On the Design of Direct Radiating Antenna Arrays with Reduced Number of Controls for Satellite Communications

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Abstract. Our activity has to do with the design of Direct Radiating Arrays (DRA) for satellite communications. The objective is to have a reduced number of controls in order to minimize the manufacturing and operating complexity. The DRAs will create a set of simultaneously overlapped multi-beams in the frequency range of 20 GHz and will satisfy certain specifications (End of Coverage (EOC) gain, grating and side lobe levels). Radio-Communications Laboratory (RCL) shall consider the DRA design and shall mainly optimize the geometry of the array and develop the appropriate software tool. The design methods which are going to be used are the Fractal Technique and the Orthogonal Method(OM) in conjunction with the Orthogonal Perturbation Method (OPM). Some preliminary examples are presented and show the effectiveness of the design methods.

Keywords: Array Synthesis, Direct Radiating Arrays (DRA), Fractal Antennas, Orthogonal Method (OM).

1 Introduction

Satellite services in the near future are expected to be demanding in terms of data rate. In order to satisfy more advanced characteristics, the next generation of satellites will use new resources (Ka and Q/V bands). Most of the satellites offer an overlapped beam spot coverage with high gain performance to ensure high figures in terms of EIRP and G/T. This approach could relax the requirements for the earth stations. This is a fundamental aspect especially for mobile applications where it is important to reduce the size of the antenna terminals.

In order to overcome the problems, which are met in Focal Array Fed Reflectors, [1], such as the reflector deployment, the feed cluster/reflector alignment and the capability to reconfigure the beam spot coverage, innovative antenna configurations are investigated. Such an antenna configuration is the Direct Radiating Array (DRA), [2]. Unfortunately, a canonical approach for the DRA design foresees a very large

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number of controls. A drastic reduction of this number is possible by using appropriate sub-arrays or horn apertures with a dimension figure of several wavelengths. The position of the above can be optimized to create lattices that produce Sparse or Thinned arrays.

The satellite is planned to have a European coverage of 19 beams and the technical requirements are given in Table 1.

Table 1. Technical requirements of the DRA

Technical requirement	**Value**
Spots number	19
Spot diameter	0.65°
Inter - Spot distance (spot spacing)	0.56°
Tx band	19.7 – 20.2 GHz
Polarization f1/f4 beams	RHCP
Polarization f2/f3 beams	LHCP
Frequency f1/f2 beams	19.7 – 19.95 GHz
Frequency f3/f4 beams	19.95 – 20.2 GHz
Single Entry C/I	> 20dB
Aggregate C/I	> 14dB
D_{EOC}	> 43.8dBi
GL on earth (out of coverage)	< -20dB
GL out of the earth	< -10dB
Maximum Array Diameter	1.8m

The methods that are used to reach a suitable solution for the afore-mentioned problem are a) the Orthogonal, [3], in conjunction with Orthogonal Perturbation Method (OPM), [4], and b) the Fractal Array Technique, [5], [6].

In the first approach we perturb the element positions by combining an iterative technique with the orthogonal method, (OM). The final position of the elements of the array is found from the last iteration where the desired approximation of the pattern is obtained. It must be noticed that in the project frame, OPM is also going to be used for the optimization of the arrays designed by the other partners Consorzio Nazionale Interuniversitario per le Telecomunicazioni(CNIT).

In the fractal technique, a planar array of four elements is used as generator and the entire system is produced by four steps of development. Optimum performance is obtained by four means: a) the suitable choice of the scaling factor value, b) the thinning of the array, c) the array feeding via one step of quantization and d) the perturbation of the element positions. The number of control points is reduced by grouping the elements in uniformly excited blocks.

Using the synthesis techniques of CNIT and RCL, and after a final optimization, the most effective layout will be manufactured (Space Engineering) for the demonstrator.

In the following sections the description and some representative examples are given for both approaches.

2 Formulation

2.1 The Orthogonal Perturbation Method

An array is a linear system composed by N element radiators. The field of the array is a vector in a vector space consisting of all the possible fields that this system can produce. After defining a norm, one can use whatever set of N linearly independent and normalized fields to define this space. The total electric field is the summation of the element fields, which can be expressed in the following matrix form:

$$\vec{\boldsymbol{E}}(\theta,\phi)=[\mathbf{W}]^{t}\cdot\left[\vec{\boldsymbol{F}}\right] \tag{1}$$

where $[\ ]^{t}$ stands for transpose. The n-th element, $\vec{F}_{n}(\theta,\varphi)$, of the vector $\left[\vec{\boldsymbol{F}}\right]$ is the electric far field produced by the n-th radiating element. The n-th weight, W_n in [W] is the respective complex amplitude excitation.

In the orthogonal perturbation method we perturb the position of the elements. In this case we keep the excitation vector [W] constant while we permit in equation (1) the vector $\left[\vec{\boldsymbol{F}}\right]$ to change. In the present study the element positions can be identified by up to two independent variables p_n, q_n. The field variation $\delta\vec{\boldsymbol{E}}(\theta,\phi)$ of the array can be written as:

$$\delta\vec{\boldsymbol{E}}(\theta,\phi)=\sum_{n=1}^{N}\mathbf{W}_{n}\delta\vec{\boldsymbol{F}}_{n}(\theta,\phi)=[\mathbf{W}]^{t}\cdot\left[\delta\vec{\boldsymbol{F}}\right] \tag{2}$$

or:

$$\delta\vec{\boldsymbol{E}}(\theta,\phi)=\sum_{n=1}^{2N}\mathbf{A}_{n}\frac{\partial\vec{\boldsymbol{F}}_{n}(\theta,\phi)}{\partial\mathbf{a}_{n}}=[\boldsymbol{A}]^{t}\cdot\left[\frac{\partial\vec{\boldsymbol{F}}}{\partial\boldsymbol{a}}\right]=[\boldsymbol{A}]^{t}\cdot\left[\vec{\boldsymbol{G}}\right] \tag{3}$$

where:

$$\begin{aligned}
&\frac{\partial\vec{\boldsymbol{F}}_{n}(\theta,\phi)}{\partial \mathrm{a}_{n}}=\frac{\partial\vec{\boldsymbol{F}}_{n}(\theta,\phi)}{\partial \mathrm{p}_{n}};\quad \mathrm{A}_{n}=\mathrm{W}_{n}\,\delta \mathrm{p}_{n},\quad n\leq N\\
&\frac{\partial\vec{\boldsymbol{F}}_{n}(\theta,\phi)}{\partial \mathrm{a}_{n}}=\frac{\partial\vec{\boldsymbol{F}}_{n}(\theta,\phi)}{\partial \mathrm{q}_{n}};\quad \mathrm{A}_{n}=\mathrm{W}_{n-N}\,\delta \mathrm{q}_{n-N},\quad 2N\geq n>N
\end{aligned} \tag{4}$$

δp_n, δq_n are the variations of the independent variables p_n, q_n of the n-th element.

Following the OM in equation (3), [4], we reach:

$$\begin{aligned}
&\{\delta \mathrm{p}_{n}\}_{\nu+1}=\{\mathrm{A}_{n}\}_{\nu+1}/\mathrm{W}_{n},\ n\leq N\\
&\{\delta \mathrm{q}_{n-N}\}_{\nu+1}=\{\mathrm{A}_{n}\}_{\nu+1}/\mathrm{W}_{n-N},\ 2N\geq n>N
\end{aligned} \tag{5}$$

The new element-coordinates follow:

$$\begin{aligned}\{\mathrm{p_n}\}_{\nu+1} &= \{\mathrm{p_n}\}_{\nu} + \{\delta \mathrm{p_n}\}_{\nu+1} \\ \{\mathrm{q_n}\}_{\nu+1} &= \{\mathrm{q_n}\}_{\nu} + \{\delta \mathrm{q_n}\}_{\nu+1}\end{aligned} \tag{6}$$

Adjusting the method to the requirements and as they are given for the far field in a bound constraint form, the desired pattern is described accordingly. Suppose that for $(\theta,\varphi)\in\Omega$, (where Ω is a specific angular domain), $|\vec{\mathbf{E}}| \le B$, (where B stands for the bound value), is needed. Then the right part of (2) defines a multi-valued function C as follows:

$$C = \begin{cases} 0 & (\theta,\phi)\in\Omega \; and \; |\vec{\mathbf{E}}| \le B \\ \left\| \vec{\mathbf{E}}^{d} - \vec{\mathbf{E}} \right\|^{2} & \text{otherwise} \end{cases} \tag{7}$$

Equivalently (2) can be left intact and the target pattern, in each iteration step, can be defined using the substitution:

$$\vec{\mathbf{E}}^{d} \to \begin{cases} \vec{\mathbf{E}} & (\theta,\phi)\in\Omega \; and \; |\vec{\mathbf{E}}| \le B \\ \vec{\mathbf{E}}^{d} & \text{otherwise} \end{cases} \tag{8}$$

2.2 The Fractal Array Approach

The fractal technique is proposed for the synthesis of a DRA with planar configuration, which when operates as a phased array can produce nineteen pencil beams with the requirements given in Table 1.

The basic item of a fractally designed array is a generating sub-array and the entire radiating system can be formed via the recursive application of the generating sub-array under a specified scaling factor, which governs how large the array grows by each repetitive application of the generating array. Due to the nature of the fractal algorithm, the array factor of the n^{th} stage is produced by the multiplication of all the factors of previous stages with the array factor of the n^{th} stage. Moreover, at the n^{th} stage the size of the array is equal to the one of the generating sub-array, multiplied by the n^{th} power of the scaling factor and the element population is the $(n+1)^{th}$ power of the number of elements of generating array. The fractal procedure leads to a rapid growth of the antenna size, the rapid increase of the number of the elements and both of these parameters lead to large gain as it is preferable for the antenna under design.

The suppression of the grating maxima that come from the gradual increase of inter-element distances of the array can be obtained by suitable selection of the scaling factor. Furthermore the fractal arrangement of the DRA elements gives the potential to execute the beam scanning by grouping the elements in uniformly excited sub-arrays. As a consequence, the required phase shifters and drivers are less than one per element and the cost and complexity of the array is reduced.

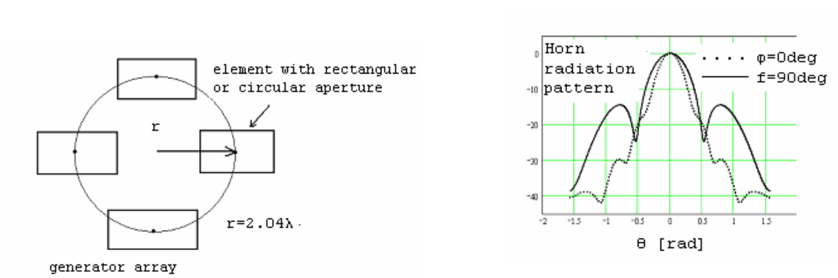
For the implementation of the proposed DRA, a planar array (Fig. 1) of four elements positioned on the circumference of a circular ring of radius r, was selected as generator. The choice of the four elements was made under the criteria of high gain and low Side Lobe Level(SLL).

The general expression of the fractal array factor in the case of the ring generator case is

$$AF_F(\theta,\phi) = \prod_{p=1}^{N_F} \left[\sum_{n=1}^{N_g} I_n e^{j\delta^{p-1}\psi_n(\theta,\phi)} \right] \quad (9)$$

where

$\psi_n = kr\sin\theta\cos(\phi-\phi_n)+\alpha_n$, $k = 2\pi/\lambda$, N_g is the number of elements of the subarray, r is the radius of the generator ring, p the stage of growth of the fractal development, δ the scaling or expansion factor of the array, I_n and a_n are the excitation current amplitude and current phase of the n^{th} element located at $\phi = \phi_n$.



(a) (b)

Fig. 1. a) The generating sub-array. b) Radiation pattern. Element type: Rectangular Horn , Directive gain ~17dB, Horn aperture about 3.98λx1.98λ, Waveguide: WR-51, a=12.9mm, b=6.48mm.

The selection of the values of r and δ was made under the requirements for the EOC directivity, the C/I ratio and the available area of occupation. Four steps of fractal development led to an array of 1024 elements and EOC directivity greater than 43.8dB, (Fig. 2a). To realize the feeding, the elements were grouped in blocks of 16, excited in phase and with equal amplitude. So, the number of control points is 64. With intense to ensure low complexity at the feeding network, all the blocks were initially considered as uniformly illuminated and solely a phase shift between adjacent blocks is necessary for the eighteen out of nineteen beams to be produced. The entire array fulfils the criteria of the directivity and occupation, for a large number of values of the pair (r, δ). The problem is that not all of these pairs guide the antenna to match the requirement of the C/I ratio. The selection of the proper pair can be made by an approximate process as follows. The array factor of Eq. (9), if we take into account that the elements of the DRA are uniformly excited, can be written as the multiplication of N_F array factors of uniform arrays of 2x2 elements. The suppression of the grating lobes could be obtained if we choose the values of r and δ such that the m^{th} maximum of the factor of p^{th} step coincides with the $(m\text{-}1)^{th}$ zero of the factor of the $(p\text{-}1)^{th}$ step.

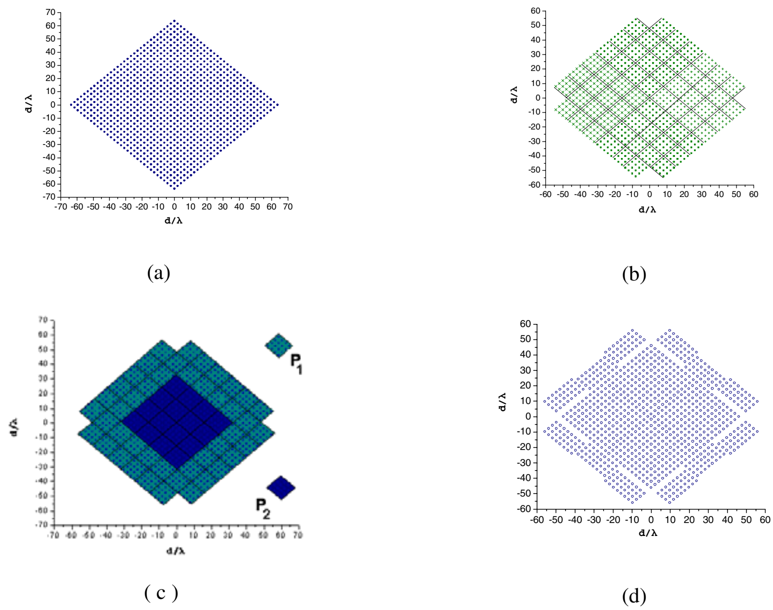


Fig. 2. a) The fractal fully populated array of 4^{th} stage. Number of elements: 1024 b) The thinned array. Number of elements: 960, Number of control points: 60, Array size: 108.34λ x 108.34λ. c) Excitation of the blocks d) The proposed thinned array. Number of elements: 960, Number of control points: 60, Array size: 111.72λ x 111.72λ. Excitation: one step of quantization, P_2:P_1=2:1.

This evaluation is approximate as is valid solely for the central beam with maximum at $\theta=0^o$ and $\varphi=0^o$. In order the performance of the array to meet the requirements for all the nineteen beams and also to obtain better results, even for the central beam, some modifications to the geometry of the fully populated array as well as to the way of feeding were made:

a) The array was thinned by missing 16 elements from each one of its four vertices. So the number of elements of the proposed array is 960, grouped in 60 blocks of sixteen elements and the number of control points is reduced to 60 (Fig.2b)
b) Non-uniform excitation between the blocks is applied (Fig. 2c).
c) The value of δ was selected as δ=1.99, that is a little smaller than 2 with intense the value of r to be $r=2.04$λ. With this pair of (r, δ) the size of the thinned array is 111.72λ x 111.72λ, whereas the value of r provides the potential to use, as radiating element, a horn antenna with aperture that gives directive gain ~17dB.
d) The positions of 16 blocks at the outline of the DRA were perturbed. So, the proposed array is that shown in Fig. 2d.

3 Results

3.1 Orthogonal Perturbation Method

In order to produce a sample result of the OPM we use a uniformly excited square array consisting of 121 (=11x11) circular apertures, (radius = 3λ), spaced 7.5λ apart. Each element is assumed to support a uniform aperture field. For the design of a broadside beam nearly 200 iterations of the OPM suffice to design an array that fulfils the requirements. The resulting array layout is given in Fig. 3. The broadside beam, accompanied by the bound constraints (red line) is given in Fig. 4a. Using one control point/ phase-shifter, per element the outermost beam is given in Fig. 4b.

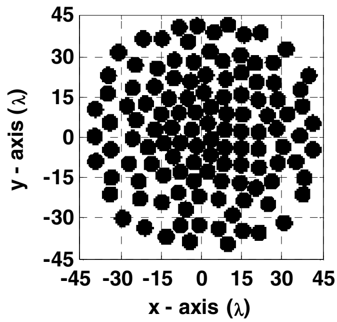


Fig. 3. The outcome of the OPM: Array Layout

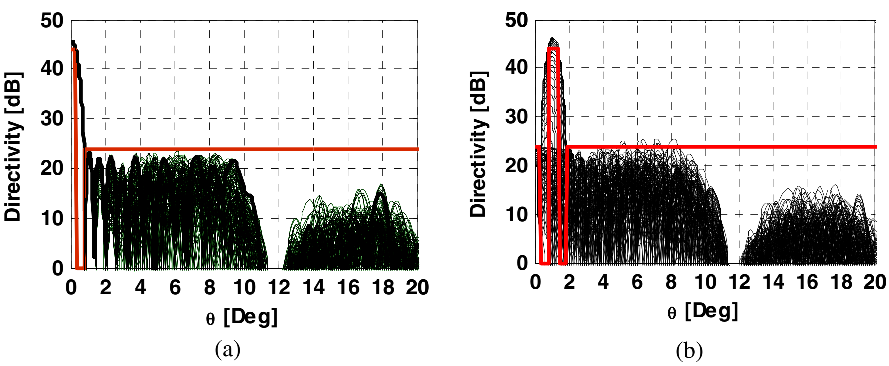


Fig. 4. The outcome of the OPM: (a) Broadside Beam, (b) Outermost beam

3.2 The Fractal DRA

Indicative results for the configuration of Fig. 2b and 2d are presented in figures 5 to 8. As source element was used a horn antenna with directivity 17.dB. The aperture horn was 3.97λ×1.97λ, it was fed by the waveguide: WR-51(a=12.9mm, b=6.48mm) and its radiation patterns on the two main planes are shown in Fig. 1b.

Figure 5 illustrates the radiation patterns of the central beam for φ=0° - 90°. The excitation of all the blocks is uniform, meanly P_2/P_1. It is shown that the antenna fails to fulfil the imposed requirements, as the C/I ratio is 10.97dB. Better results were received when one step of quantization was imposed. The results approached the requirements but are not judged satisfactory. In Table 2, analytical information about the operation of the DRA is presented.

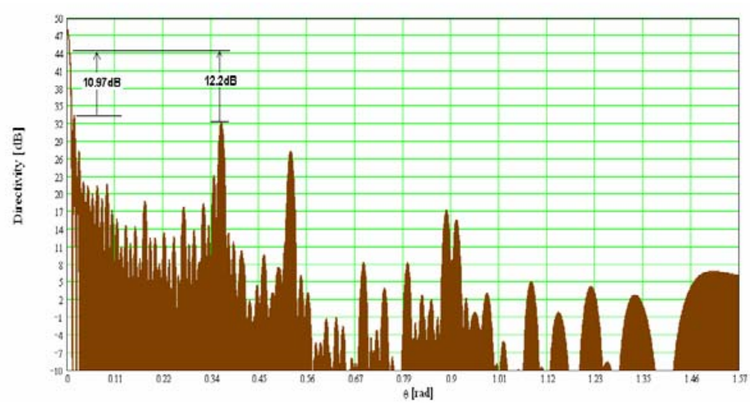


Fig. 5. Patterns, for φ=0° - 90°, of the central beam of the DRA of fig. 2d. Excitation: P_2/P_1=1.

Table 2. DRA records for various P_2/P_1 values

P_2/P_1	Max. directivity [dB]	EOC directive gain [dB]	C/I [dB]	Out of earth level [dB]
1	48.1	44.5	11	12.2
2	46.8	43.8	17.9	15.3
3	45.6	42.9	19.4	14.9
4	44.8	42.4	18.5	14.7

A small perturbation of 16 blocks at the perimeter, led the DRA operation to match the imposed requirements. In this case two steps of excitation with ratio $P_2/P_1 = 2$ are necessary. Analytical results are shown in figures 6 and 7. In Fig. 6 the radiation patterns of the central beam and two adjacent beams 1.12deg apart from the central are depicted. For all the three beams we have D_{max} > 45dB, C/I > 23dB and D_{EOC} > 43dB. Respective results for the central beam and two adjacent beams 0.56^o apart from the central are depicted in Fig. 7. In this case the records for beams C and D are: D_{max}=45dB, C/I=20.2dB and D_{EOC}=42.5dB. The range in which the values of these parameters vary, for all the nineteen beams, are presented in summary in Table 3.

In figure 8 the patterns of the central beam for azimuth angles φ between 0^o and -90^o are illustrated. It is shown that not only inside the coverage area but also out of it – on earth and out of earth - grating lobes with levels ~23dB and ~15.8dB, respectively, lower than that of the maximum radiation are ensured.

Table 3. Values of the performance parameters for all beams

Max. directivity [dB]	EOC directive gain [dB]	C/I[dB]	Out of earth level [dB]
45 - 47.9	42.5 – 45.6	20.2 – 24	<12.8

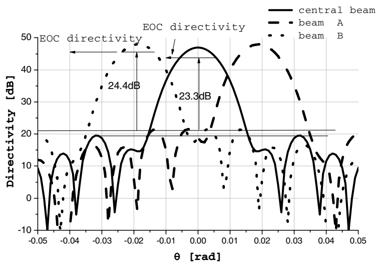


Fig. 6. The central beam and two adjacent-beams 1.12° apart from the central. Beams A, B: max. directivity 47.9dB, EOC directivity 45.6dB, C/I= 24.3dB Central Beam : max. directivity 46.9dB, EOC directivity 43.7dB, C/I= 23.4dB.

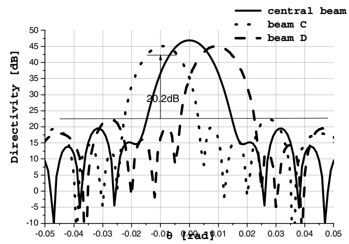


Fig. 7. The central beam and two adjacent-beams 0.56° apart from the central. Beams C, D: max. directivity 45.1dB, EOC directivity 42.5dB, C/I=20.2dB.

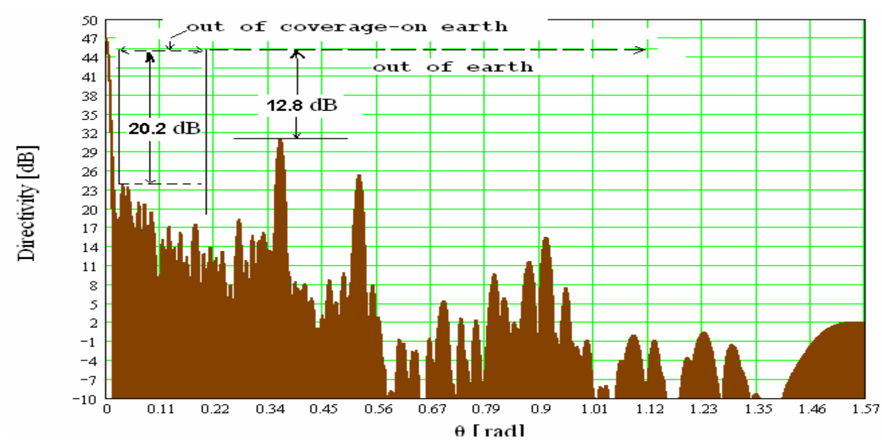


Fig. 8. Patterns, for φ= 0° - 90°, of the central beam of the DRA of fig. 2d. Excitation: P_2 / P_1=2.

4 Conclusions

Two design methods for the synthesis of Direct Radiating Arrays (DRA) with a reduced number of controls are given in the current work. The effort is part of the work included into the framework of a joint ESA program. The DRAs are to form a set of simultaneously overlapped multi-beams for satellite communications in the frequency range of 20 GHz and satisfy certain specifications (End of Coverage (EOC) gain, grating and side lobe levels).

The design methods are the Orthogonal Method (OM) in conjunction with a Perturbation (OPM) technique and the fractal technique. Some preliminary examples are presented and show the effectiveness of the design methods.

The OPM is enforced on a square array of uniformly excited circular element radiators. The desired pattern embodies the technical requirements of the broadside beam in the form of a bound constraints curve, (mask). The method is robust enough to produce an acceptable solution which can be further improved by using more than one type of elements and/ or quantized excitation. The ongoing effort is focused on those issues to further improve the method's performance.

The fractal technique is proved efficient for the design of a DRA of 960 elements which produce nineteen pencil beams for a satellite communication network. The inherent advantages of the fractal development permitted us to obtain, for all the beams, maximum and EOC directivity higher than 45dB and 42.5 dB respectively. C/I ratio larger than 20.2dB was attained by proper selection of the scaling factor, the perturbation of the positions of some blocks and applying one quantization step 2:1 of feeding. Moreover the fractal arrangement of the elements of the array and the ability to thin the array offered the potential to group the elements in blocks of uniformly excited elements. So, the number of the control points was reduced to 60, that is sixteen times smaller than it would be if one per element feeding was implied.

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