20.704 dB with Directivity decreased to 17.323 dB. However, in this case as well amplitude variation gave better results using the same technique.

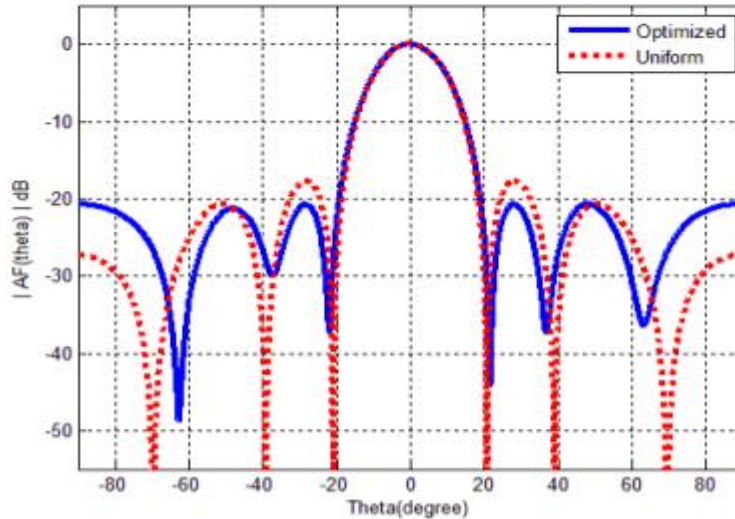


Fig. 5 The array factor optimized array for SLL using phase variation

Amplitude variation proved to be more effective with the minimum resulting SLL of -35.630 dB as compared to -26.656 dB with phase variation. The simulations resulted in a SLL reduction that caused a decrease in Directivity in all cases. Therefore, Directivity needs to be taken into account as well in the optimization.

Parameter Variation for Directivity Optimization

The fitness function in this part was merely taken to be the negative of Directivity in dB. The objective is to find an array with the best possible Directivity without taking into consideration the SLL. The fitness function is merely taken to be:

$$F_2 = -Directivity \tag{12}$$

A. Excitation Amplitude Variation

The Spiral optimization resulted in a slightly higher Directivity with 17.476 dB. Whereas the SLL increased a bit from -17.685 dB to -17.255 dB. The resulting array factor is shown in Fig. 6 where the second sidelobes appear attenuated compared to the uniform excitation.

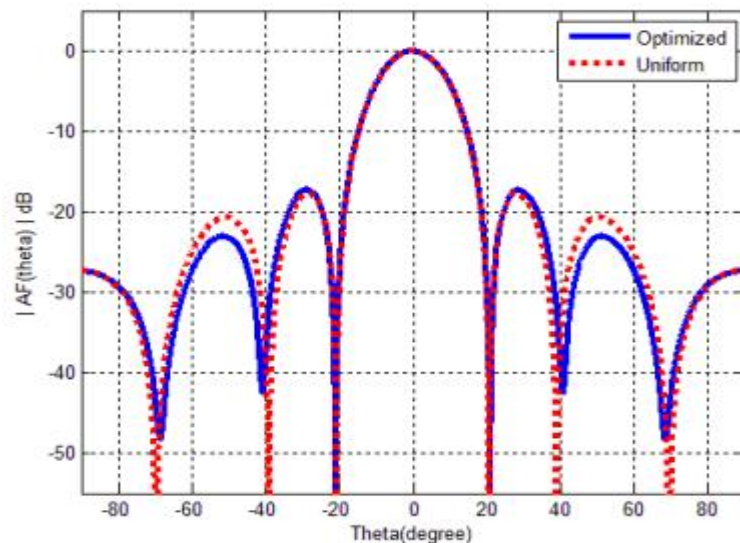


Fig. 6 The array factor optimized for DIR using amplitude variation

B. Excitation Phase Variation

The Spiral inspired algorithm was able to increase Directivity up to 17.466 dB which is slightly less than the one obtained with amplitude variation (17.476 dB). The SLL increased to -15.132 dB apparent at the first Sidelobe on the right side of the main beam as shown in Fig. 7.

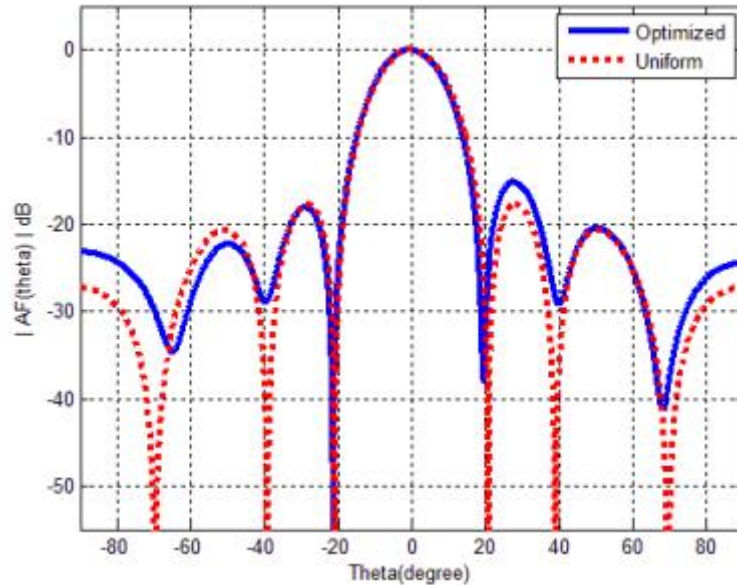


Fig. 7 The array factor optimized array for DIR using phase variation

When Directivity was used to select the fittest, the obtained values for the excitation amplitude and phase showed a low standard deviation. This means that the optimal excitations are very close to being uniform. Moreover, the obtained radiation patterns for most cases showed high similarity with the pattern of the uniform array, although the obtained arrays showed sometimes slightly sharper lobes which resulted in higher Directivity.

Parameter Variation for Both SLL and Directivity Optimization

The objective in this third section is to improve both SLL and Directivity, for this reason both attributes were included in the fitness function as:

$$F_3 = \alpha \times SLL - Directivity \tag{13}$$

With

$$\alpha = 1 \quad Directivity > Directivity_d$$

$$\alpha = 0 \quad \textit{Otherwise}$$

$Directivity_d$ is the minimum desired Directivity.

The above definition of the fitness function leads to the optimization of Directivity when it is lower than to the generated arrays with Directivity higher than the threshold are going to be optimized further.

A. Excitation Amplitude Variation

The Spiral optimization was successful in optimizing both Directivity with a reached value of 17.450 dB, and SLL which was reduced to -19.935 dB. The resulting array factor is shown in Fig. 8.

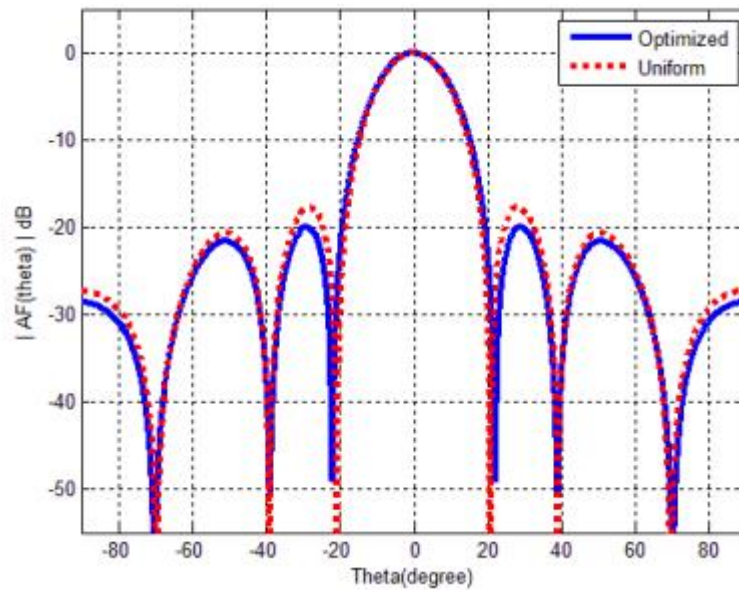


Fig. 8 The array factor optimized for DIR and SLL using amplitude variation

B. Excitation Phase Variation

The Spiral algorithm resulted in an improvement on both parameters with Directivity increasing to 17.450 dB, and SLL decreasing to -18.735 dB. The resulting array factor is shown in Fig. 9.

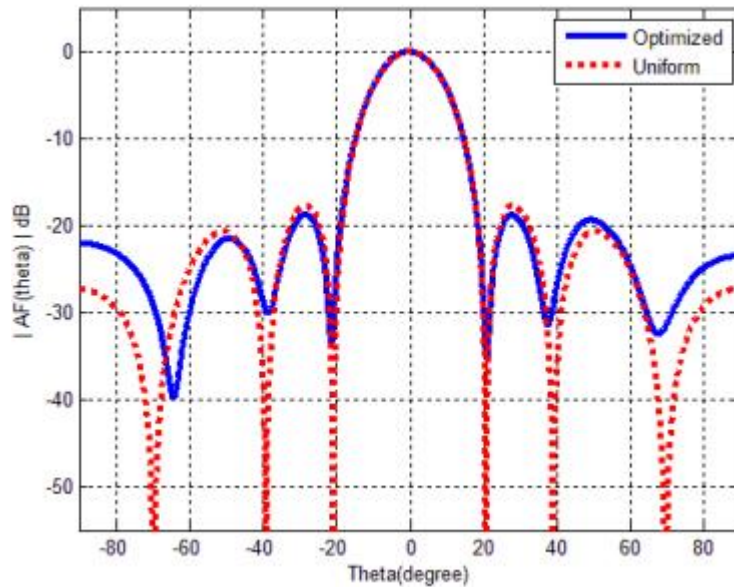


Fig. 9 The array factor optimized array for DIR and SLL using phase variation

Using the new fitness function involving both SLL and Directivity, both parameters were optimized, especially SLL that was reduced down to -19.935 dB with corresponding Directivity of 17.450 dB using the Spiral optimization technique. It is clear that the amount by which one parameter can be enhanced depends on the other parameter. So one needs to find the best compromise between them and this depends on the desired application, especially when using amplitude or phase variation. The approach of varying element position can be considered to attempt to refine the results. However it would result in a Non-Uniform CRA which is less flexible, although it could simplify the feeding network. Table 1 summarizes the obtained results

Table 2 Results of obtained SLL and DIR

Variation	SLL only		DIR only		SLL and DIR	
	SLL (dB)	DIR (dB)	SLL (dB)	DIR (dB)	SLL (dB)	DIR (dB)
Amplitude	-28.154	15.748	-17.255	17.476	-19.935	17.450
Phase	-20.704	17.323	-15.132	17.466	-18.735	17.450

5. CONCLUSIONS

This work presented the optimization of a Non-Uniformly excited Concentric Ring Antenna Arrays using the spiral inspired optimization technique. The varied parameters were excitation amplitude, and phase in a separate manner and then jointly. The objective was to minimize the SLL and keep the Directivity within a suitable level.

At start up, the array factor was optimized for SLL reduction by varying amplitude, then phase excitation of the array elements. This resulted in a significant decrease achieved. For the Directivity-only optimization, the obtained results show less significant improvement in directivity due to the fact that the uniform array is already known to possess a good directivity. The improved Directivity however, caused the SLL to increase. In the last step, both Directivity and SLL were included into a single fitness function with the purpose to optimize both attributes. The spiral inspired optimization technique yielded relatively fair results. The performance of the used optimizer was very encouraging; it is believed that it is possible to enhance this technique further to obtain better results in terms of both convergence and speed of convergence. The solution lies in the hybridization of the used technique with the classical local search methods as this can be a profitable approach to reach better optima. Another plan is to use the technique of solution or population doping which can help the algorithms converge more quickly.

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