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ISOPHORIC ARRAY ANTENNAS WITH A LOW NUMBER OF CONTROL POINTS: A 'SIZE TAPERED' SOLUTION

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Abstract—We propose a new architecture for array antennas able to achieve a high-gain performance by using a low number of elements and uniform-amplitude excitations. The solution is realized through a fast and deterministic design technique able to accurately emulate, by exploiting only the feeds' size as degree of freedom of the synthesis, 'ideal' continuous aperture sources fulfilling at best the assigned directivity requirements. The given theory is supported by numerical examples concerning the synthesis of isophoric direct radiating arrays devoted to a multibeam coverage of Europe from a geostationary satellite.

1. MOTIVATIONS, AND RATIONALE OF THE SYNTHESIS APPROACH

In the field of array antennas synthesis, the deterministic use of the feeds' size in order to fulfill given power pattern constraints represents an innovative idea. In fact, usual degrees of freedom are either the excitations of a fixed-geometry structure [1–5], or the locations (and occasionally the phase excitations) of the fixed-amplitude radiating elements [6–12], or even both of them [13–15]. In particular, the second of these problems is of interest in the design of Direct Radiating Arrays (DRA) for telecommunications from satellites [16].

In fact, arrays easily lend themselves to multibeam and reconfigurability applications. Moreover, in communications from

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geostationary satellites, a substantial saving in the array number of elements is gained from the fact that a minimum spacing in the order of 3.5 wavelengths can be safely used to reject the grating lobes out from the Earth's disc [12, 16–18]. In these applications, in order to optimally exploit the available power, it is usually required that all the (identical) amplifiers work under the same (optimal) conditions. This feature results in equi-amplitude entry points and leads to the so-called 'isophoric' DRA [6–12]. Such a circumstance, together with the need of keeping the number of amplifiers (and antennas) as low as possible, has stimulated research activities aimed at the optimal synthesis of sparse arrays [7–12], thinned arrays [17], and clustered arrays [18].

Notably, in usual sparse array architectures, the quest for low sidelobes, which is indeed of interest in multibeam applications, leaves empty a large portion of the aperture plane. Such feature results in a reduction of the antenna directivity (and gain) with respect to the theoretical maximum performance. As gain is of the outmost relevance in satellite applications, the chance to exploit two different kinds of radiating elements in an otherwise sparse-array architecture has been recently proposed [12], developed [9], and optimized [10]. In particular, it has been shown that the exploitation of two kinds of feeds allows both a better filling of the space at disposal and hence an improved radiation performance. A small-scale demonstrator of this basic concept has also been successfully designed, realized and tested [19].

In this paper, by relying on these results, as well as from the circumstance that radiating elements with a 90% aperture efficiency can be successfully realized [19], we develop and optimize a 'size-only tapered' architecture for high-gain isophoric DRA. In particular, we present a fast deterministic design procedure such to fulfill fixed power pattern (and directivity) requirements by using *only* the feeds' size as degree of freedom of the problem.

It must be stressed that such a synthesis framework does not result explored or investigated in the available literature (we cite [1–22] just for the sake of concision) and results in a completely new array antenna architecture.

A seemingly similar concept had been introduced in [20]. In that case, however, the array elements' sizes are fixed in advance rather than being synthesized in some optimal fashion. As a consequence, contents of [20] are indeed very different from what follows.

The devised synthesis procedure is presented in Section 2. Section 3 is devoted to show numerical results concerning its application to the design of DRA for multibeam communications from a geostationary satellite. Conclusions follow.

2. THE SYNTHESIS PROCEDURE

By taking advantage from the capability to design and realize high-efficiency elements (see [19]), the proposed approach assumes that the single array elements are uniform-amplitude aperture antennas. Hence, feeds carrying the same overall power but having different sizes produce, on their aperture, different field levels. The smaller the feed becomes, the larger the field level on its aperture results. Hence, a smart positioning of elements with a different size can allow one not only to optimally fill the space at disposal but also to realize the desired tapering on the overall array aperture. By taking into account this simple yet powerful concept, the following four-steps strategy has been devised:

1. choose the area S of the smallest DRA element to be employed and the number N of different sizes for the DRA feeds;
2. synthesize a continuous source having a 'step-like' behaviour of the kind shown in Fig. 1 and able to fulfill the assigned technical requirements by exploiting just N amplitude levels;
3. identify the area to be assumed by each DRA feed in order to realize, on the array aperture, the N field levels above. The feeds' area must be Q^2S in those regions where the normalized square-amplitude aperture field is equal to $1/Q^2$;
4. establish the DRA elements locations and geometrical shapes such to fill as much as possible the available space by employing only feeds having the areas identified in step 3.

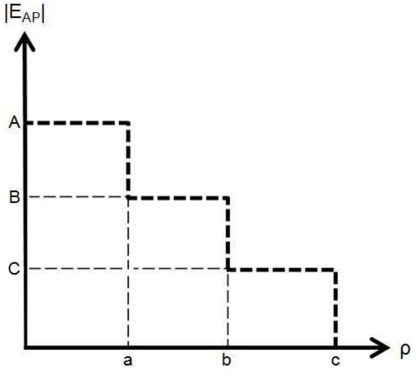


Figure 1. Typical amplitude distribution of continuous aperture sources used as a reference in the antenna design.

In order to keep under control the DRA cost and complexity, the number of unknown continuous source's levels should be very low. Therefore, the second step of the procedure can be performed in a fast and effective fashion even through global optimization procedures (dealing with an extremely low number of unknowns). Advantage could be taken also from hybrid optimization approaches (such as the one in [13]) by taking advantage from the design procedure in [21].

3. AN ASSESSMENT OF PERFORMANCE IN AN ACTUAL SYNTHESIS SCENARIO

We used the above approach to design an isophoric DRA for a multibeam coverage of Europe from Geostationary Earth Orbit (GEO) satellites [16]. The technical requirements aim at realizing 19 different spots located as shown in Fig. 2, having a diameter of 0.65° and located with a constant spacing of 1.12°. The source must cover a circular aperture having a radius not larger than 60λ (λ being the wavelength in free space) and realize a directivity not lower than 43.8 dBi in the reference spot. Also, each beam has assigned a specific frequency sub-band and polarization in order to avoid interferences amongst adjacent spots. Two different sub-bands and circular polarizations are adopted. The interfering spots, i.e., the 'iso-frequency' and 'iso-polarization' regions, are usually indicated by the same color (see Fig. 2). In the

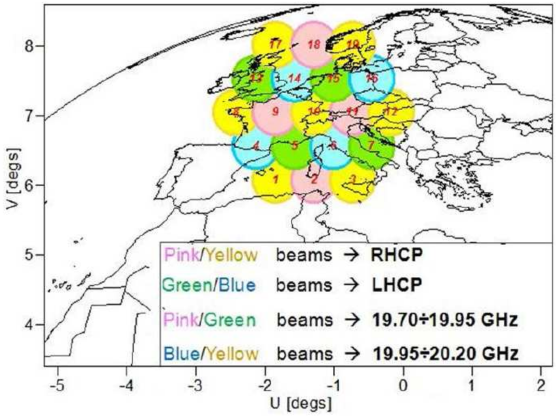


Figure 2. 'Four-colors' re-use scheme (with polarization and sub-bands details) recently proposed by the European Space Agency to realize a multibeam coverage of the Europe from Geostationary Earth Orbit satellites.

iso-color spots, the maximum directivity must be at least 20 dB lower than the minimum directivity guaranteed in the reference spot.

In order to test the validity of the basic idea in a simple case, we fixed $N = 3$. Moreover, we exploited square feeds, which is consistent with the desire of filling as much as possible the aperture. To this end, the radiating elements will be positioned on a regular grid in the central zone, while they will be organized along rings in the external regions. Finally, we fixed $S = 16\lambda^2$, which is consistent with the choices in [19].

As a first step of the synthesis procedure, we looked for a real and positive, circularly symmetric continuous aperture source fulfilling the above constraints by exploiting just three different amplitude levels. By denoting with A, B, and C the source's possible amplitudes and with a, b, and c the aperture radial dimensions of the three zones (see Fig. 1), the far field spectrum can be expressed as:

$$E_{TOT} = 2\pi\left\{a^2(A-B)\frac{J_1(\beta a\sin\theta)}{\beta a\sin\theta}+b^2(B-C)\frac{J_1(\beta b\sin\theta)}{\beta b\sin\theta}\right.$$
$$\left.+c^2C\frac{J_1(\beta c\sin\theta)}{\beta c\sin\theta}\right\} \tag{1}$$

In Eq. (1), we fixed the reference level A equal to 1, and, following [16], $c = 60\lambda$. Then, a global optimization procedure (or even an enumerative technique) could be used in order to determine the values of a, b, B and C such to optimize the directivity for a given separation amongst main beam and iso-color spots (or vice versa).

In so doing, care has to be taken in the choice of C. In fact, vanishingly small values of C imply very large dimensions for the corresponding feeds. In turn, the latter imply considerable problems in the beam scanning. A quantitative analysis of such a point can be found in [22].

In order to reduce complexity of both the array architecture and the optimization step, we will assume in the following $C = 0.5$. In fact, this choice will allow to use in the external region a feed which is nothing but the assembly of four of the feeds used in the central region. Such a choice is also suggested from the characteristics of the aperture field distributions discussed in [21], i.e., continuous sources fulfilling at best the above requirements and exhibiting a dynamic range ratio equal to 2.

Then, we evaluated the radiation performance for a dense grid of values of the parameters B, a and b. The value of B has been iteratively fixed in the range 0.7–0.85λ (sampled with a distance of 0.025 units) and, for each of these choices, we looked for the values of a and b corresponding to the best radiation performance. In particular, amongst all the solutions guaranteeing an acceptable directivity value at the edge of the central spot, we found the one optimizing the power separation amongst the main beam and the iso-color spots.

The analysis led to the choice: $B = 0.8$, $a = 20\lambda$, $b = 35\lambda$. Figs. 3 and 4 show the outcomes of the numerical experiments as functions of a and b, for $B = 0.8$. Fig. 3 shows the minimum directivity guaranteed by

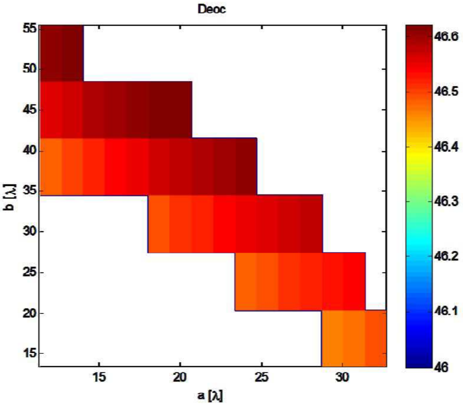


Figure 3. Continuous aperture source's minimum directivity guaranteed in each spot, for $B = 0.8$, as a function of the parameters a and b.

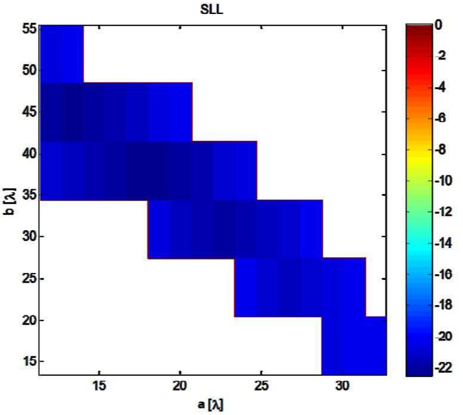
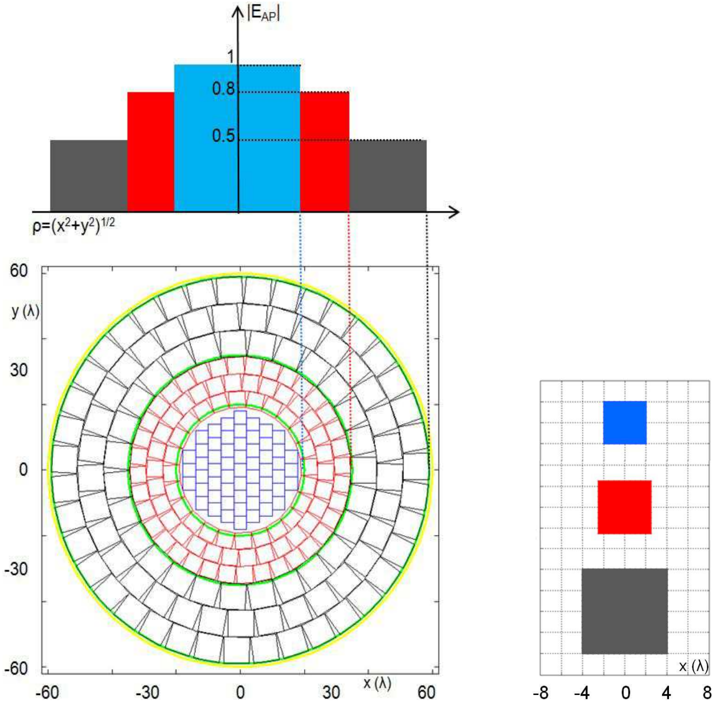


Figure 4. Continuous aperture source's maximum sidelobe level as a function of the parameters a and b, evaluated for $B = 0.8$ in the interfering spots with respect to the directivity values depicted in Fig. 3.

the continuous source in the reference spot. Fig. 4 shows the difference between the maximum directivity achieved in the interfering spots and the directivity of Fig. 3.

The synthesized continuous aperture source guarantees a directivity not lower than 46.6 dBi in the reference spot and not larger than 25.3 dBi in the interfering spots. The DRA designed by exploiting this reference distribution fulfills by a wide margin all the imposed constraints. Both the continuous source and the corresponding array are depicted in Fig. 5(a). Notably, the synthesized stair-case source guarantees in each spot a minimum directivity which is just 0.2 dB lower than the one provided in [21]. The corresponding size-tapered array is composed by 246 isophoric feeds of areas 16, 25 and $64\lambda^2$ (see Fig. 5(b) for a pictorial view of the adopted kinds of radiating



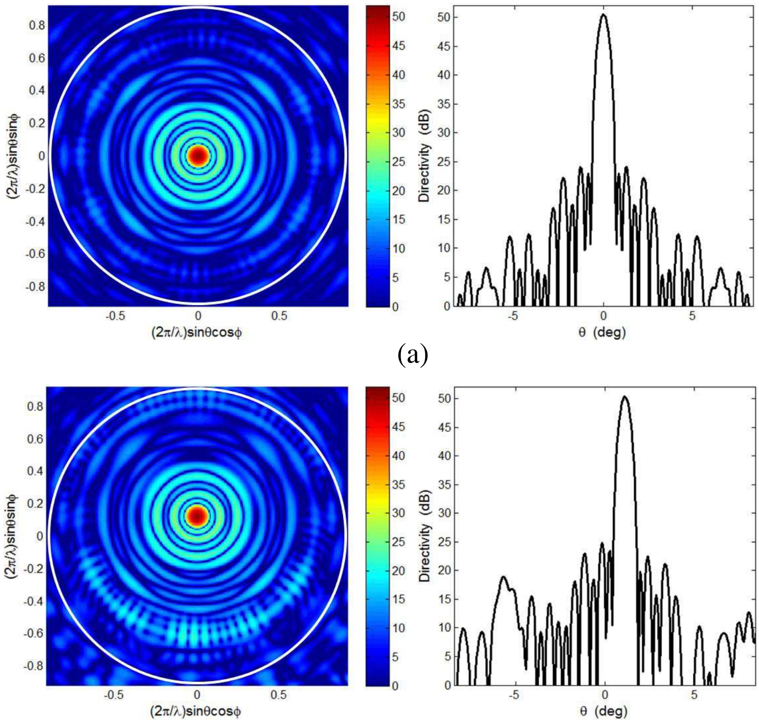
(a) (b)

Figure 5. Synthesis approach: (a) reference source distribution (top sub-plot) and corresponding DRA layout (bottom sub-plot) fulfilling all the constraints listed in [12, 16–19, 21, 22]; (b) pictorial view of the three kinds of adopted feeds.

elements).

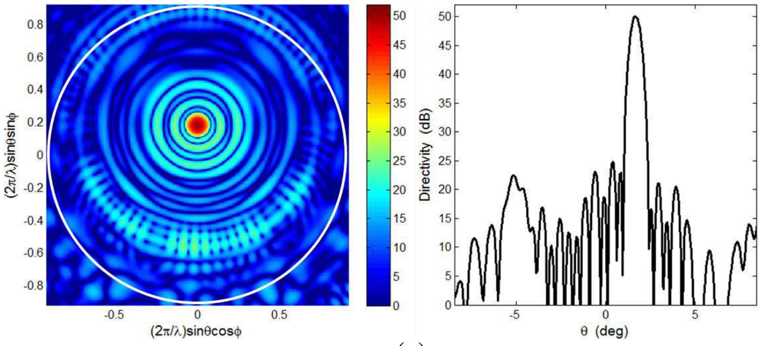
The achieved directivity is shown in Fig. 6. In such a figure the Earth's disc (as seen from geostationary satellite) is depicted in white color. In order to test the DRA ultimate limitations, the radiated fields have been evaluated by using ideal feeds, i.e., uniform-amplitude apertures. However, according to [19], a shift in the order of just −1 dB is expected when using actual feeds.

Notwithstanding we fixed a priori the value of C, the proposed architecture is able to provide at boresight a directivity very close to the ultimate feasible performances achievable by a whatever source having the same dimensions. In fact, at the edge of a generic spot, the array shown in Fig. 5(a) achieves a directivity equal to 46.2 dBi, which is just 0.6 dB lower than the value reachable by an ideal, smoothly-varying continuous source of the same size [21]. Moreover, the synthesized DRA provides an excellent performance in terms of beam scanning capabilities. In fact, it allows to safely scan the beam, by still fulfilling all requirements on sidelobes, up to 1.68°. Considering the beamwidth of interest in the application at hand, such a circumstance allows to get a multibeam antenna realizing 37 different beams. Therefore, it



(a)

(b)



(c)

Figure 6. Performance of the synthesized isophoric DRA. Directivity in the spectral plane (with the Earth's disc depicted in white color) and as a function of the aperture elevation angle θ (for an aperture azimuthal angle $\phi = \pi/2$): (a) boresight performance; (b) performance at a scanning angle of 1.12°; (c) performance at a scanning angle of 1.68°.

outperforms the usual 19-beams solution presented in [12, 16–19]. In all cases, the peak sidelobe level does not exceed the $-20\,\mathrm{dB}$ value with respect to the minimum gain guaranteed at the edge of each spot.

4. CONCLUSIONS

With reference to high-gain array antennas with a reduced number of control points and uniform-amplitude excitations, a new convenient architectural solution has been introduced. Moreover, an effective antenna design procedure, resulting deterministic and extremely fast even in case of arrays composed by a very large number of elements, has been given. An important enhancement with respect to the available DRA synthesis procedures has been provided: ideal continuous aperture sources are optimally emulated by employing only the array feeds' size as degree of freedom of the antenna design.

The proposed solution has been successfully tested in the power pattern synthesis of direct radiating arrays for multibeam telecommunications from geostationary satellites. In such a scenario, it has been shown the capability of achieving a radiation performance very close to the ultimate physical limitations.

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