Design of Multi-beam Circular Antenna Arrays using CORPS and Differential Evolution

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Abstract. An innovative way to analyze the design of beam-forming networks (BFN) for scannable multi-beam circular antenna arrays using the CORPS (Coherently Radiating Periodic Structures) concept is introduced. This design of CORPS-BFN considers the optimization of the complex inputs of the feeding network by using the Differential Evolution (DE) method. Simulation results for different configurations of CORPS-BFN for a scannable circular array are presented. The results shown in this paper illustrate certain interesting characteristics in the behavior of the array factor for the scannable circular array. The most significant aspect that is unique to this proposal is the simplification of the feeding network based on CORPS

Keywords: Coherently radiating periodic structures, circular antenna array, differential evolution method.

1. Introduction

The flexibility and re-configurability are two important features of the present and future antenna systems. These two properties could be very easily defined combining smartly different independent beams or signals of the same antenna system. These systems, which are capable of managing independently different beams, are usually referred to as multi-beam systems.

The CORPS [1]-[5] concept starts from the idea to reproduce the behavior of the human eye and to apply its detecting strategies to the antenna field. The main idea behind CORPS is to try to find solutions to the common trade-offs in antenna arrays systems design, such as angular resolution, signal-to-noise ratio, coupling and grating lobes. For instance, one of the most interesting procedures used by the human eye to obtain the information corresponding with every spot or pixel of the image is the fact that this information is received effectively for many cones thanks to the coherent coupling that exists between the photo-detectors. The procedure is performed by small chained chemical reactions firstly originated by the excitation of one of the photo-detectors. This coupling generates high overlapped radiation zones, making the human eye capable to generate simultaneously high directive beams very close in the angular space, obtaining an impressive resolution.

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In our case, it will introduce an innovative way to analyze the design of beam-forming networks (BFN) for scannable multi-beam circular antenna arrays using the CORPS concept. The main objective of this paper is to combine the technology based on CORPS to define the BFN and the Differential Evolution (DE) [6]-[11] method to look for optimal excitations, in order to generate a scannable multi-beam circular array. The contribution of this paper is to present a perspective of the design of CORPS-BFN considering scannable multi-beam circular arrays.

2. Behavior of the CORPS-BFN

A schematic representation of a CORPS-BFN of *n* inputs, *N* outputs and 3 layers is presented in Figure 1. As shown in Fig. 1, a CORPS-BFN is conformed by a mesh interconnected by means of Split (S)-nodes and Recombination (R)-nodes. The CORPS-BFN works as follows. The signal entered by one input port is divided in two and added with the arriving signals of the neighboring input ports. Following the path of each signal, we will find something like an inverted triangle which has the lower vertex at the input port. The opposite side of this vertex will define the output ports receiving some information from this input port, or in other words, the effective radiating area from which every input signal (or orthogonal beam) will be radiated. Since the isolation between the input ports is ensured and the spreading of the signal inside the structure is controlled, the CORPS-BFN is able to handle simultaneously several orthogonal beams without any problem. In the outermost branches, the inputs that are not used are finished with a matched load in order to avoid reflections.

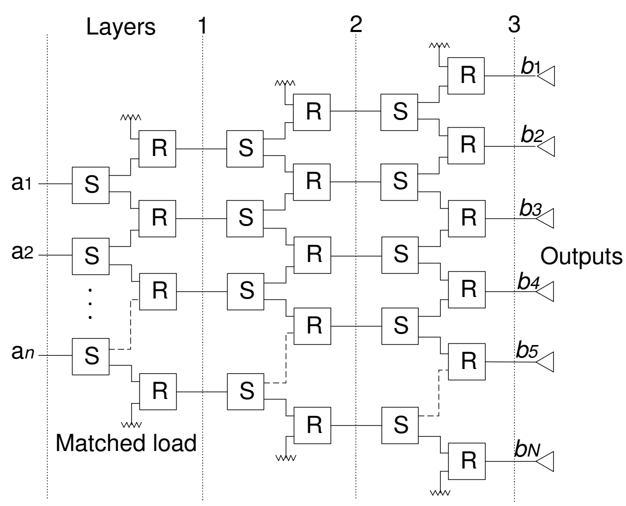


Figure 1. Schematic representation of a CORPS-BFN with S and R nodes

From [1] and [3] the Unitary Cell Scattering matrix that represents the behavior of an S-node could be extracted as follows:

$$[S]=\begin{bmatrix} 0 & j/\sqrt{2} & j/\sqrt{2} \\ j/\sqrt{2} & 0 & 0 \\ j/\sqrt{2} & 0 & 0 \end{bmatrix} \tag{1}$$

It is also shown in this paper that an S-node can act also like an R-node. In the same way, in order to evaluate the fields after an S-node or R-node the next expression can be used

$$V^{-} = S\ V^{+}. \tag{2}$$

In (2) *S* is the Scattering Matrix of an S-node and V^{+} is the Amplitude and Phase of the field at input ports of an S-node. Using (2) and the schematic representation of a CORPS-BFN (Fig. 1) it is possible to establish an iterative code (i.e. with MATLAB) that represents the propagation of signal throughout a general configured CORPS-BFN.

It is possible to establish different configurations for the CORPS-BFN with different number of inputs, outputs and layers. In this case, several orthogonal beams could be generated simultaneously by intercalating or interleaving the inputs of the CORPS-BFN, i.e., a group of different inputs will generate the beam # 1 and another group of inputs could generate the beam # 2. Following the philosophy of CORPS, each group of inputs must be established in a strategic way in order to have the capability to control electronically the corresponding beam pattern (over a scanning range) with a smaller number of complex inputs with respect to the number of antenna elements employed. Several configurations for the CORPS-BFN could be evaluated and studied. To set an example, the next configurations could be of interest.

1) For a system of 26 radiators and 25 input ports (i.e., a CORPS-BFN of one layer) two orthogonal beams could be generated simultaneously by intercalating the inputs of the CORPS-BFN, as shown in the Fig. 2. The interesting aspect of this case is that the group of 13 inputs (that generates the beam # 1) could control the 26 radiators of the array, and the remaining 12 (used for the beam # 2) could control to 24 of them.

2) For the system of 26 radiators, we could use a CORPS-BFN of two layers with 24 input ports. Two orthogonal beams could be generated simultaneously by intercalating the inputs of the CORPS-BFN by pairs as illustrated in the Figure 3. In the case of the beam # 1, 12 of 24 input ports could control 24 radiators of the array. For the beam # 2, the remaining 12 input ports control to 24 of 26 radiators.

For a set of complex inputs [**a**] feeding the CORPS-BFN, as shown in Fig. 1, the characteristics of Directivity (*D*) and Side Lobe Level (*SLL*) for each beam pattern can be calculated using the equation of the array factor as [12], [8]

$$AF(\phi,\mathbf{a}) = \sum_{n=1}^{N} b_n \exp\left[jkr\left(\cos\left(\phi-\Delta\phi_n\right)-\cos\left(\phi_0-\Delta\phi_n\right)\right)\right] \tag{3}$$

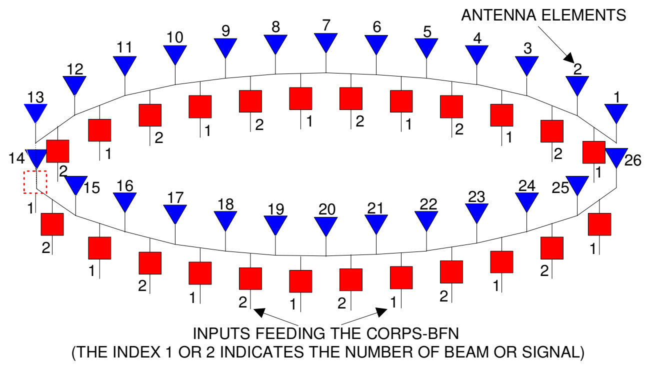


Figure 2. System of 26 radiators and 25 input ports.

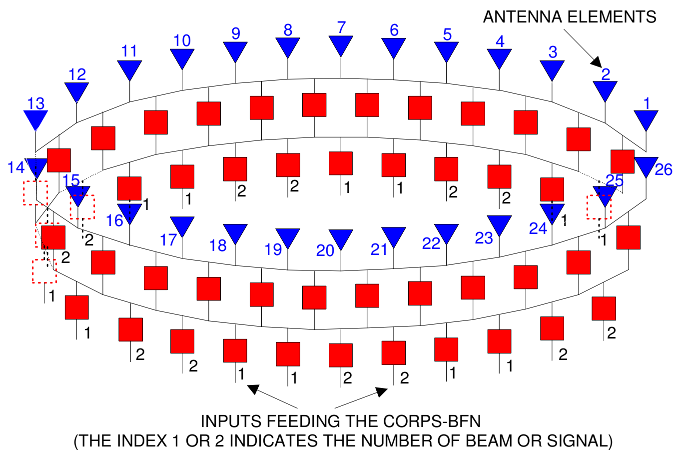


Figure 3. System of 26 radiators and 24 input ports

where b_i represents the complex excitation of the ith antenna element of the array, $\Delta\phi_n=2\pi(n-1)/N$ for $n=1,2, \ldots, N$ is the angular position of the nth element on the x-y plane, $kr=Nd$, i.e., $r=Nd\lambda/2\pi$, ϕ_0 is the direction of maximum radiation and ϕ is the angle of incidence of the plane wave.

In order to include the effect of mutual coupling for the circular array, the method of induced electro-motive force (EMF) [12] for thin and finite dipoles is considered. In this case, it is considered the side-by-side configuration and dipole lengths $l=\lambda/2$.

Next, the objective function and the evolutionary optimization technique used to optimize the complex inputs of the CORPS-BFN are described.

3. Objective function and the technique used

One of the latest evolutionary computational techniques is the DE algorithm, in which some individuals are randomly extracted from the solution population and geometrically manipulated [6], avoiding the destructive mutation of Genetic Algorithms (GA) [13]-[18]. The main advantage of DE is its low computation time compared to that of GA. DE is an alternative to speed up the GA.

First an initial population is formed in which the individuals have a Gaussian distribution. For each vector or solution (amplitude and phase of the complex inputs feeding the CORPS-BFN) of the population (N_p) X_i, i=1, 2, …, N_p of the G_{th} iteration, two new trial members, ε_{t1} and ε_{t2}, are generated as follows:

$$\varepsilon_{t1} = \varepsilon_{r1}^{(G)} + F\left(X_i^{(G)} - \varepsilon_{r2}^{(G)} \right) \tag{4}$$

$$\varepsilon_{t2} = \varepsilon_{r1}^{(G)} + F\left(X_i^{(G)} - \varepsilon_{r3}^{(G)} \right) \tag{5}$$

where $F \in [0, 2]$ is a real constant factor range suggested in [9], which controls the amplification of the differential variation, and the integers r_1, r_2, $r_3 \in [1, N_p]$ are randomly chosen such that $r_1 \neq r_2 \neq r_3$.

In this case each individual generates an array factor of certain characteristics of *SLL* and *D*. Therefore, the design problem is formulated as minimize the next objective function

$$Obj\text{-}fun=(|AF(\phi_{SLL}, \mathbf{a})| \;/\; max|AF(\phi, \mathbf{a})|)+(1/D(\phi, \mathbf{a})) \tag{6}$$

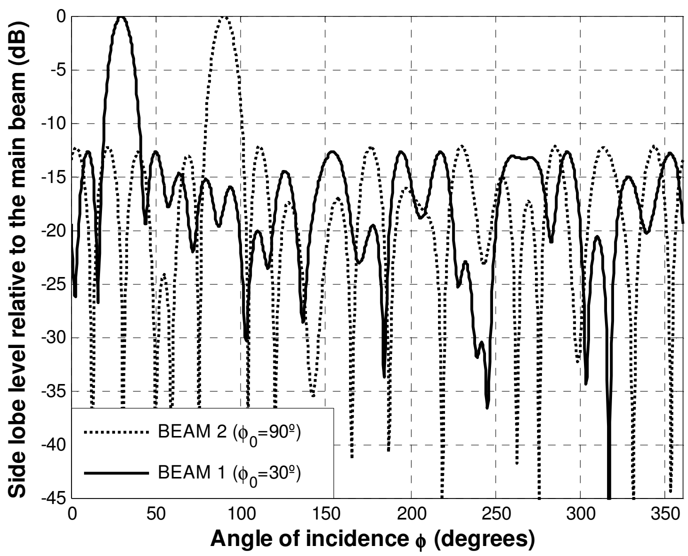
where ϕ_{SLL} is the angle where the maximum side lobe is attained. In this case both objectives (*SLL* and *D*) are uniformly weighted in the cost function.

After the objective function evaluation, the best solution in the set $\{\varepsilon_i, \varepsilon_{t1}, \varepsilon_{t2}\}$ becomes the new member for the next iteration, ε_i^{G+1}. Some individuals in the new population occasionally generate array factors which are not physically realizable, and an adjusting process is needed [7]. Taking the best solution into account, a termination criterion is proposed by fixing a number of iterations without an improvement over this solution. In [7], it is explained the procedure of DE in detail.

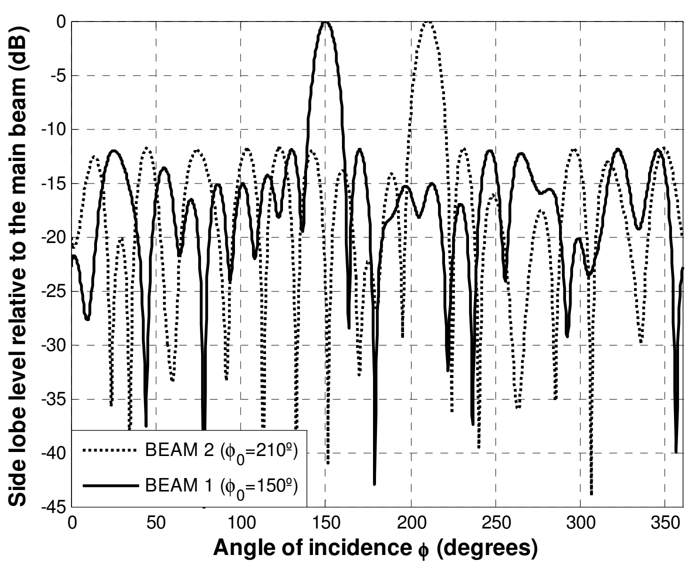
The simulation results of using this evolutionary algorithm for the optimization of the complex inputs of the feeding network are presented in the next section.

4. Simulation results

The DE algorithm was implemented to study the behavior of the array factor generated by the configurations shown in the Section II. The experiments parameters were set as follows: maximum number of generations r_{max}=500, population size N_p=200, and F=0.5 [6]. Figures 4-5 illustrate the behavior of the array factor generated by the configurations shown in Fig. 2 and Fig. 3.

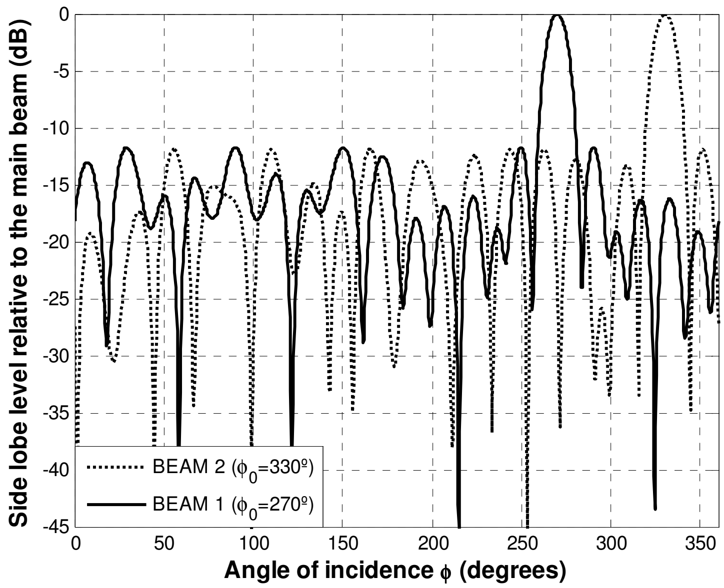


a)



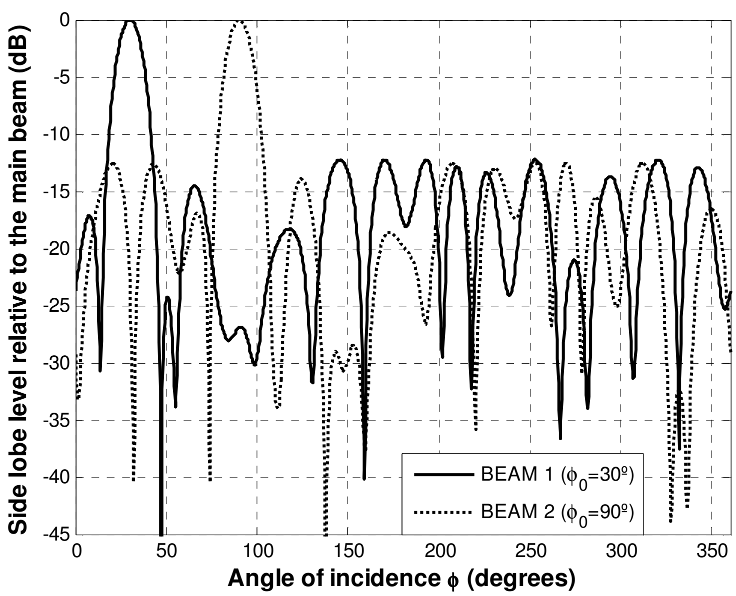
b)

Figure 4. Array factor generated by the configuration 1 shown in Fig. 2, a) ϕ_0=30º for beam # 1 and ϕ_0=90º for beam # 2, b) ϕ_0=150º for beam # 1 and ϕ_0=210º for beam # 2, c) ϕ_0=270º for beam # 1 and ϕ_0 =330º for beam # 2.



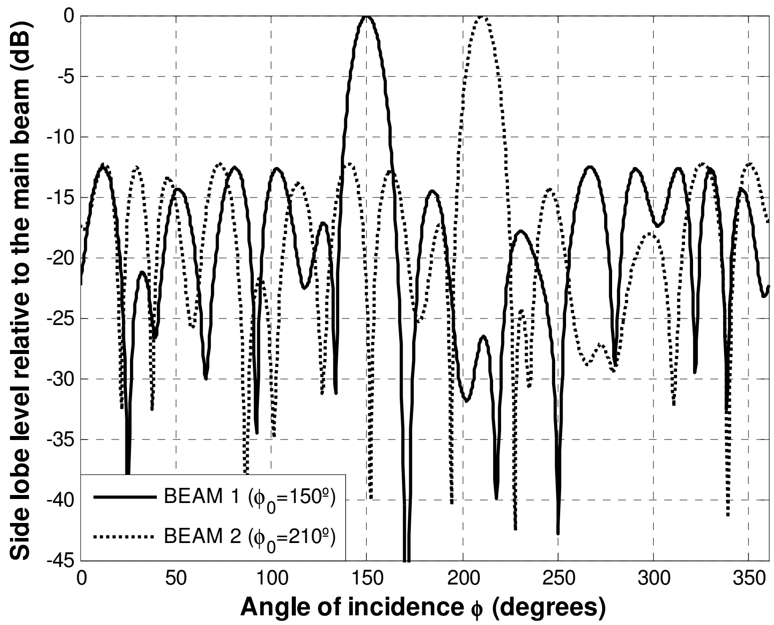
c)

Figure 4. (continued)

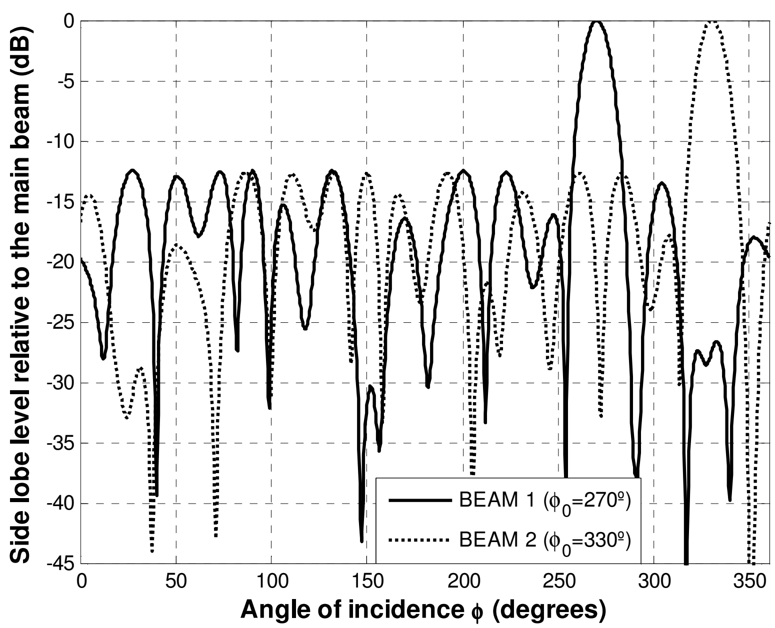


a)

Figure 5. Array factor generated by the configuration 2 illustrated in the Figure 3, a) ϕ_0 =30º for beam # 1 and ϕ_0 =90º for beam # 2, b) ϕ_0 =150º for beam # 1 and ϕ_0 =210º for beam # 2, c) ϕ_0 =270º for beam # 1 and ϕ_0 =330º for beam # 2.



b)



c)

Figure 5. (continued)

If it is considered the beam 1 from the Fig. 4, it is obtained a *SLL*=-12.66 dB and *D*=13.62 dB for ϕ_0=30º, *SLL*=-11.95 dB and *D*=13.55 dB for ϕ_0=150º, and *SLL*=-11.71 dB and *D*=13.54 dB for ϕ_0=270º. For the beam 2, it is obtained a *SLL*=-12.21 dB and *D*=13.57 dB for ϕ_0=90º, *SLL*=-11.8 dB and *D*=13.4 dB for ϕ_0=210º, and *SLL*=-11.92 dB and *D*=13.51 dB for ϕ_0=330º. Considering the beam 1 from the Fig. 5, it is obtained a *SLL*=-12.22 dB and *D*=13.44 dB for ϕ_0=30º, *SLL*=-12.58 dB *D*=13.44 dB for ϕ_0=150º, and *SLL*=-12.47 dB and *D*=13.49 dB for ϕ_0=270º. For the beam 2, it is obtained a *SLL*=-12.53 dB and *D*=13.49 dB for ϕ_0=90º, *SLL*=-12.23 dB *D*=13.46 dB for ϕ_0=210º, and *SLL*=-12.63 dB and *D*=13.45 dB for ϕ_0 =330º.

If these results are compared with respect to the uniform excitation case with conventional progressive phase excitation for *N*=26 (*SLL*=-6.92, dB and *D*=13.21 dB), we have a very significant performance improvement in terms of the side lobe level and a very significant simplification of the feeding network, i.e., the interesting aspect is that these two scannable beams are generated with *N*/2 complex inputs.

In this paper the idea was to demonstrate the possibilities of simplifying the feeding network for multi-beam circular antenna arrays by using CORPS. Although it was presented the case to generate two scannable beams, it is perfectly possible to define independently the number of input ports (defined by the number of orthogonal beams to be used simultaneously) and the number of radiating elements.

5. Conclusions

The design of beam-forming networks for scannable multi-beam circular antenna arrays using CORPS has been presented. Simulation results reveal that the design of CORPS-BFN optimizing the complex inputs with the DE algorithm could generate scannable multiple beams with a significant simplification of the feeding network. The behavior of the array factor for different configurations of CORPS-BFN for a scannable multibeam circular array was studied and analyzed.

Future work will deal with the design of CORPS-BFN for scannable multibeam planar (bi-dimensional) arrays and the study of new structures for designing BFN for multiple beam antenna systems.

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