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Circular-Ring Antenna Arrays Being at the Same Time Sparse, Isophoric, and Phase-Only Reconfigurable: Optimal Synthesis via Continuous Aperture Sources

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Abstract—An innovative and general approach is proposed to the optimal, mask-constrained power synthesis of circular continuous aperture sources able to dynamically reconfigure their radiation behavior by just modifying their phase distribution. The design procedure relies on an effective a-priori exploration of the search space which guarantees the achievement of the globally-optimal solution. The synthesis is cast as a convex programming problem and can handle an arbitrary number of pencil and shaped beams. The achieved solutions are then exploited as reference and benchmark in order to design phase-only reconfigurable isophoric circular-ring sparse arrays. Numerical results concerning new-generation telecommunication systems are provided in support of the given theory.

1. INTRODUCTION

The capability of easily reconfiguring the radiation behavior of a direct-radiating array antenna is crucial in several applications, including radar and satellite telecommunications [1–14]. Amongst the different kinds of reconfigurability, a very effective one is undoubtedly represented by *phase-only* control, as it allows both a simplification of the beam forming network and an increase of the amplifiers' efficiency [1–11].

Moreover, arrays are often required at the same time *sparse*, i.e., having an aperiodic layout which is designed on the basis of the technical requirements at hand, and *isophoric*, i.e., having a constant excitation amplitude at each entry point (see Fig. 1). In fact, sparsity induces a decrease of the number of radiating elements for equivalent beamwidth performances, an improvement of the bandwidth, and a lowering of the sidelobe level without resorting to an excitation-amplitude tapering, while isophoricity allows the minimization of the beam forming network's complexity, cost, and weight [14–17].

Recently, solicited by a number of Invitation To Tenders (ITTs) by the European Space Agency (ESA) (see for instance [14] and Fig. 2), array-design methods trying to accommodate *all* constraints of sparsity, isophoricity, and phase-only control started appearing. Nowadays, the only successful techniques seem being the ones introduced in [3] and [10], respectively. In both these contributions, in order to circumvent the high non-linearity of the synthesis problem at hand, the arrays are conceived as the 'discretization' of provably-optimal continuous sources acting at the same time as reference and benchmark.

This paper is aimed at giving a contribution in such a topic. In particular, it proposes a new approach to the optimal, mask-constrained power-pattern synthesis of Circularly Symmetric Continuous Aperture Sources (CSCASs) [18] able to dynamically reconfigure their radiation behavior by just modifying their phase distribution. The achieved solutions are then used as reference in the optimal

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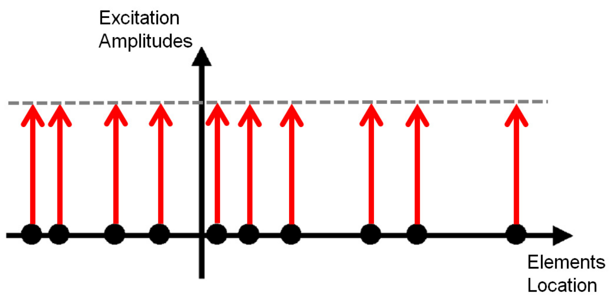


Figure 1. Sketch of a one-dimensional isophoric sparse array: the excitation amplitude distribution must be kept constant over the whole aperture, while the excitation phases and the (aperiodic) layout represent the degrees of freedom of the design problem.

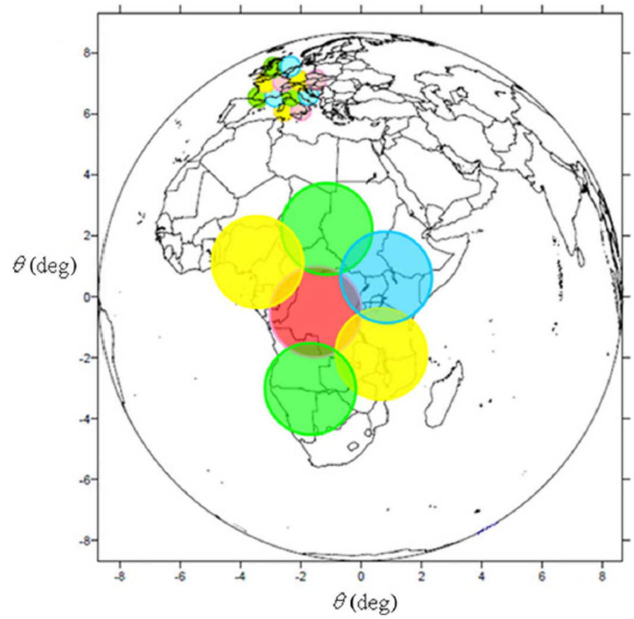


Figure 2. From ESA ITTs [14]: Earth coverage from a geostationary satellite wherein steerable beams switchable between two different widths have to be generated. The required antenna must be of the kind dealt with in the present paper as well as in [3, 10], i.e., isophoric and phase-only reconfigurable.

synthesis of phase-only reconfigurable Circular Ring Isophoric Sparse Arrays (CRISAs) for applications of high interest (including the multibeam satellite coverage of Earth as shown in Fig. 2). In particular, the proposed approach represents the extension to the 2-D circular case of 1-D approach introduced in [3].

As a distinguishing feature, despite the strong non-linearity of the problem (which is a power-pattern, mask constrained synthesis wherein both the array locations and excitation phases are unknowns), the proposed solution procedure has been conceived as a Convex Programming (CP) optimization plus a couple of deterministic steps. This has been possible by virtue of the joint, optimal exploitation of the techniques respectively published in [9] (for an optimal exploration of the search space), [19] (for the optimal synthesis of CSCASs), and [17] (for the fast deterministic discretization of CSCASs into CRISAs).

Being able to address the synthesis of isophoric *planar* arrays by exploiting only *CP* algorithms, the proposed approach represents a remarkable novelty with respect to the available methods. In fact, it is innovative with respect to the method published in [3] (which avoids global optimization but only applies to 1-D arrays) as well as to the one presented in [10] (which applies to 2-D array but resorts to global optimization).

In the following, the design approach is presented in Section 2 and assessed in Section 3. Conclusions follow.

2. THE SYNTHESIS PROCEDURE

As effective techniques are available to derive the layout of an isophoric sparse array from a 'reference' continuous aperture-field distribution (see for instance [15–17]), in the following we first focus on the synthesis of a phase-only reconfigurable CSCASs fulfilling at best the radiation requirements at hand. Then, in Section 3, we will show how, by applying the technique in [17] to the achieved solutions, also the fast design of phase-only reconfigurable CRISAs can be effectively dealt with.

The approach takes decisive advantage from the circumstance that, in the power synthesis of a shaped beam, a multiplicity of *equivalent* source distributions can be identified. This holds true not only in the case of equispaced 1-D arrays [20], but also in the case of CSCASs [19].

For the sake of simplicity, in order to describe the approach let us focus on the case wherein the power pattern must be phase-only reconfigured between a desired pencil beam $E_1(\theta)$ and a desired shaped beam $E_2(\theta)$, θ denoting the observation angle with respect to boresight. Concerning the radiation constraints, according to canonical definitions [18–20], let us conceive the pencil beam as a far field whose square amplitude must be equal to a fixed value A^2 in a target direction θ_T and, at the same time, lower than an upper-bound function UB_1 in the sidelobes region (say Ω). Moreover, let us conceive the shaped beam as a far field whose square amplitude must lie in a prescribed mask, i.e., $LB_2(\theta) \leq |E_2(\theta)|^2 \leq UB_2(\theta)$, LB_2 and UB_2 respectively denoting the upper and lower bound functions pertaining to the technical requirements at hand.

Under these hypotheses, the proposed procedure for the synthesis of a phase-only reconfigurable CSCAS is as follows:

1. identify the optimal (real and non-negative) source generating $E_1(\theta)$;
2. identify the multiplicity of optimal (complex) sources generating $E_2(\theta)$;
3. select, amongst all the source distributions coming out from step 2, the closest, in terms of amplitude, to the one coming out from step 1;
4. set the source coming out from step 3 as the final aperture field pertaining to the 'shaped beam' radiation modality, say $f_2(\rho)$, with $f_2(\rho) = |f_2(\rho)|e^{j\varphi(\rho)}$ (φ and ρ respectively denoting the source's phase and the radial coordinate spanning the aperture);
5. set the amplitude of the source coming out from step 3 as the aperture field pertaining to the 'pencil beam' radiation modality, say $f_1(\rho)$, with $f_1(\rho) = |f_2(\rho)|$.

A number of comments are given in the following concerning the above procedure.

Steps 1 and 2 can be performed through the techniques respectively developed from Bucci and co-workers in [18] (pencil beam case) and [19] (shaped beam case). These approaches guarantee the global optimality of the solutions achieved in the two separate synthesis problems.

Step 3 derives from the general philosophy in [9] and allows identifying the shaped beam's source which most easily lends itself to be reconfigured into the other radiation modality. In order to gain a better understanding of the aim of this step (as well as of the way in which it is fulfilled), Fig. 3 is provided.

Finally, step 4 guarantees that the reconfigurable source radiates a shaped beam fulfilling the given mask, while step 5 is expected to provide a pencil beam very close to the optimal one given by step 1 (and hence fulfilling the initial constraints as well). In fact, the source radiating the shaped beam comes in a straightforward fashion from step 2, while (due to step 3) the pencil beam's source just consists in a 'slight' modification of the optimal one coming out by step 1.

Summarizing, at the end of the overall procedure no radiation-performance losses will be experienced by the shaped beam, and the only price to be paid in order to achieve the phase-only reconfigurability will consist in slight losses on the pencil beam's performances. These losses will be proportional to the difference (in terms of amplitude distribution) between the source coming out by step 1 and the one coming out by step 4, whose extent will be expressed by the radius of the hypersphere depicted in Fig. 3†.

It is worth noting that, whatever the mission scenario at hand, the overall 5-steps procedure above essentially consists in the solution of CP problems plus a number of spectral factorizations (each one being an instant operation [19, 20]), with the inherent advantages in terms of solutions' optimality and computational time.

† The proposed procedure also guarantees the minimization of the hypersphere's radius. In fact, step 2 exploits the *spectral factorization* method introduced in [20] and refined in [19], which makes the user 'aware' of *all* the possible source distributions able to radiate the desired shaped beam. Therefore, the search space over which the subsequent step 3 is performed is 'complete' from the point of view of the 'candidate' sources, and hence it is guaranteed that the identified minimal hypersphere is the one leading to the minimum possible distance amongst the different sources.

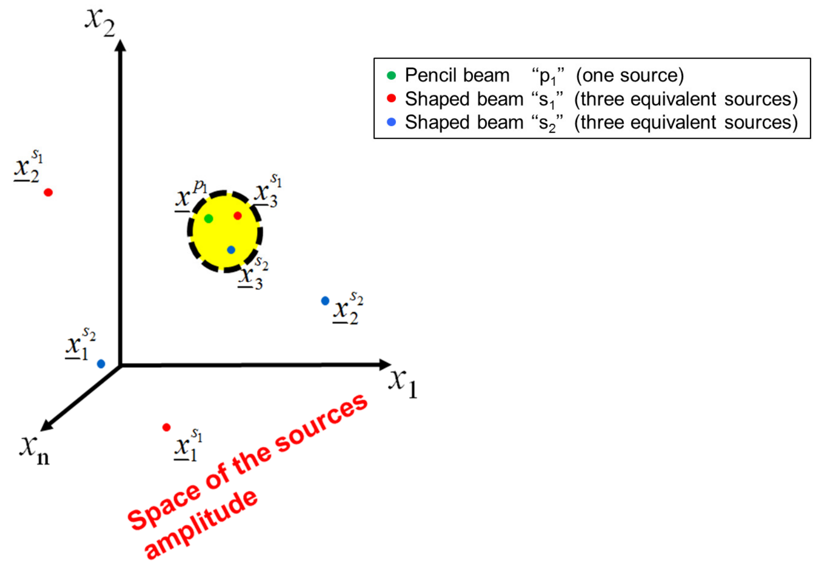


Figure 3. Representation, in the space of CSCASs' amplitude of the sources corresponding to three different far fields ($x_k^{q,l}$ denoting the k-th amplitude sample of the l-th source radiating the q-th pattern). Identifying the *smallest* hypersphere (coloured in yellow) containing at least one solution for each beam means identifying the solutions which 'most easily' lend themselves to be reconfigured.

Notably, the approach can be exploited also in the cases where the amplitudes of the sources pertaining to the two radiation modalities must be equal to each other over only *a limited portion* of the aperture. In particular, once $f_2(\rho)$ is determined, 'common core' or 'common tail' [13] architectures can be achieved by substituting the above step 5 with the following CP optimization [in the unknown $f_1(\rho)$]:

$$\min_{f_1(\rho)} \int_0^a |f_1(\rho)|^2 \rho d\rho \tag{1}$$

subject to :

$$\begin{cases} |E_1(\theta)|^2 \leq UB_1(\theta) & \forall \theta \in \Omega \quad (2) \\ E_1(\theta_T) = |A| & \quad (3) \\ f_1(\rho) = |f_2(\rho)| & \forall \rho \in \Gamma \quad (4) \end{cases}$$

with:

$$E_1(\theta) = \int_0^a f_1(\rho) J_0\left(\frac{2\pi}{\lambda}\rho \sin\theta\right) \rho d\rho \tag{5}$$

denoting with a and λ the aperture radius and the wavelength, respectively. In fact, the problem in Eqs. (1)–(3) is equivalent to the one in [18] [wherein the minimization of the aperture power in Eq. (1) allows to maximize the directivity without incurring into 'super-directive' solutions] while linear constraint in Eq. (4) enforces the desired 'common core' or 'common tail' behavior as long as the Γ region denotes, respectively, the central or outlying area within the aperture.

In the next section, examples concerning the proposed procedure as well as the discretization of the sought continuous sources into CRISAs are shown.

3. NUMERICAL ASSESSMENT

In order to assess the proposed design technique, we show in the following the outcomes achieved in the synthesis of a phase-only reconfigurable CSCAS providing, from a geostationary satellite, an uniform coverage of both the Europe (in the pencil-beam modality) and the Earth (in the shaped-beam modality).

The power patterns coming out from steps 1–3 for $a = 11\lambda$ are shown in Fig. 4 and fulfill radiation requirements derived from the ESA ITTs [14], i.e.,

- the pencil beam has a Peak Sidelobe Level (PSL) equal to $-26.2\,\text{dB}$ for $|\theta| \geq 3.5°$;
- the shaped beam has a maximum ripple not larger than $\pm 0.5\,\text{dB}$ for $|\theta| \leq 9°$, and a maximum PSL lower than $-20\,\text{dB}$ for $|\theta| \geq 14°$.

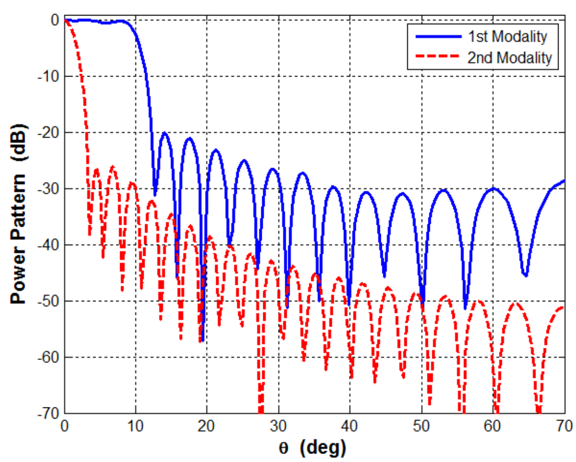


Figure 4. Power patterns coming out from steps 1–3 of the procedure in such a way to guarantee the uniform coverage of both the Europe (red curve) and the Earth (blue curve).

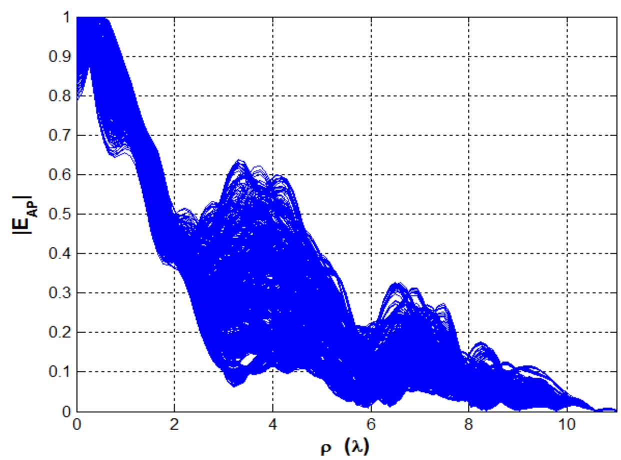


Figure 5. Amplitude of the multiplicity of equivalent sources coming out from step 2 of the procedure, i.e., able to radiate the shaped beam depicted in blue color in Fig. 4.

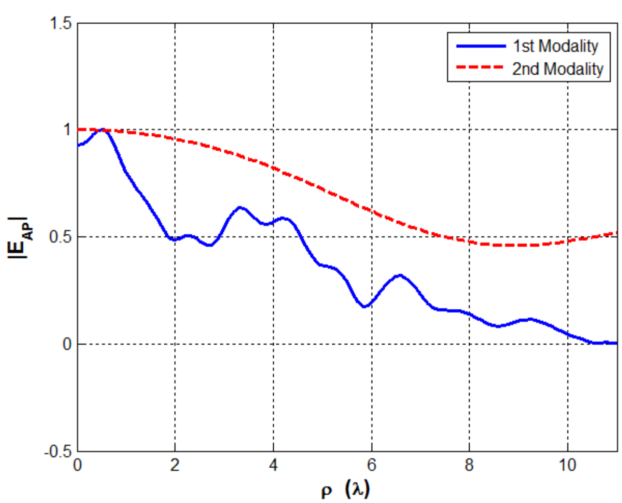


Figure 6. Superposition between the source radiating the pencil beam depicted in Fig. 4 and the amplitude of the source selected (through step 3) amongst the ones shown in Fig. 5.

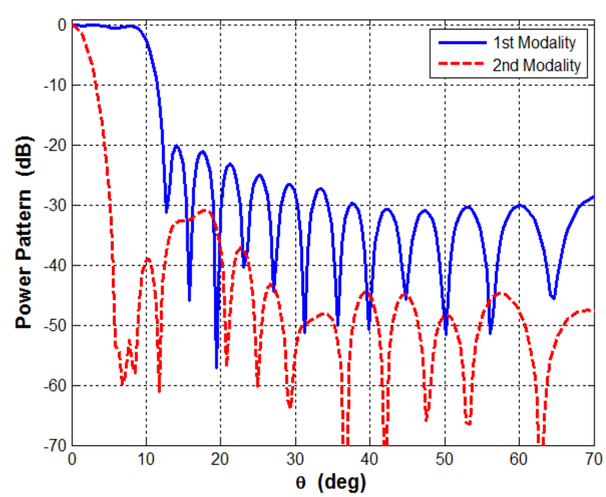


Figure 7. Final phase-only reconfigurable power patterns.

Figure 5 shows the amplitude of the 1024 equivalent sources generating the shaped beam depicted in Fig. 4.

The source pertaining to the pencil beam modality as well as the one coming out from step 3 are shown in Fig. 6. Notably, despite they are able to fulfill quite different radiation constraints, the two sources have a very similar amplitude distribution. This circumstance attests that, in the space of the sources' amplitude (see Fig. 3), the minimal hypersphere containing at least one solution for each desired beam has indeed a small radius.

The final, phase-only reconfigurable power patterns and the CSCAS coming out from steps 4 and 5 of the procedure are shown in Figs. 7 and 8, respectively. As expected, the shaped beam is identical to the reference one shown in Fig. 4 while, as a proof of the high effectiveness of the overall approach, the only effect induced on the pencil beam by reconfiguration is a slight beamwidth increase (while PSL performances results even better than the reference ones).

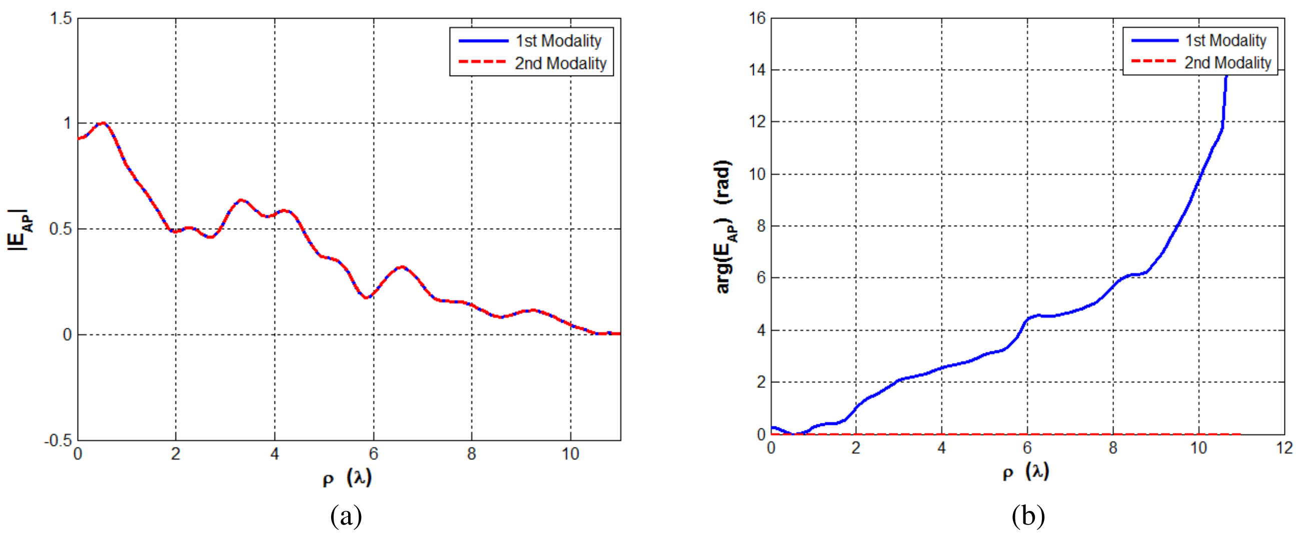


Figure 8. (a) Common amplitudes and (b) different phases of the CSCAS generating the reconfigurable power patterns shown in Fig. 7.

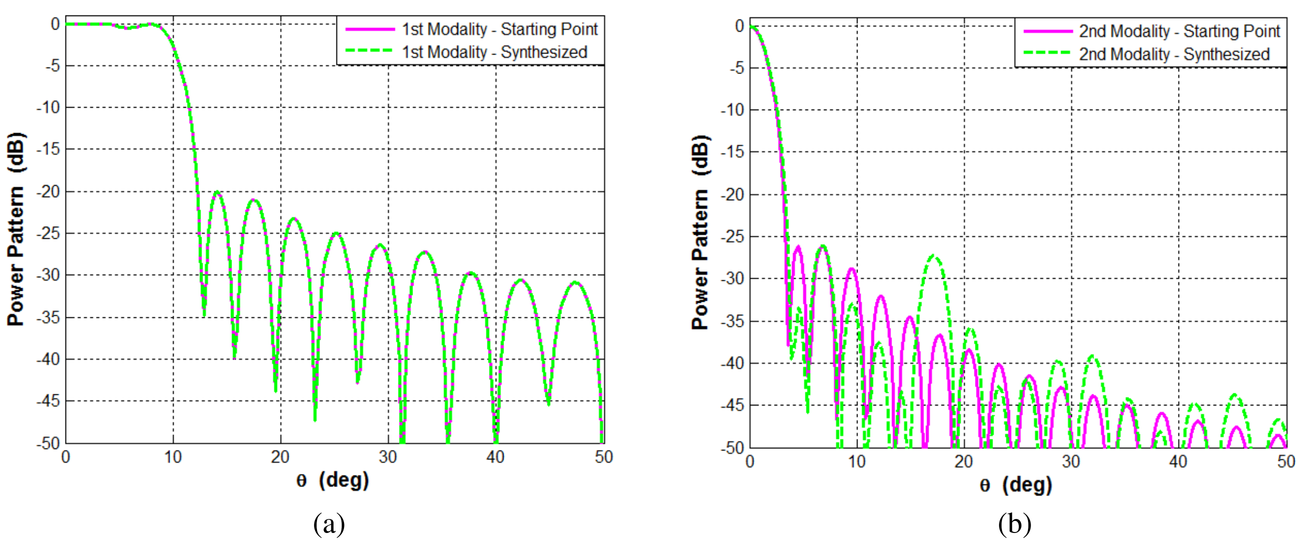


Figure 9. Comparison between the reference and final reconfigurable power patterns achieved for the shaped beam [subplot (a)] and the pencil beam [subplot (b)] in the case of 'common core' sources.

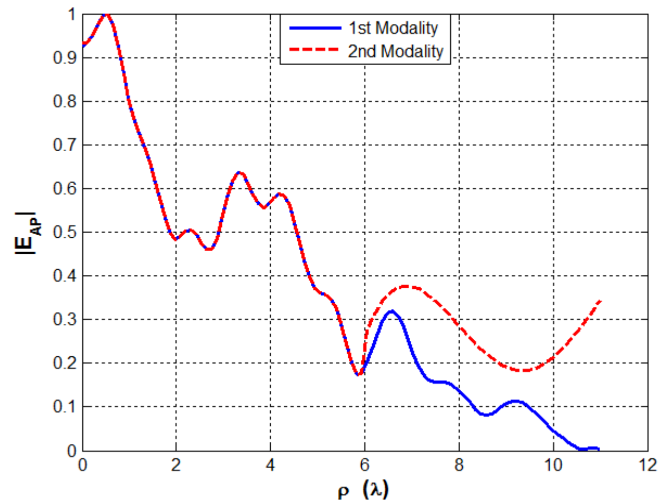


Figure 10. 'Common core' amplitude of the sources generating the reconfigurable fields shown in Fig. 9.

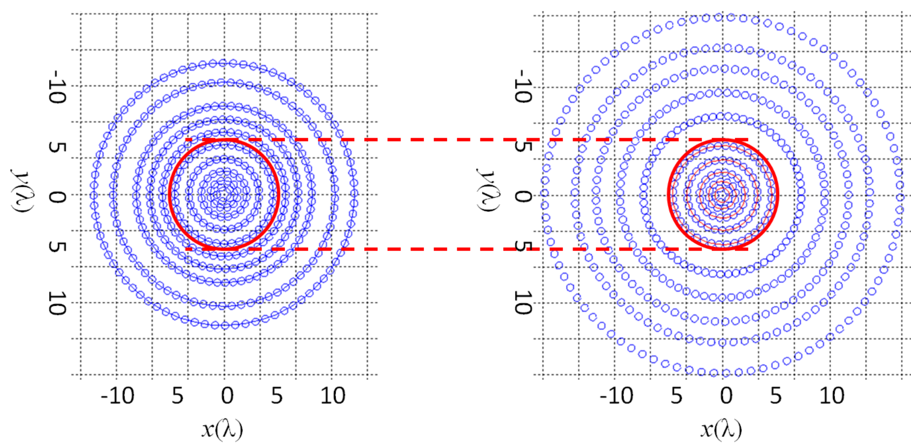


Figure 11. Sketch of CRISA layouts derivable from 'common core' reconfigurable sources.

As a second test case, formulation (1)–(4) has been assessed. In particular, the previous experiment has been repeated by also enforcing a 'common core' behavior of the sources, i.e., by setting Γ as the region $\rho \in [0, 6\lambda]$. The achieved power patterns and the amplitude of the corresponding sources are shown in Figs. 9 and 10, respectively. This kind of CSCASs is useful in those cases where it is allowed to generate the reconfigurable fields by varying not only the excitation phases but also the outer part of the CRISA layout (see Fig. 11).

As a final numerical experiment, the sources shown in Fig. 8 have been discretized into a phase-only reconfigurable CRISA. This has been done by applying the deterministic technique in [17] to the source pertaining to the shaped beam modality, which led to the array layout and excitation phases shown in Figs. 12 and 13(b), respectively.

The synthesized CRISA is composed by 567 isotropic elements and hence allows a reduction of roughly the 20% of elements with respect to a fully-populated array covering the same aperture (i.e., a circular region of radius 7.5λ) with a constant $\lambda/2$ inter-element spacing. By using an uniform excitation amplitude, this array is able to generate:

- the pencil beam depicted in Fig. 14, as long as all excitation phases are set to zero as shown in Fig. 13(a);
- the shaped beam depicted in Fig. 15, as long as the excitation phases of Fig. 13(b) are adopted.

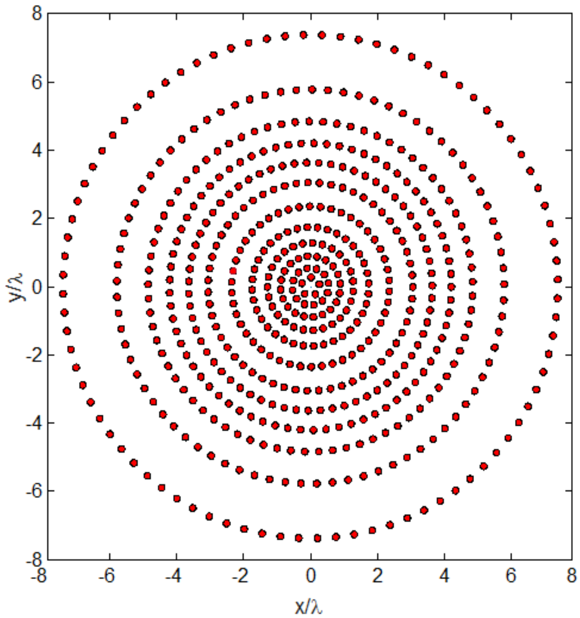
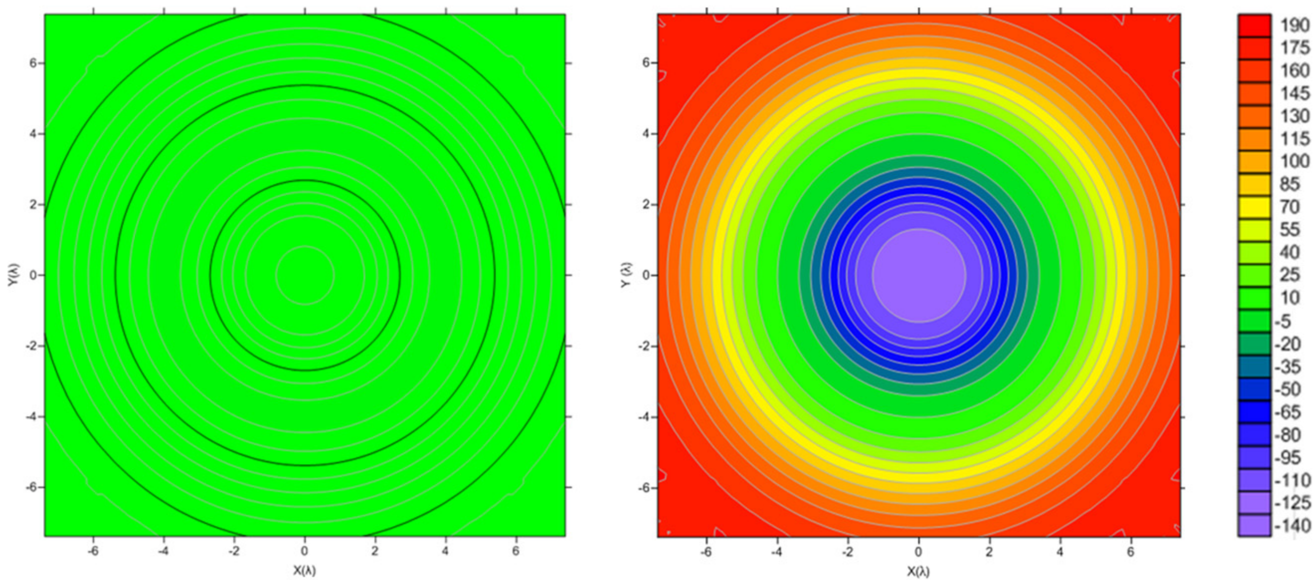


Figure 12. Synthesized isophoric sparse ring array layout (isotropic element pattern embedded).



(a) (b)

Figure 13. Excitation phase distribution (in degrees) synthesized for the pencil beam [subplot (a)] and the shaped beam [subplot (b)].

Notably, in order to effectively evaluate the achieved radiation performances, in both Figs. 14 and 15 the reconfigurable array's power patterns are compared with the ones corresponding to the reference continuous source. As it can be seen, despite the adoption of isotropic feeds, of a constant excitation amplitude, and of a number of elements considerably reduced with respect to a $\lambda/2$-equispaced array, the CRISA guarantees performances very close to the maximum theoretical ones. This circumstance confirms not only the validity of the proposed approach from the theoretical point of view, but also its profitable applicability to the realization of antennas for applications of high interest [21].

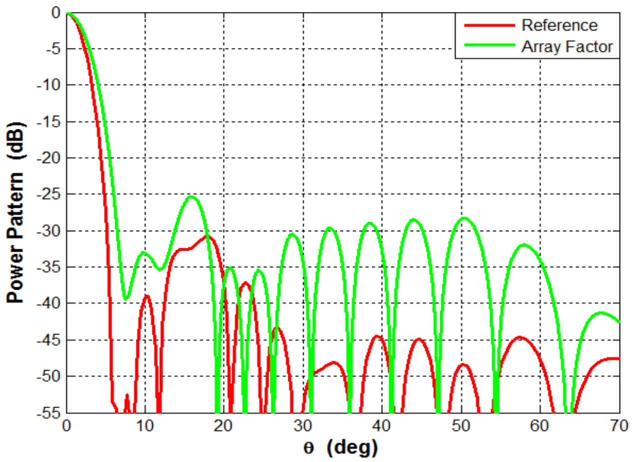


Figure 14. Pencil beam radiation modality: comparison between the power patterns radiated by the reference continuous source and the synthesized isophoric array shown in Fig. 12 and excited with the phase distribution shown in Fig. 13(a).

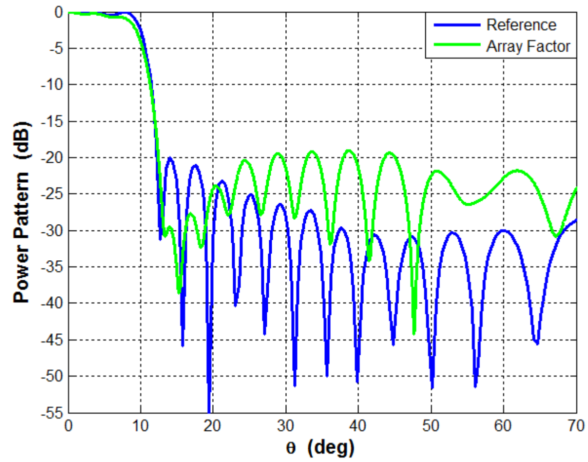


Figure 15. Shaped beam radiation modality: comparison between the power patterns radiated by the reference continuous source and the synthesized isophoric array shown in Fig. 12 and excited with the phase distribution shown in Fig. 13(b).

4. CONCLUSIONS

A new approach to the synthesis of phase-only reconfigurable continuous circular sources and isophoric sparse ring arrays has been presented and assessed.

The proposed technique is able to deal with an arbitrary number of shaped and pencil beams, and exploits at best all the knowledge available in the separate synthesis of the different patterns. The engine of the procedure is based on convex programming optimizations and fast spectral factorizations, guaranteeing at the same time a low computational burden and the achievement of globally-optimal solutions.

The approach represents the extension to the 2-D circular case of 1-D approach introduced in [3].

Being at the same time isophoric and phase-only reconfigurable, the achieved solutions grant at the same time all the advantages of the antennas designed in [3, 10, 22–29].

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