Evaluation of Low-Cost Compact Multi-beam Reflectarray Antenna

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***Abstract*—A technique for the design of passive multi-beam reflectarray antennas based on a one-feed-per-beam configuration is presented. The reflection coefficients modeling the behavior of the reflectarray cells are selected to equalize the performance of all feeds in the system. An optimization process is proposed, which is based on the compensation of the phase errors in the reflected fields tangential fields associated to each feed position. Using this technique, a compact multi-beam antenna is designed. An offset focal arc geometry is introduced, which prevents feed blockage while providing wide-angle scanning ranges in a compact configuration (F/D below 0.7).Highly directive beams are simultaneously achieved for a 50-degree range while showing a scan loss of 0.4 dB, side-lobe levels (SLL) below -15 dB and minimal overall distortion in the beam shapes.**

***Index Terms*—compact antennas, reflectarray, multi-beam, Ka-band.**

I. INTRODUCTION

Over the past years there has been an increasing interest in high-throughput satellite communications, typically in Ka-band. High-gain wide-angle beam-scanning and multi-beam antennas are an essential component in these systems [1], [2], in particular for the ground segment. Large active arrays provide great flexibility thanks to their electronic reconfigurability, but suffer from lossy distribution networks and prohibitively expensive prices [3]. Space-fed antennas such as reflectarrays, transmitarrays or metasurfaces provide a cost-effective and low-loss alternative.

When it comes to beam-scanning reflectarray antennas, the steering can be achieved in two ways. The first one consists on incorporating an active element in the reflectarray cell, either electronic [4] or mechanical [5]. These designs have the potential for the highest flexibility thanks to the ability to alter each element's response, but suffer from complex and heavy control circuitry –which increases with aperture size– and low efficiency due to element losses and poor control resolution. The second way, which is the focus of this contribution, relies on mechanical changes to the overall antenna (i.e. movements and rotations of the reflectarray, feed element or both) to change the panel illumination and thus the radiated beam. This results in a more restrictive design in terms of reconfigurability. In exchange, it can often reduce the complexity of the design, thus reducing the production and material costs. Since the radiated beams depend only on the relative position of the feed, these designs are particularly well-suited for a one-feed-per-beam multi-beam system.

Mechanical beam scanning systems rely on a reflectarray response that focuses the reflected beam in different directions based on the panel illumination generated by the feed. A popular geometry for this purpose is based on positioning the feed along a 'focal arc' centered in a point on the reflectarray surface –typically the center. Multiple examples can be found in the literature [6]–[8], where wide scanning ranges are achieved by setting the beam direction at or near the specular reflection direction for each feed. These designs all suffer from beam blockage effects around the broadside direction, and they are ill-suited for a multi-beam system since the arc of feeds would introduce substantial distortion to all the beams. We propose a similar geometry where an offset has been applied to the focal arc, eliminating blockage problems while retaining wide-angle scanning ranges.

II. DESIGN PRINCIPLES

Reflectarray antennas rely on introducing a variable phase shift to the incident electromagnetic fields, which is defined at discrete points along the reflectarray surface [9]. A unit cell of the array is characterized by how it relates the incident and reflected fields, which takes the form of a matrix of reflection coefficients. For a linearly polarized antenna, this is expressed as

$$\begin{pmatrix} E_x^r(\vec{r}_n) \\ E_y^r(\vec{r}_n) \end{pmatrix} = \begin{pmatrix} \rho_n^{xx} & \rho_n^{xy} \\ \rho_n^{xy} & \rho_n^{yy} \end{pmatrix} \cdot \begin{pmatrix} E_x^i(\vec{r}_n) \\ E_y^i(\vec{r}_n) \end{pmatrix}, \tag{1}$$

where $E_{x|y}^i$ and $E_{x|y}^r$ represent the $x|y$ Cartesian field components associated to the incident and reflected fields respectively, and $\vec{r}_n = (x_n, y_n, 0)$ is the position of the n-th cell on the reflectarray surface. Henceforth, the analysis is particularized for a linear x-polarized antenna, and thus the design technique is developed around obtaining the appropriate phase distribution for the E_x^r component. The direct radiation coefficient ρ_n^{xx} is modeled as an ideal phase shifter independent of the incidence angle (i.e. $\rho_n^{xx} = e^{j\phi_n}$). The cross-coefficient ρ_n^{xy} is assumed to have negligible amplitude. These properties can be achieved by a low-loss linear-polarized cell with at least a full cycle (i.e. 360 degrees) of phase response range, low cross-talk between polarizations, and good angular stability for moderate incidence angle [10].

A. Single-feed collimated beam

It is known from array theory that in order to generate an optimally collimated beam in a direction (θ_0, φ_0), a progressive phase distribution on the array surface is required. Considering the phase of the incident field $\phi_n^i = \angle E_x^i(\vec{r}_n)$ on a cell located at $\vec{r}_n = (x_n, y_n, 0)$, the desired phase shift for each cell is given by:

$$\begin{aligned}\phi_n = &- k_0(x_n \sin\theta_0 \cos\varphi_0 + y_n \sin\theta_0 \sin\varphi_0) \\ &- \phi_n^i - \Delta\phi \end{aligned} \tag{2}$$

with $k_0 = \frac{2\pi}{\lambda_0}$ being the wave number in vacuum, $n = 1, 2, ..., N_c$ the index of the cell in the array, and $\Delta\phi$ an arbitrary phase constant. This ideal solution is analytical and it achieves the maximum gain for a given illumination of the reflectarray surface.

B. Multi-beam optimization

A system of N_f feeds is considered, with different positions and orientations relative to the reflectarray. Under these conditions, N_f different illumination patterns must be considered. Each feed also has an arbitrary preferred radiation direction (θ_k, φ_k) for its reflected beam. Thus, a different desired phase shift distribution is defined for each feed by applying (2):

$$\begin{aligned}\tilde{\phi}_{n,k} = &- k_0(x_n \sin\theta_k \cos\varphi_k + y_n \sin\theta_k \sin\varphi_k) \\ &- \phi_{n,k}^i - \Delta\phi_k \end{aligned} \tag{3}$$

for $k = 1, 2, ..., N_f$. It is apparent that an optimal phase distribution cannot be achieved simultaneously for multiple feeds. A compromise must be made to determine the phase shift for each cell that generates the least overall distortion to all of the beams. This can be calculated as the phase of the weighted mean of the ideal $\tilde{\rho}_{n,k}^{xx}$ values for each feed:

$$\phi_n = \angle\left(\sum_{k=1}^{N_f} w_k |E_{x,k}^i(\vec{r}_n)| e^{j\tilde{\phi}_{n,k}}\right) \tag{4}$$

where w_k is an additional weight factor introduced for each feed. This is used to correct for different levels of degradation in certain beams associated to the geometry (e.g. poorer illumination efficiency) or a highly oblique beam directions. This expression depends on (3), which has a constant phase constant factor for all cells $\Delta\phi_k$. This factor is independent for each feed, and should be selected such that the overall error between the actual phase distribution ϕ_n and the optimal one $\tilde{\phi}_{n,k}$ is minimized:

$$\begin{aligned}\Delta\phi_k &= \arg\min_{\Delta\phi_k} \sum_{n=1}^{N_c} |E_{x,k}^i(\vec{r}_n)| |e^{j\phi_n} - e^{j\tilde{\phi}_{n,k}}| \\ &= \arg\min_{\Delta\phi_k} \sum_{n=1}^{N_c} |E_{x,k}^i(\vec{r}_n)| \sqrt{1 - \cos(\phi_n - \tilde{\phi}_{n,k})} \end{aligned} \tag{5}$$

It can be observed that the phase shift distribution on the reflectarray surface, as described by (4), requires a phase constant to be defined for every feed. However, the selection of the phase constant should be done to minimize the errors in an existing phase shift distribution. To solve this, an iterative process is proposed here:

1) Generate a phase shift distribution that can be considered a rough approximation of the final result. This can be the ideal $\tilde{\phi}_{n,k}$ values for a given feed, using an arbitrary phase constant.
2) Calculate $\Delta\phi_k$ for every feed using (5).
3) Calculate the optimal ϕ_n for the selected phase constants with (4).
4) Re-calculate the optimal phase constants for the new phase shift distribution. If there is a substantial change from the previous values, go back to step 3. Otherwise, take the calculated ϕ_n.

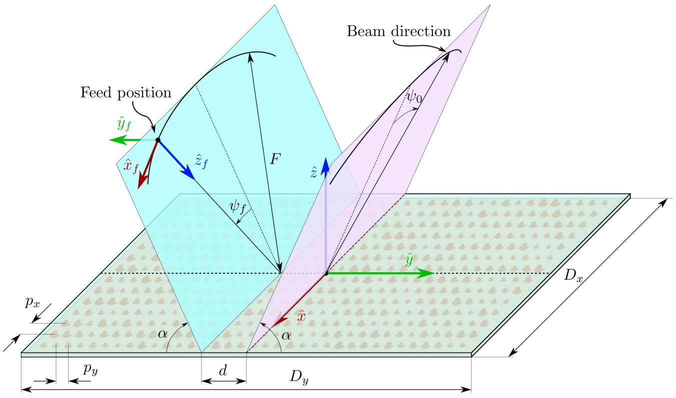


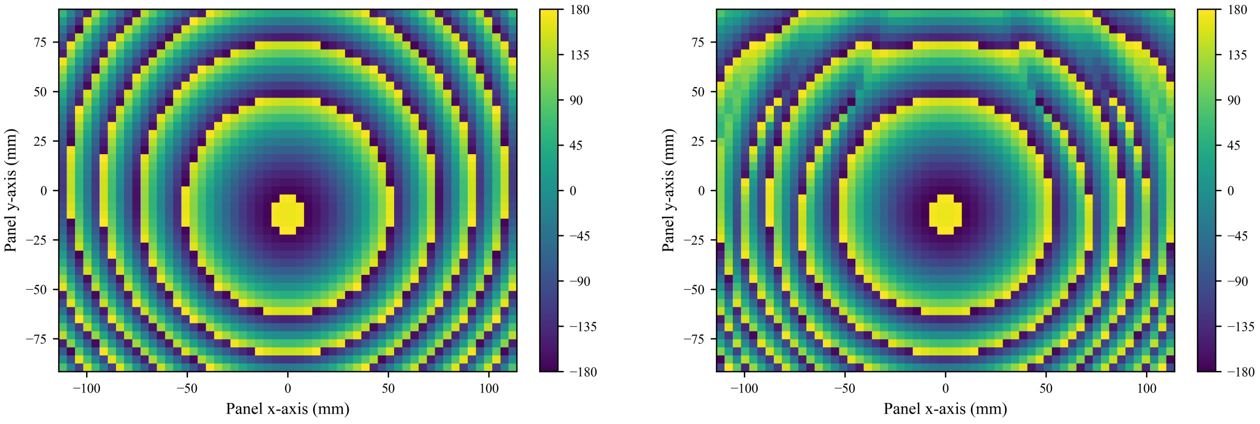
Fig. 1. Antenna geometry based on an arc of feeds in a plane oblique to the reflectarray surface.

III. Validation

A. Antenna geometry

To validate the synthesis process, a reflectarray antenna is designed at 29.5 GHz.The reflectaray panel is made up of 56 by 45 unit cells arranged in a rectangular grid with periodicity of 4.07 mm ($0.4\lambda_0$) in both dimensions. The overall size of the reflectarray panel is 183 by 228 mm. Feed elements are positioned along an arc of radius $F = 0.67D_y$, as shown in Fig. 1. Reflectarray scanning antennas based on feed focal arcs have been used previously to achieve wide-angle scanning reflectarray antennas [6] [7]. However, these designs suffered from beam blockage by the radiating feed for certain beam directions. They were also meant for a single movable feed rather than multiple coexisting ones due to blockage limitations.

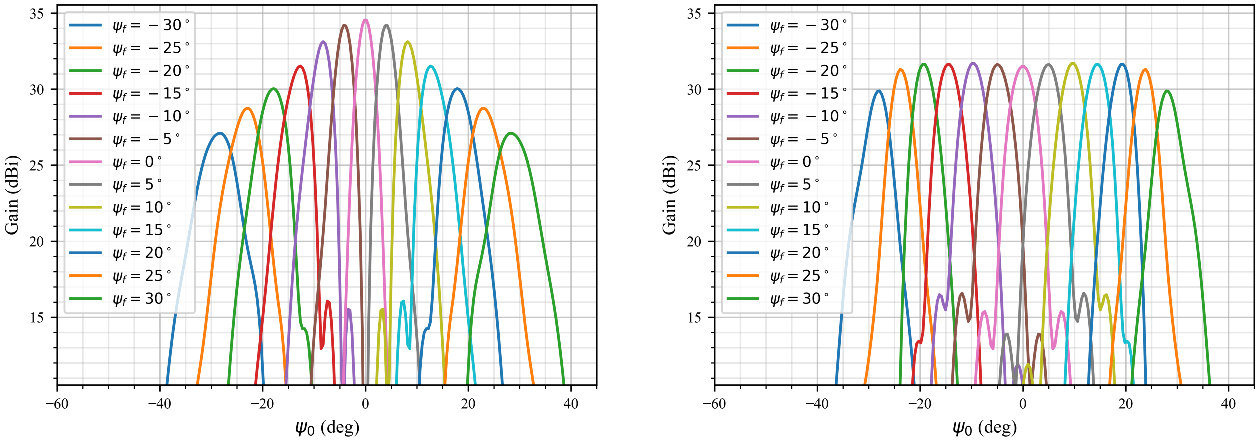
This design introduces a tilt angle $\alpha = 70°$ to the plane containing the feeds in order to prevent distortions by blockage. The scanned plane is thus also oblique to the reflectarray surface, as it is defined by the specular reflection of the incident beams generated by each feed. All the feeds have an identical linear-polarized field pattern, and they oriented towards the middle point of the intersection between the feed and reflectarray planes. A rotation is applied to each of them so that their E-plane is the same as the feed plane. A ‘cos-q’



(a)

(b)

Fig. 2. Phase shift distribution ϕ_n for (a) the initial single-feed design and (b) the optimized multi-feed design.



(a)

(b)

Fig. 3. Radiation pattern cut along the scanned plane for (a) the initial single-feed design and (b) the optimized multi-feed design.

field model is used to reproduce the illumination pattern of a typical small horn [11]:

$$\vec{E}(\vec{r}) = E_0 \frac{k_0}{2\pi r} e^{-jk_0 r} (\cos\varphi\hat{\theta} - \sin\varphi\hat{\varphi}) \cos^q\theta, \qquad (6)$$

which results in a pure x-polarized radiation pattern of the form $G(\theta) = G_0 \cos^{2q}\theta$, where q was set to 6 and the gain of the feeds to 14 dBi.

In order to reduce the blockage caused by the feeds, the feed plane is offset a certain distance d from the reflectarray center point. Using geometric optics and considering a point feed, the contributions from the cells at the $y = -D_y/2$ edge of the panel will experience no blockage if $d \geq D_y/2 - 2F\cos\alpha = 7.6$ mm. A value of $d = 10.3$ mm is selected to account for the size of a physical feed. The resulting an illumination taper at both $x = \pm D_x/2$ and $y \pm Dy/2$ edges is -12 dB or lower for all feeds.

B. Results

An initial phase shift distribution is obtained using (2) for the feed situated at $\psi_f = 0$, i.e. the middle point of the arc, in order to generate a collimated beam towards $\psi_0 = 0$ (see Fig. 2a). This is used as the starting point for the optimization process described in Section II-B. Additional feeds are defined along the arc with a 5-degree spacing for the interval $\psi_f = -25, -20, ..., +25^\circ$. The desired radiation direction for each one is set as $\psi_0 = \psi_f$ in order to obtain their optimal individual phase distributions $\tilde{\phi}_n^k$. After two iterations, the optimization algorithm converges with all of the recalculated phase constants $\Delta\phi^k$ differing by less than 0.5° from their previous values. The final phase shift distribution ϕ_n is shown in Fig. 2b.

The multi-beam and scanning performance of the resulting phase distribution is evaluated by studying the radiation diagram cut along the scanned plane for different feed positions, shown in Fig. 3. Beam distortion is minimal for feeds in the $\psi_f = -25^\circ$ to $\psi_f = +25^\circ$ range, with similar beamwidth

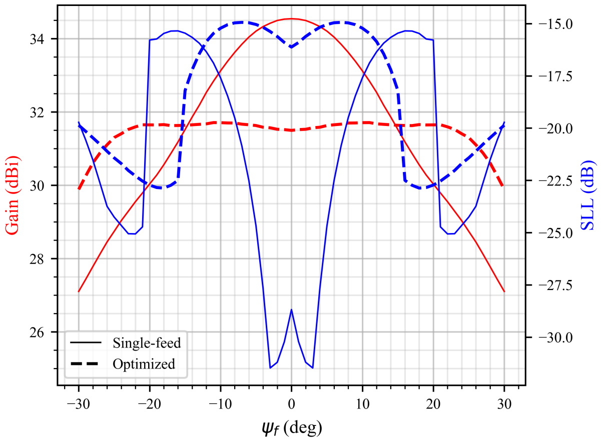


Fig. 4. Scanning performance comparison between a single-feed and an optimized multi-feed design.

and gain levels. In contrast, the single-feed design shows a significant scan loss and beam widening.

Another critical parameter for multi-beam application is the side-lobe level (SLL) along the scanned set of directions, since the side-lobe from one beam introduces interference to neighboring beams. These are all kept below -15 dB in the scanned plane, which should introduce minimal interference between beams. Fig. 4 shows a summarized view of the scanning performance of this antenna before and after the optimization in terms of both maximum gain and relative SLL along the scanned plane. Notice that the optimized design suffers a drop of about 3dB of maximum gain compared to the single-feed antenna, but achieves a flat gain across the -25° to $+25^\circ$ scanning range with a scan loss of 0.4 dB. In contrast, the single-feed design experiences clear de-focusing and shows a scan loss of nearly 6 dB for the same range.

IV. CONCLUSION

In this work, a simple yet powerful optimization technique is presented for the design of multi-feed reflectarray antennas. The design process described here can be applied to any reflectarray antenna which requires proper operation under multiple illumination patterns (i.e. multiple feeds, feed positions and/or orientations), either simultaneously or switched. No restrictions are imposed to the desired beam shape associated to each feed, so it would be possible to implement multiple relatively complex radiation patterns. However, a compromise in accuracy is necessary in order to accommodate all the beams with reasonable distortion.

A wide-angle multi-beam antenna is designed using this technique. A 50-degree scanning range is achieved with minimal gain fluctuations between beams. A novel offset focal arc geometry is used, which focuses each beam towards its specular reflection direction. This builds on top of previous works using similar non-offset setups by preventing beam distortions caused by feed blockage.

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