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(Article begins on next page)

Optimization-based Design of Isoflux Reflectarray

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***Abstract*—In this communication, some preliminary results on the design of an isoflux reflectarray, suitable for being mounted on board a satellite or even a CubeSat, carried on with a global optimization technique, are presented. The obtained radiation patterns, relative to a small-medium size configuration, are good and confirm the effectiveness of the proposed procedure.**

***Index Terms*—Reflectarrays, cubesat, optimization.**

I. Introduction

Efficient, low-mass, and low-cost solutions for data downlink antennas are a major resource for Earth Observation, scientific missions, and, recently, 5G and 6G non-terrestrial satellite networks.

Current data downlinks at X-band (8.02-8.4 GHz) are becoming an increasing constraint on the amount of data that can be handled. Therefore, the use of higher frequencies is necessary to increase the transmission capacity. For example, the frequency band allocated to telemetry at Ka-band (25.5-27.0 GHz) will provide the required bandwidth for high data rate downlink in future EO missions.

Data downlink systems operating at X-band predominantly use low gain (typically 6 dBi) fixed coverage isoflux antennas due to their simplicity and reliability. The use of such antennas may be considered for Ka-band (i.e., design scaled from X-band). However, the use of three times higher frequencies in the Ka-band, compared to the X-band, implies not only substantially higher free space losses (i.e., about 10 dB) but also higher propagation attenuation and uncertainty losses caused by the proximity of the Ka-band to the 22 GHz water vapor absorption band. It results in a definite need for the design and development of higher gain, isoflux, downlink antennas to meet the anticipated gain requirements for increased data rates and compensate for the other losses at Ka-band compared to X-band.

Among the existing solutions, helix antenna [1] and multi-stage choke rings antennas, employing a multimode cylindrical open waveguide [2] or a ridged aperture [3] as feeder, are the most common solutions to design circularly polarized isoflux antennas. Recently, new solutions based on the use of a metasurface [4] or an impedance surface fed by a low-profile short hat feed [5] have been suggested. All these antennas are not suitable to be installed on a CubeSat. On the contrary, the possibility to integrate a high-gain deployable reflectarray on a CubeSat for a mission on Mars has been recently demonstrated [6]. Thus reflectarrays, characterized by low profile, mass, and volume, can represent a promising solution for a new generation of low-orbit satellite communication constellations [7].

In this paper, a low-profile reflectarray antenna with an isoflux pattern working in Ka-band is proposed for use in a CubeSat on a low Earth orbit. In particular, a modified Biogeography Based Optimization procedure, named M_QC_{10}-BBO, and the Social Network Optimization (SNO) have been exploited to synthesize the phase delay map required to obtain the isoflux pattern. Then, the local periodicity approach has been used to set the reflectarray elements' dimensions.

II. Reflectarray Optimization

A. Definition of the mask

The reflectarray antenna is supposed to be mounted on a CubeSat orbiting at 1100 km above the Earth surface. The isoflux pattern gives a coverage of 40° with a circular beam footprint of about 800 km of diameter. The desired antenna gain at nadir is assumed greater than 9 dBi at the central frequency of 30 GHz. The allowed ripple in the illuminated zone is 2 dB, while the side lobe levels for $\theta > 30°$ are below –15 dB.

B. Optimization algorithms

Among the different available global optimization approaches, as the Genetic Algorithm (GA) [8] or the Particle Swarm Optimization (PSO) [9], here an enhanced version of the Biogeography Based Optimization (BBO) [10], the M_QC_{10}-BBO, and the Social Network Optimization are adopted, since they have already shown good performance when applied to antenna problems and in particular to the optimization of reflectarrays [11]–[15]. In the following, their principal characteristics are summarized.

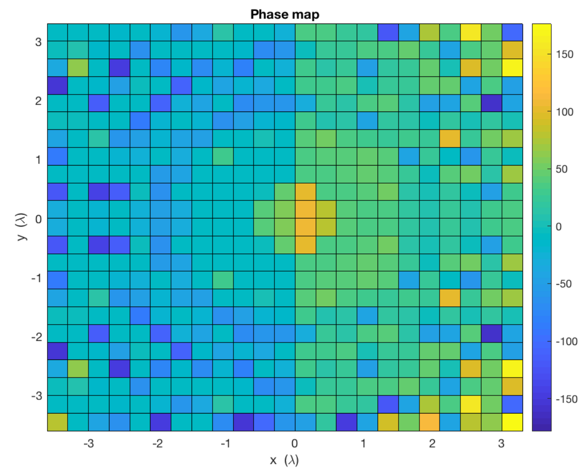
As the standard BBO, also the M_QC_{10}-BBO is inspired by the distribution of biological organisms in different geographic areas and their migration from one place to another. The possible solutions are represented by 'islands or 'habitats', and their fitness score is represented by their Habitat Suitability Index (HSI). Depending on the value of the HSI associated with the different habitats, species migrate from one to another; this transition of features from one solution to another is regulated by the emigration (μ) and immigration (λ) rates. Differently from the BBO, in the M_QC_{10}-BBO they have a quadratic dependence from the number of species in a habitat, and this helps to improve the convergence of the high performing solutions to the optimum. Another reason that can limit the BBO performance is that it is a too much 'deterministic' approach and, therefore, it has been modified introducing a novel implicit restart procedure, named "cataclysm": if the fitness value does not change for $5n$ following iterations, all the solutions, but not the best, are destroyed (cataclysm) and new ones are randomly generated. These modifications of the standard BBO have been codified in the acronym of the approach, adding "MQ" for the type of mutation model adopted, and introducing "C10", where 10 is n, and therefore gives the information about the number of iterations between two following cataclysms.

The SNO has been inspired by the process of diffusion of information in online social networks. For this reason, two data structures have been defined, that of the users, forming the population used by the algorithm, and the post written by the users. These variables of the optimization problem are instead codified in post status, related to the opinions of the users, and evolve during the optimization procedure. At each iteration, the post status change according to the interaction among users, which could occur through two different networks: the users' friends and the followers. Users belonging to friends group are strongly connected, and friendship evolves according to the number of common friends among users. The network of the follower is characterized by weaker connections among its members, that evolve based on the previous reputation and of the visibility of the users: when a user publishes a post with high visibility, his reputation increases.

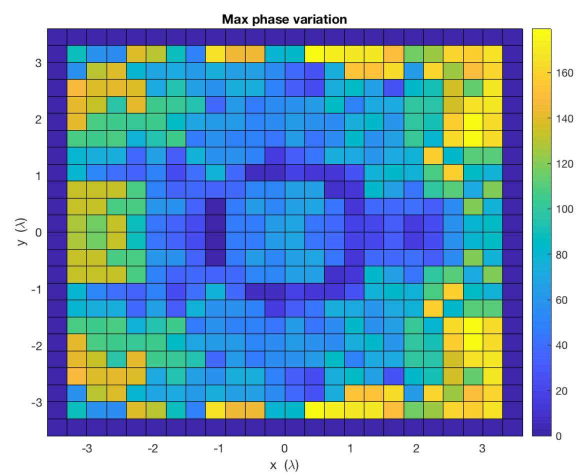
III. Preliminary Results

The M_QC_{10}-BBO and the SNO have been applied to the design of a small-medium size square RA, consisting of 24×24 unit-cell. The reflectarray is center-fed with the horn described in [16].

The phase of the reflection coefficient provided by each re-radiating element is controlled through the degrees of freedom of the problem, that are the geometrical parameters of the unit-cells. If, as in the considered case, each unit-cell has only one variable geometrical parameter, the total number of variables would be 576, but, thanks to the symmetries, it reduces to



(a)



(b)

Fig. 1: (a) Phase map obtained with the SNO (left) and the M_QC_{10}-BBO (right); (b) maximum variation between the phase provided by each unit-cell with respect to the adjacent ones.

144. Since the aim of the optimization procedure is to design the reflectarray in such a way its radiation pattern satisfied the constraints defined in Sect. II-A, the cost function is defined as the quadratic error between the evaluated field and the upper and lower masks. The phase map obtained at the end of the optimization process carried on with the SNO and the M_QC_{10}-BBO are shown on the left and right part of the same plot of Fig. 1a. The maximum variation between the phase of each cell and the adjacent ones is shown in Fig. 1b: it appears that in the central part of the RA this variation is kept down, while it increases in correspondence of the most external cells and in particular for those at the corners, that however provides a weak contribution to the total re-radiated field, mainly affecting the side lobes.

In Figs. 2 and 3 preliminary results obtained with the SNO

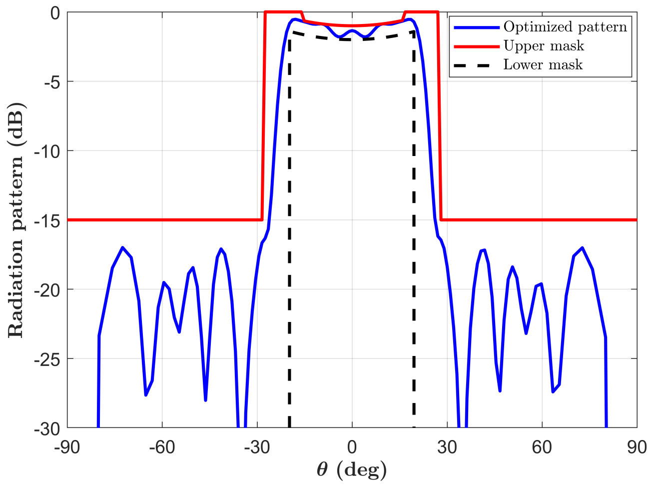


Fig. 2: Radiation pattern of the reflectarray optimized with the SNO in the plane $\phi = 0°$ and masks adopted for the optimization.

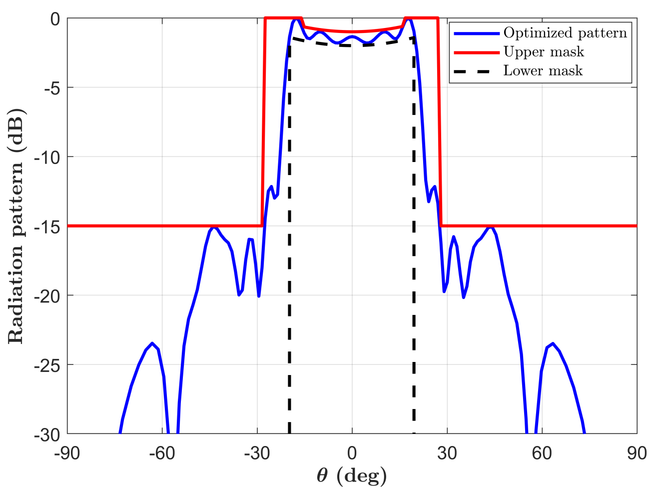


Fig. 3: Radiation pattern of the reflectarray optimized with the SNO in the plane $\phi = 90°$ and masks adopted for the optimization.

are shown: they are the radiation patterns in the two principal planes obtained at the end of the optimization process. In the figures the masks are also plotted: in both the planes they are satisfied nearly everywhere. Same consideration can be done also relatively to Fig. 4, where the 3D radiation pattern evaluated with the M_QC_{10}-BBO is shown, together with the adopted masks. All these results confirm the effectiveness of the proposed procedures and the antenna feasibility.

IV. Conclusions

The possibility to use a global optimization approach for the design of an isoflux reflectarray for CubeSat applications is here investigated. The obtained preliminary results are encouraging and prove the antenna feasibility.

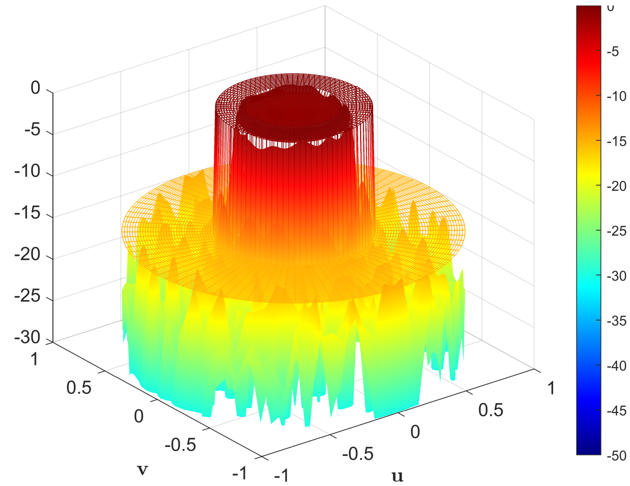


Fig. 4: 3D radiation pattern of the reflectarray optimized with the M_QC_{10}-BBO and corresponding masks.

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