Improved Cross-Polarization Performance in Reflectarray Antennas by Direct Optimization of the XPD and XPI Parameters

Daniel R. Prado*, Manuel Arrebola†, Marcos R. Pino†, George Goussetis*
*Institute of Sensors, Signals and Systems, Heriot-Watt University, Edinburgh, U.K. Email: {dr38, g.goussetis}@hw.ac.uk
†Group of Signal Theory and Communications, Universidad de Oviedo, Spain. Email: {arrebola, mpino}@uniovi.es

***Abstract*—Current satellite missions for communications demand a high polarization purity, with figures of merit such as the crosspolar discrimination (XPD) better than 33 dB. In order to accomplish these values, some kind of optimization must be carried out to improve cross-polarization performance. The most common approach is to minimize the crosspolar component of the radiation pattern in the region of interest. Nevertheless, this strategy produces suboptimal results since the figure of merit for cross-polarization performance is optimized indirectly. Thus, it is proposed to directly optimize the XPD to improve the polarization purity of reflectarrays for satellite missions. For that purpose, the generalized Intersection Approach algorithm is employed to optimize a very large shaped-beam reflectarray for a direct broadcast satellite application with a European coverage. It is shown that directly optimizing the cross-polarization figure of merit provides better results than the usual approach of minimizing the crosspolar pattern.**

***Index Terms*—Reflectarray, satellite mission, crosspolar discrimination (XPD), crosspolar isolation (XPI), shaped beam, direct broadcast satellite**

I. INTRODUCTION

The improvement of cross-polarization performance in shaped-beam reflectarray antennas for space applications is a challenging task. Some missions, such as direct broadcast satellite (DBS), require values of the crosspolar discrimination (XPD) or cross-polar isolation (XPI) parameters better than 33 dB. Thus, some techniques are required to improve these figures of merit. In the past years, a number of strategies have been proposed to minimize the cross-polar pattern of reflectarray antennas. The first approaches dealt with a symmetric arrangement of the unit cells [1], [2] in order to cancel the contribution of the reflectarray elements to the cross-polar pattern. Another approach was to directly minimize the cross-polarization introduced by each reflectarray element, minimizing the undesired tangential field [3], [4]. The main advantage of these techniques that work at the element level is that they are relatively fast. However the crosspolar pattern is minimized indirectly, the techniques are limited in scope and provide suboptimal results.

A better approach is to work at the far field level, directly minimizing the cross-polar component by means of a cost function. The first attempts were done with a full-wave technique based on local periodicity (FW-LP) [5], resulting in a slow algorithm which only dealt with one polarization and small reflectarrays. Later, some computational improvements were introduced in [6] that allowed to optimize very large reflectarrays with a FW-LP tool and handle thousands of degrees of freedom with success. A faster approach for the direct optimization of reflectarray antennas is the use of databases instead of a FW-LP tool, since computations are considerably accelerated [7]. All these approaches have in common that the cost function minimizes the crosspolar component of the far field, so that parameters of interest such as the XPD or the XPI are improved indirectly, thus providing again suboptimal results.

In this work, it is proposed to directly optimize the XPD or XPI parameters in the cost function. In this way, the cross-polarization performance of the final reflectarray antenna will improve. It will be shown how this strategy provides better results than to directly minimize the crosspolar pattern. For this task, the generalized Intersection Approach algorithm is chosen to optimize a large reflectarray for DBS service as an example of application. Nevertheless, the technique is general and may be employed for other applications such as multibeam or synthetic aperture radar, where cross-polarization performance is also important.

II. ANTENNA DESIGN

A. Antenna Definition and Requirements

A representation of the antenna geometry under consideration is shown in Fig. 1. The reflectarray is elliptical with a total of 4 068 elements distributed in a regular grid with 74 and 70 unit cells in the main axes. The periodicity is 14 mm × 14 mm while the working frequency is 11.85 GHz. The feed is modelled with a $\cos^q\theta$ function with $q = 23$, generating an illumination taper of -17.9 dB at the edges. In addition, the feed is at $(-358, 0, 1070)$ mm with regard to the reflectarray center. The antenna is placed on a satellite in geostationary orbit at 10° E longitude. For the unit cell substrate, the bottom layer has a height of $h_A = 2.363$ mm and a complex relative permittivity $\varepsilon_{r,A} = 2.55 - j0.0023$, while the top layer has a height of $h_B = 1.524$ mm and a complex relative permittivity $\varepsilon_{r,B} = 2.17 - j0.0020$.

The copolar requirements for both linear polarizations are shown in Fig. 2. A European footprint with two distinct coverages zones has been chosen, each with a different copolar gain specifications: 28.5 dBi for Zone 1 and 25.5 dBi for Zone 2. The outer solid contours for each zone represent

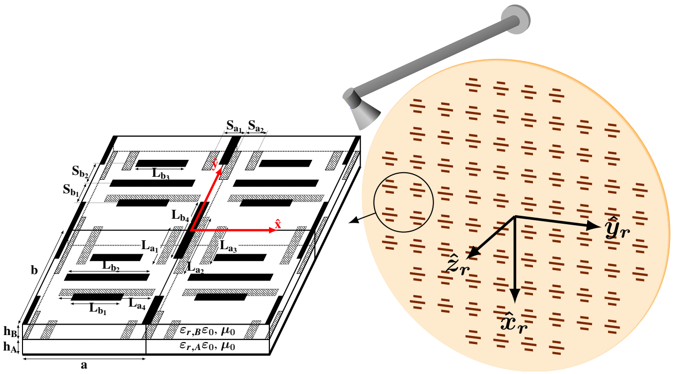


Fig. 1. Representation of the reflectarray configuration considered in this work and the unit cell for dual-linear polarization applications.

the specifications taking into account typical satellite pointing errors (0.1° in roll and pitch, 0.5° in yaw). The outer contours will be employed in the optimization as well as for the representation of the obtained results.

B. The Generalized Intersection Approach

For this work, the generalized Intersection Approach (IA) [8] has been chosen as optimization algorithm. It is an iterative algorithm that performs two operations on the radiated field at each iteration:

$$\vec{E}_{i+1} = \mathscr{B}\left[\mathscr{F}\left(\vec{E}_i\right)\right], \tag{1}$$

where $\mathscr{F}$ is the forward projector, which computes the radiated field and then trims it according to some specifications; and $\mathscr{B}$ is the backward projector, which minimizes the distance between the current radiated field by the reflectarray and the field trimmed by the forward projector that complies with the specifications.

The forward projector imposes the requirements of the radiation pattern by means of masks for the copolar and crosspolar patterns. In this way, following the notation in [6], the radiation pattern should fulfil the following condition:

$$T_{\text{cp,min}}(u,v) \leq G_{\text{cp}}(u,v) \leq T_{\text{cp,max}}(u,v), \tag{2a}$$

$$T_{\text{xp,min}}(u,v) \leq G_{\text{xp}}(u,v) \leq T_{\text{xp,max}}(u,v), \tag{2b}$$

where T_{min} and T_{max} denote the minimum and maximum mask specifications, respectively; and G_{cp} and G_{xp} are the copolar and crosspolar components, respectively, of the radiation pattern in gain. Using the conditions in (2), the crosspolar pattern is minimized and thus the XPD and XPI are optimized indirectly. In this work it is proposed to substitute the condition (2b) by another condition which takes into account the figure of merit of interest for cross-polarization, either the XPD or the XPI, while the condition in (2a) is left untouched to guarantee that copolar requirements are also met.

C. Initial Copolar Design

Before performing the optimization of the cross-polarization parameters, a phase-only synthesis (POS) in dual-linear polarization is carried out in order to obtain a suitable starting point for the crosspolar optimization. Thus, the followed approach is a two-step procedure. The POS produces a phase-shift that each reflectarray element must provide in order to radiate the desired copolar pattern. Then, the layout is obtained using a zero-finding routine [9], adjusting the lengths of the dipoles shown in Fig. 1. Fig. 3 shows the initial radiation pattern for polarization X. As it can be seen, the copolar pattern perfectly complies with the requirements in the two coverage zones. Similar results were obtained for polarization Y. Regarding the cross-polarization performance for Zone 1, the XPD_{min} is 31.46 dB and the XPI is 30.13 dB, the same for both linear polarizations. For Zone 2, the XPD_{min} is 27.98 dB and 28.45 dB for polarizations X and Y, respectively; while the XPI is 25.92 dB and 26.44 dB for polarizations X and Y, respectively.

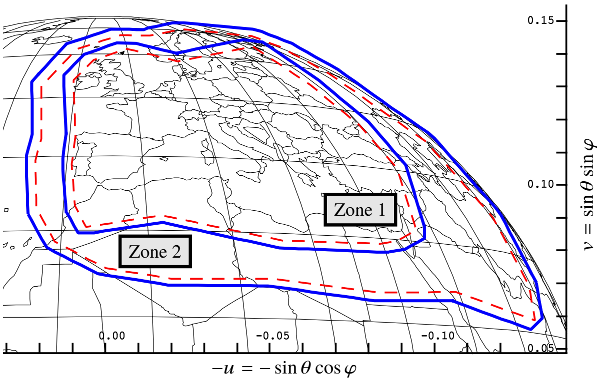


Fig. 2. European footprint with two coverage zones. The copolar requirements are 28.5 dBi and 25.2 dBi for Zones 1 and 2, respectively.

III. CROSS-POLARIZATION IMPROVEMENT

A. Optimization of XPD and XPI

For the purpose of the cross-polarization performance optimization, the XPD and XPI are considered in linear scale. Thus, the XPD is defined as the ratio, point by point, of the copolar gain and the crosspolar gain:

$$\text{XPD}(u,v) = \frac{G_{\text{cp}}(u,v)}{G_{\text{xp}}(u,v)}, \quad \forall(u,v) \in \Omega, \tag{3}$$

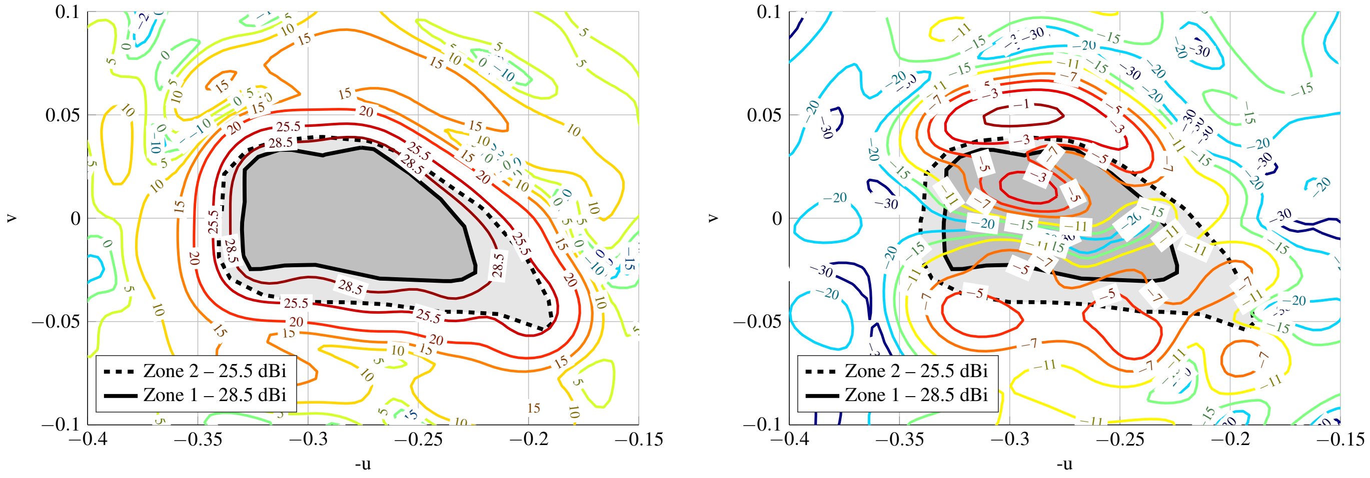
where Ω is a subset of the visible region $(u^2 + v^2 < 1)$ corresponding to a coverage zone. The performance of the XPD is constrained by its minimum value, which will be the one considered in the optimization:

$$\text{XPD}_{\text{min}} = \min\left\{\text{XPD}(u,v)\right\}. \tag{4}$$

Similarly, the XPI is defined as the ratio between the minimum copolar gain and the maximum crosspolar gain for the coverage zone:

$$\text{XPI} = \frac{\min\left\{G_{\text{cp}}(u,v)\right\}}{\max\left\{G_{\text{xp}}(u,v)\right\}}, \quad (u,v) \in \Omega. \tag{5}$$

Taking into account the definition of XPD_{min} and XPI, the goal of the optimization is to maximize their values. Thus,



(a) (b)

Fig. 3. Radiation pattern in dBi for polarization X obtained after the POS. (a) Copolar. (b) Crosspolar.

only minimum mask specifications are necessary, fulfilling the following conditions:

$$T_{\mathrm{XPD_{min}},\min} \leq \mathrm{XPD_{min}}, \tag{6a}$$

$$T_{\mathrm{XPI},\min} \leq \mathrm{XPI}. \tag{6b}$$

Then, condition (2b) in the forward projector is substituted by either (6a) or (6b), depending on the parameter that will be optimized.

B. *Crosspolar Optimization Results*

The proposed approach will be tested by performing three different optimizations. The first optimization consists in minimizing the crosspolar pattern using the condition (2b) in the forward projector. In this case, the template is set 40 dB below the maximum copolar gain to reduce the crosspolar pattern as much as possible. The second optimization uses (6a) to maximize the $\mathrm{XPD_{min}}$, and the template is also set to 40 dB. Finally, the third optimization employs the condition (6b), setting the template to 40 dB to directly improve the XPI. For all these optimizations, the starting point is the same (shown in Fig. 3), and the copolar template specified by means of (2a) is also considered, in order to maintain the copolar gain within specifications while the cross-polarization performance is improved.

Table I shows the results for the three optimizations including the starting point as reference. In all cases, the minimum copolar gain in both coverage zones for both linear polarizations complies with the requirements of 28.5 dB for Zone 1 and 25.5 dB for Zone 2. In addition, the cross-polarization performance was greatly improved. The first optimization strategy (XP opt., i.e. minimize the crosspolar far field) improves the $\mathrm{XPD_{min}}$ and XPI between 3.18 dB and 5.19 dB. The largest improvement is for the XPI in Zone 2, since the starting point presented a very low XPI. In this case, the XPI is improved 5.19 dB in polarization X and 4.63 dB in polarization Y.

When directly optimizing the $\mathrm{XPD_{min}}$, the achieved results are considerably better. In this case, the improvement in $\mathrm{XPD_{min}}$ and XPI for both coverage zones and polarizations range between 7.33 dB and 8.31 dB, which contrasts with the previous case where the improvements were lower. Since the $\mathrm{XPD_{min}}$ is the optimization parameter, its improvement is better than the XPI, as shown in Table I. In addition, due to the definitions in (4) and (5), the XPI is a stricter parameter than the $\mathrm{XPD_{min}}$, and the XPI will be always lower or equal than the $\mathrm{XPD_{min}}$, regardless of the parameter which is object of the optimization. Finally, optimizing the XPI improves the results of the XPI parameter with regard to the previous case, while keeping the overall improvement of the cross-polarization performance higher than when minimizing the crosspolar pattern.

Finally, Tables II and III summarize the improvement in cross-polarization performance for the three strategies with regard to the starting point. The new proposed approach of directly improving the $\mathrm{XPD_{min}}$ or XPI provides results that are 3 dB to 5 dB better than when minimizing the crosspolar pattern.

IV. CONCLUSION

This work has proposed the direct optimization of the figure of merit for cross-polarization to improve the performance of the final antenna. The usual approach consists in the minimization of the crosspolar component of the far field, so parameters such as the crosspolar discrimination (XPD) or crosspolar isolation (XPI) are optimized indirectly. Thus, in this work the direct optimization of the XPD and XPI has been addressed to improve the cross-polarization performance of reflectarrays for space applications. The chosen algorithm is the generalized Intersection Approach, where the copolar and crosspolar requirements are specified as minimum and maximum masks. Thus, by properly setting minimum masks attending to the definition of $\mathrm{XPD_{min}}$ and XPI, those

Table I
Results of the direct optimization of a reflectarray antenna with a European footprint with two coverage zones comparing different strategies: the usual approach of minimizing the crosspolar component of the radiation pattern (XP opt.) and the new strategy of directly optimizing the figure of merit (XPD$_{\text{min}}$ opt. and XPI opt.). CP$_{\text{min}}$ is in dBi, XPD$_{\text{min}}$ and XPI are in dB.

	Zone 1 (28.5 dBi)						**Zone 2 (25.5 dBi)**					
	Pol. X			**Pol. Y**			**Pol. X**			**Pol. Y**		
	CP$_{\text{min}}$	**XPD$_{\text{min}}$**	**XPI**	**CP$_{\text{min}}$**	**XPD$_{\text{min}}$**	**XPI**	**CP$_{\text{min}}$**	**XPD$_{\text{min}}$**	**XPI**	**CP$_{\text{min}}$**	**XPD$_{\text{min}}$**	**XPI**
Initial	29.29	31.46	30.13	29.32	31.46	30.13	26.03	27.98	25.92	26.03	28.45	26.44
XP opt.	29.30	35.10	34.57	29.26	35.60	33.38	26.27	31.85	31.11	26.31	31.63	31.07
XPD$_{\text{min}}$ opt.	29.00	39.64	37.46	29.08	39.36	37.46	25.96	35.96	33.46	25.67	36.76	33.81
XPI opt.	29.04	39.53	39.25	29.01	40.32	39.00	25.80	34.78	34.49	26.06	36.29	35.75

Table II
Improvement in dB of the cross-polarization performance for Zone 1.

	Pol. X		**Pol. Y**	
	XPD$_{\text{min}}$	**XPI**	**XPD$_{\text{min}}$**	**XPI**
XP opt.	3.64	4.44	4.14	3.25
XPD$_{\text{min}}$ opt.	8.18	7.33	7.90	7.33
XPI opt.	8.07	9.12	8.86	8.87

Table III
Improvement in dB of the cross-polarization performance for Zone 2.

	Pol. X		**Pol. Y**	
	XPD$_{\text{min}}$	**XPI**	**XPD$_{\text{min}}$**	**XPI**
XP opt.	3.87	5.19	3.18	4.63
XPD$_{\text{min}}$ opt.	7.98	7.54	8.31	7.37
XPI opt.	6.80	8.57	7.84	9.31

parameters can be effectively optimized. As an example, a large reflectarray for Direct Broadcast Satellite application has been considered with a European footprint with two different coverage zones. As starting point, a layout obtained after a phase-only synthesis is employed. Then, the geometry of the reflectarray was directly optimized following three different strategies: first, minimizing the crosspolar pattern, second maximizing the XPD$_{\text{min}}$ and third maximizing the XPI. The results show that all three strategies improve the cross-polarization performance while keeping the copolar pattern within requirements. However, the new proposed approach of directly improving the XPD$_{\text{min}}$ or XPI provides results that are 3 dB to 5 dB better than when minimizing the crosspolar pattern. This means that the improvement over the starting point is better than 7 dB, and reaches an improvement in the XPI of more than 9 dB. Finally, the proposed strategy may be applied to circular polarized reflectarrays as well as to the optimization over a certain bandwidth.

Acknowledgment

This work was supported in part by the Ministerio de Ciencia, Innovación y Universidades under project TEC2017-86619-R (ARTEINE); by the Ministerio de Economía, Industria y Competitividad under project TEC2016-75103-C2-1-R (MYRADA); by the Gobierno del Principado de Asturias/FEDER under Project GRUPIN-IDI/2018/000191; by the Gobierno del Principado de Asturias through Programa “Clarín” de Ayudas Postdoctorales / Marie Courie-Cofund under project ACA17-09; by Ministerio de Educación, Cultura y Deporte / Programa de Movilidad “Salvador de Madariaga” (Ref. PRX18/00424).

References

[1] D.-C. Chang and M.-C. Huang, “Multiple-polarization microstrip reflectarray antenna with high efficiency and low cross-polarization,” *IEEE Trans. Antennas Propag.*, vol. 43, no. 8, pp. 829–834, Aug. 1995.

[2] H. Hasani, M. Kamyab, and M. Ali, “Low cross-polarization reflectarray antenna,” *IEEE Trans. Antennas Propag.*, vol. 59, no. 5, pp. 1752–1756, May 2011.

[3] C. Tienda, J. A. Encinar, M. Arrebola, M. Barba, and E. Carrasco, “Design, manufacturing and test of a dual-reflectarray antenna with improved bandwidth and reduced cross-polarization,” *IEEE Trans. Antennas Propag.*, vol. 61, no. 3, pp. 1180–1190, Mar. 2013.

[4] R. Florencio, J. A. Encinar, R. R. Boix, G. Pérez-Palomino, and G. Toso, “Cross-polar reduction in reflectarray antennas by means of element rotation,” in *10th European Conference on Antennas and Propagation (EuCAP)*, Davos, Switzerland, Apr. 10–15, 2016, pp. 1–5.

[5] O. M. Bucci, A. Capozzoli, G. D’Elia, and S. Musto, “A new approach to the power pattern synthesis of reflectarrays,” in *Proc. URSI International Symposium on Electromagnetic Theory (EMTS’04)*, Pisa, Italy, May 23–27, 2004, pp. 1053–1055.

[6] D. R. Prado, M. Arrebola, M. R. Pino, R. Florencio, R. R. Boix, J. A. Encinar, and F. Las-Heras, “Efficient crosspolar optimization of shaped-beam dual-polarized reflectarrays using full-wave analysis for the antenna element characterization,” *IEEE Trans. Antennas Propag.*, vol. 65, no. 2, pp. 623–635, Feb. 2017.

[7] M. Zhou, S. B. Sørensen, O. S. Kim, E. Jørgensen, P. Meincke, and O. Breinbjerg, “Direct optimization of printed reflectarrays for contoured beam satellite antenna applications,” *IEEE Trans. Antennas Propag.*, vol. 61, no. 4, pp. 1995–2004, Apr. 2013.

[8] O. M. Bucci, G. D’Elia, G. Mazzarella, and G. Panariello, “Antenna pattern synthesis: a new general approach,” *Proc. IEEE*, vol. 82, no. 3, pp. 358–371, Mar. 1994.

[9] J. Huang and J. A. Encinar, *Reflectarray Antennas*. Hoboken, NJ, USA: John Wiley & Sons, 2008.