Comparative Study of Different Approaches to Analyze Unit Cells of Reflectarray Antennas

Andrés Gómez-Álvarez, Borja Imaz-Lueje, Daniel R. Prado, Manuel Arrebola and Marcos R. Pino
Group of Signal Theory and Communications, Universidad de Oviedo, Spain.
Email: {UO250487, bimaz, drprado, arrebola, mpino}@uniovi.es

***Abstract*—We present a comparative study of reflectarray antenna analysis using two different techniques. Two different reflectarrays are simulated, with an isoflux pattern and with a squared-cosecant pattern in elevation and sectored-beam in azimuth. Each antenna is analysed using two techniques to obtain the reflection coefficients matrix. Both techniques are based on the Floquet theorem assuming local periodicity. First, we use the commercial software HFSS to analyze reflectarray cells based on two stacked rectangular patches. The finite element method of HFSS is employed. The second method is an in-house ad hoc method of moments (MoM). In all cases, each reflectarray element is analyzed considering the real angle of incidence instead of the common approach of using normal incidence curves. Results show good agreement between the two approaches for the computation of the reflection coefficients as well as for the prediction of both the copolar and crosspolar components of the radiation patterns.**

***Index Terms*—Full wave analysis based on local periodicity, Ansys HFSS, finite element method (FEM), method of moments (MoM), reflectarray antenna, mega-constellation, 5G base station**

I. Introduction

When tackling the analysis of reflectarray antennas, there are a number of possibilities. On the one hand, reflectarray elements may be considered ideal phase shifters with no losses and no crosspolarization. [1]. This method is very fast, but it is only useful to predict the copolar pattern and it is not suitable to obtain the antenna layout. As an alternative to using ideal phase-shifters, full-wave simulation tools based on local periodicity (FW-LP) [2] may be employed. The main advantage of this approach is that it allows to simulate any arbitrary reflectarray element, although at the expense of higher computing time. A trade-off between flexibility and computing time may be achieved by analysis tools based on local periodicity aimed at particular unit cells, such as stacked patches [3] or dipoles [4]. These ad hoc tools need validation and it is usually done with commercial software or through measurements of prototypes.

In this work we aim to compare two of the above-mentioned approaches, i.e. a commercial full-wave analysis software, Ansys HFSS with its finite element method (FEM) solver in the present case [5], and an in-house ad hoc method of moments [3]. In both techniques, local periodicity is assumed for the analysis of the unit cell. To this end, we have developed an automatic methodology to analyze a reflectarray antenna considering the real angle of incidence at each reflectarray element. Two different reflectarray antennas are analyzed, one with an isoflux pattern for use in mega-constellation applications, and another with a squared-cosecant pattern in elevation and sectored-beam in azimuth for 5G base stations. Results are shown for the reflection coefficients on the reflectarray surface as well as the radiation pattern showing excellent agreement between the two analysis techniques.

II. Reflectarray Analysis

A. Reflection Coefficients and Radiation Pattern

We consider a single-offset reflectarray configuration comprised of a feed whose phase center is located in the focal point, and a planar surface with K reflecting elements. The feed generates an incident field on the reflectarray surface, $\vec{E}_{\text{inc}} = E_{\text{inc},x}\hat{x} + E_{\text{inc},y}\hat{y}$, which is reflected by the elements obtaining the field $\vec{E}_{\text{ref}} = E_{\text{ref},x}\hat{x} + E_{\text{ref},y}\hat{y}$. Both fields are related through the matrix of reflection coefficients:

$$\boldsymbol{R}_k = \begin{pmatrix} \rho_{xx,k} & \rho_{xy,k} \\ \rho_{yx,k} & \rho_{yy,k} \end{pmatrix} \tag{1}$$

with $k = 1, 2, \ldots, K$. This matrix is computed by a FW-LP tool by embedding the unit cell in a periodic environment comprised of the same unit cell [6]. Each matrix component corresponds to the fundamental Floquet harmonic, although the cell structure is analyzed taking into account several Floquet harmonics [2]. In addition, mutual coupling and specular reflection from the ground plane are also taken into account. The matrix in (1) completely characterizes the electromagnetic behavior of the reflectarray element.

Once the tangential reflected field $\vec{E}_{\text{ref}}$ is obtained on the reflectarray surface, the radiation pattern in dual-linear polarization may be readily obtained by applying Love's equivalence principle as in [7]. The copolar and crosspolar patterns are obtained by using Ludwig's third definition of cross-polarization [8].

B. Cell Analysis with Commercial and In-House Tools

The computation of the radiation patterns for reflectarray antennas as laid out previously, can be done with classical array theory [9] by calculating the reflected tangential field $\vec{E}_{\text{ref}}$ at each reflectarray element and then applying the Fourier transform to obtain the far field. However, in order to obtain $\vec{E}_{\text{ref}}$, the reflection coefficients in (1) must be computed with a FW-LP numerical technique and it is thus a very important step.

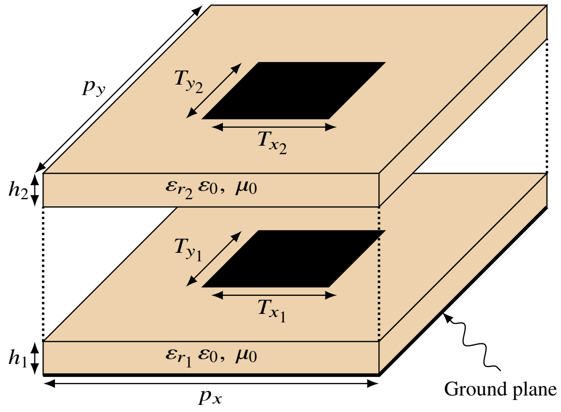

Fig. 1. Sketch of the reflectarray unit cell employed in this work. It is comprised of two stacked microstrip rectangular patches backed by a ground plane.

The value of the reflection coefficients will depend on each particular unit cell. In the present case, we employ a unit cell consisting in two layers of stacked microstrip rectangular patches backed by a ground plane [10], as depicted in Fig. 1. There are two options for its analysis: using a general commercial software (HFSS in this case, although other suites could be employed), or an in-house ad hoc analysis tool. Both options will be reviewed next.

1) Analysis with HFSS: The use of general purpose commercial software for the analysis of reflectarray unit cells has the advantage of a greater flexibility to analyse arbitrary elements compared to in-house ad hoc tools. However, this generality limits its application when large arrays comprised of hundreds or thousands of elements are analysed. To partially overcome this limitation, we have developed a methodology to facilitate the analysis of reflectarray antennas using HFSS.

The cell analysis is automatized through the HFSS scripting interface. The unit cell geometry is drawn and fully parametrized. Master and slave boundaries must be defined on the cell edges to reproduce the local periodicity (LP) conditions, and Floquet modes are used as excitation. Most often, only the fundamental TE and TM modes are considered since higher order ones are evanescent for common cell configurations. In addition, de-embedding is applied to remove the effect of the air box from the phases of the reflection coefficients. When defining the cell excitation, the angle of incidence is also set, and can be configured in the same way as any other geometry parameters. To perform a per-element analysis of a reflectarray, a parameter sweep is configured, where all the element-specific parameter values can be arbitrarily set. Such values are loaded from a plain text file directly through the HFSS interface, and multiple independent sweeps can be performed on a single execution. The FEM solver is employed, which analyses the whole unit cell (i.e. all layers) at once. Since this methodology is directly supported by the tool, the process is efficiently parallelized within a single HFSS instance.

The results from a parametric sweep are exported as the S-parameter matrix between the considered Floquet modes. As such, a TE-TM basis is given, which must then be converted into Cartesian basis through the appropriate rotation matrix to allow comparisons with the MoM software. S-parameters are also transformed into the reflection matrix in (1), for which an impedance correction is required [11]. Both transformations require information of the angle of incidence for each specific element.

2) Analysis with an In-House Ad Hoc Tool: Employing in-house ad hoc tools for the analysis and design of reflectarray antennas presents the advantage of relatively fast computations. This is achieved at the expense of less flexibility since an ad hoc tool is aimed at specific unit cells, such as the stacked rectangular patches shown in Fig. 1.

Here, we employ the modular technique proposed in [3]. It is a full-wave method of moments (MoM) based on the use of the generalized scattering matrix (GSM). This technique analyses each layer of the unit cell independently, calculating the GSM for each layer. Then, the entire multilayer cell is fully characterized through a cascading process, which only requires matrix operations. In this way, multilayer unit cells consisting of rectangular stacked patches are analysed in a very simple fashion, since any additional layer only requires solving an additional two-layer problem plus simple matrix operations for the cascade process. It contrasts with the methodology employed by the HFSS FEM solver, in which all layers are meshed and analysed at the same time.

Here, the GSM of a periodic surface is computed and treated as a building block in a multilayer problem. The incident field is assumed to be a summation of Floquet harmonics, instead of a single plane wave, and all the elements of the GSM are computed at once, reducing the complexity of the problem. As a result, an accurate and time-efficient technique is obtained.

III. RESULTS

In this section we will compare simulations of the two reflectarray designs under study. The reflectarray for mega-constellations is elliptical and comprised of 366 elements with metallization (i.e. stacked rectangular patches). It also has a dielectric frame comprised of 70 elements with only substrate. This frame is used to place screws to fit the reflectarray into a supporting structure. Thus, this design has a total of 436 unit cells to be simulated. On the other hand, the design for 5G base stations has a total of 1521 unit cell, divided into 1369 elements with metallizations and 152 for the dielectric frame.

A. Unit Cell Characteristics

Substrate characteristics and periodicity depend on the reflectarray design. For the antenna with isoflux pattern for mega-constellations the working frequency is 17 GHz. For the substrate, the commercially available Rogers 3003 has been chosen for both layers, with a dielectric constant of $\varepsilon_r = 3$ and a loss tangent of $\tan\delta = 0.001$. A thickness of $h_1 = 0.762$ mm has been selected for the bottom layer, while the top layer has a thickness of $h_2 = 1.524$ mm. The periodicity is 8.82 mm in both axes.

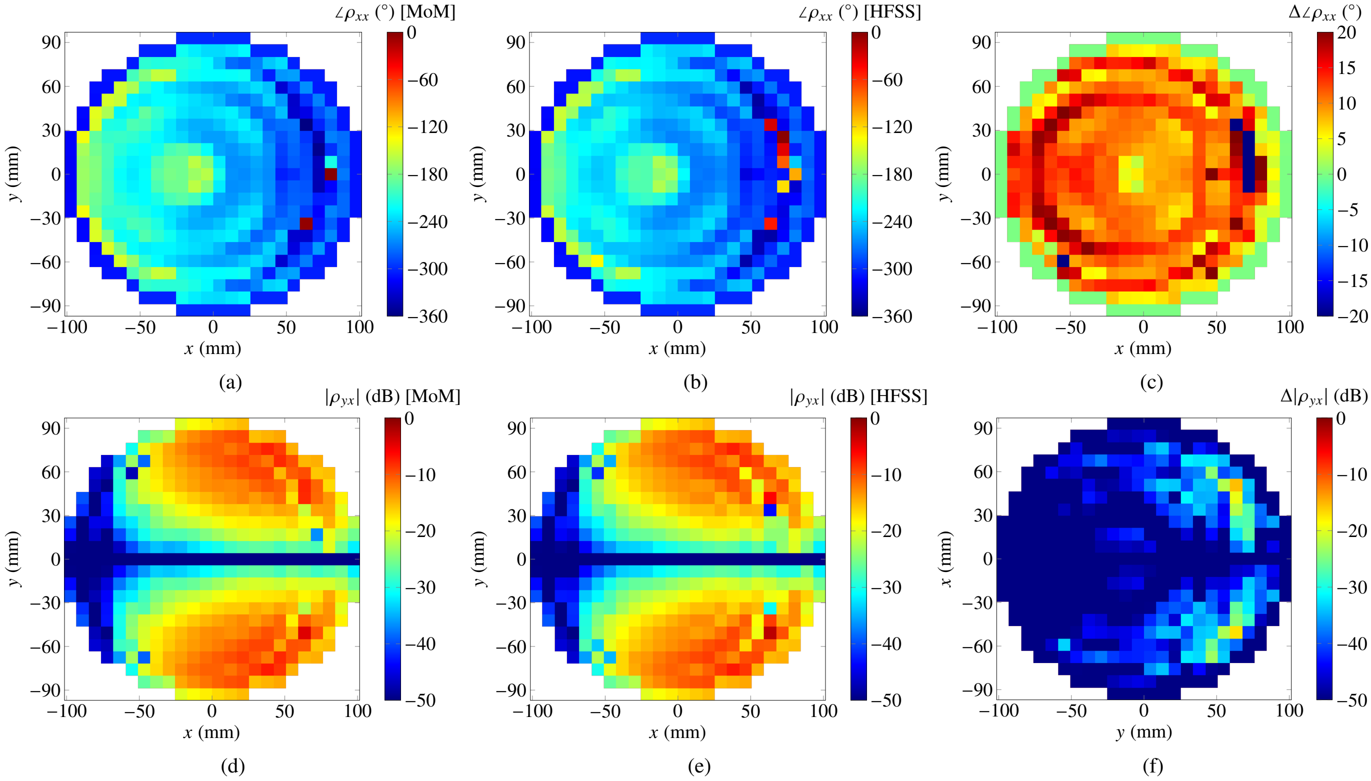

Fig. 2. Comparison of the phase of ρ_{xx} (top) and the magnitude of ρ_{yx} (bottom) between the MoM (left) and the HFSS FEM (center) simulations, including the difference (right) between both simulations.

For the reflectarray for 5G base stations, the working frequency is 28 GHz and the periodicity is 5.1 mm in both axes. Diclad 880 is employed for both layers, with $\varepsilon_r = 2.3$ and $\tan\delta = 0.005$. The thickness of the bottom layer is $h_1 = 0.8383$ mm while the thickness of the top layer is $h_2 = 0.762$ mm.

B. Reflection Coefficients

First, we will show the comparison in the prediction of the reflection coefficients in the surface of the reflectarray. For this first comparison, the design for mega-constellations has been chosen, although similar results are obtained for the other design. Fig. 2 shows the phase of the reflection coefficient ρ_{xx} and the magnitude of ρ_{yx} for both the MoM and HFSS FEM simulations. It also includes the difference between both simulations. The phase of ρ_{xx} has been chosen since it is the component that shapes the copolar pattern for linear polarization X. On the other hand, the cross-coefficient ρ_{yx} has a significant contribution to the crosspolar pattern. As it can be seen, both methods offer very similar reflection coefficients when the reflectarray layout is simulated. In the case of $\angle\rho_{xx}$ the difference between the phases is typically smaller than 15°. In fact, the mean absolute deviation (MAD) for the difference shown in Fig. 2(c) is 12.7°. On the other hand, the MAD for $\Delta|\rho_{yx}|$, shown in Fig. 2(f) is −42.8 dB. Similar results were obtained for the other reflection coefficients.

C. Radiation Patterns

Since the simulation of the reflection coefficients with both techniques produced similar results, it is expected that the radiation pattern will show a similar agreement.

Fig. 3 shows the main cuts in θ for $\varphi = 0°$ and $\varphi = 23°$ of the radiation pattern for polarization X of the reflectarray with an isoflux pattern for mega-constellations. It can be seen that the agreement in both the copolar and crosspolar pattern between the two simulation tools is very good. There are some small discrepancies in the region of secondary lobes, but the difference in the coverage area, i.e., the region with the highest gain, is very small. Even the crosspolar pattern shows a good agreement between the in-house MoM-LP used in this work and the HFSS simulation. One issue with the crosspolar pattern is that it strongly depends on the cross-coefficients, whose magnitude is usually very low (see Fig. 2) when compared with the magnitude of the direct coefficients, and thus they are more sensitive. However, in this case both techniques produce similar results.

Fig. 4 shows the main cuts in elevation and azimuth for the reflectarray for 5G base stations. This radiation pattern presents a squared-cosecant cut in elevation and a sectored-beam in azimuth. In addition, the cut in elevation has a dynamic range in the coverage zone of 10 dB where the copolar component has to smoothly decrease over an angular span of 50°, making it a challenging pattern to design. However, as

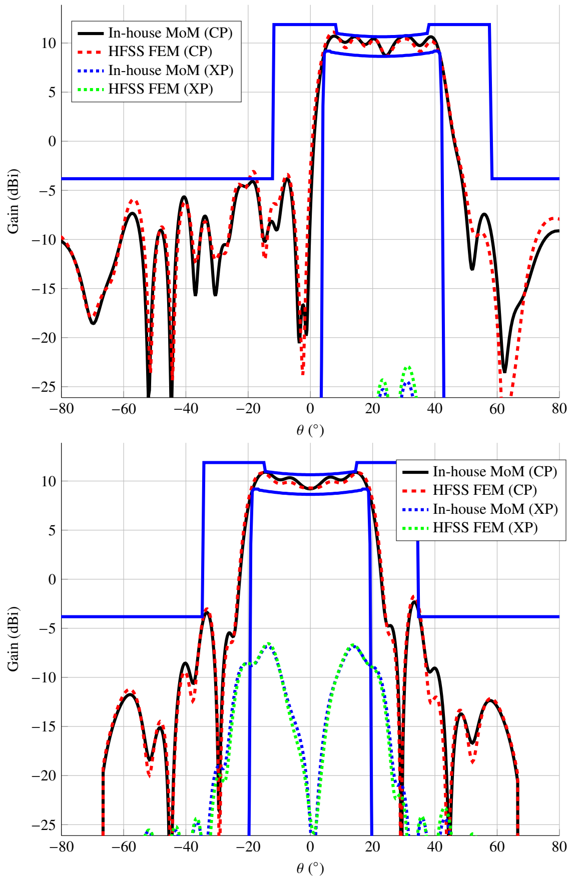

Fig. 3. Main cuts of the radiation pattern for polarization X of the reflectarray design for mega-constellations for (a) $\varphi = 0°$ and (b) $\varphi = 23°$, showing the comparison between the in-house MoM and HFSS-based simulations using the FEM solver.

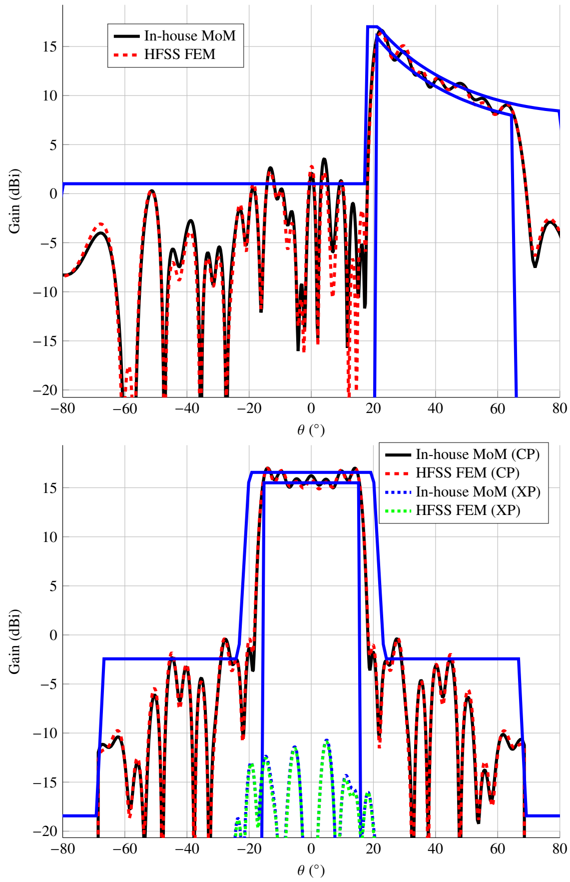

Fig. 4. Main cuts of the radiation pattern for polarization X of the reflectarray design for 5G base stations in (a) elevation and (b) azimuth, showing the comparison between the in-house MoM and HFSS-based simulations using the FEM solver.

in the previous case, both analysis techniques offer similar results, including the coverage area in the elevation cut. The crosspolar pattern also matches in both simulations.

Finally, Fig. 5 shows a 3D representation of the copolar pattern of the reflectarray for 5G base station for polarization X, simulated with the in-house MoM and the HFSS FEM solver. As it happens with the main cuts, both simulations offer very similar results.

D. Analysis Time

For the analysis time comparison, two different computers have been employed. To run the MoM simulations a regular laptop with an Intel Core i7-4712MQ CPU at 2.3 GHz has been used. The HFSS simulations were carried out in a workstation with two Intel Xeon E5-2650v3 at 2.3 GHz. The computing time for both approaches and reflectarrays is shown in Table I. As expected, simulation with the HFSS is several orders of magnitude slower than the in-house ad hoc tool, even though the workstation allows more threads to run parallel simulations. Nevertheless, it is a reasonable analysis time taking into account that it is fully automatized to simulate whole reflectarray antennas with arbitrary unit cells. As a remark, the full wave simulation of the whole antenna, though possible, may be limited to arrays with fewer elements [12], since computational requirements (both time and memory) grow at least quadratically with the number of unknowns.

Table I

AVERAGE SIMULATION TIME FOR THE REFLECTARRAY UNIT CELL COMPARING THE TWO ANALYSIS TECHNIQUES EMPLOYED IN THIS WORK FOR THE TWO REFLECTARRAY DESIGNS.

Tool	Average simulation time per cell	
	Squared-cosecant RA	Isoflux RA
MoM	6.8 ms	19.7 ms
HFSS FEM	44.0 s	92.5 s

IV. CONCLUSION

We have presented a comparative study of reflectarray antenna analysis using two different techniques. On the one hand, the HFSS FEM solver with periodic boundaries is employed to analyze a reflectarray unit cell comprised of two stacked rectangular patches. On the other hand, an in-house ad hoc MoM is used. Both analysis techniques are used to compute the reflection coefficients of two reflectarray antennas, whose radiation patterns are then obtained with classic array theory.

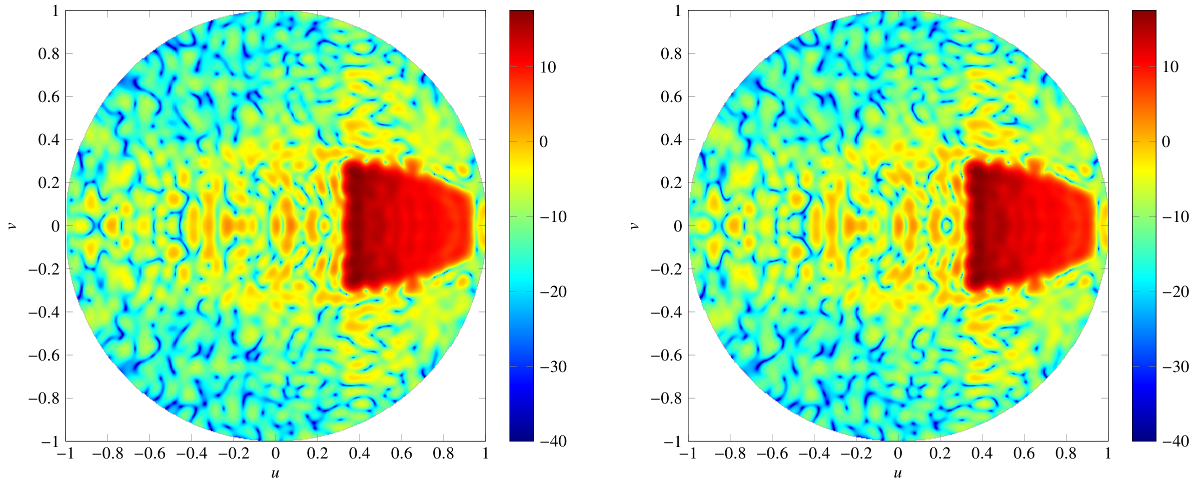

Fig. 5. 3D representation of the copolar far field for polarization X of the reflectarray for 5G base station simulated with (a) the in-house MoM and (b) the HFSS FEM solver.

Comparisons of the reflection coefficients on the reflectarray surface as well as the radiation patterns (both copolar and crosspolar components) show a good degree of agreement between the two methodologies.

Even though using commercial software such as HFSS in the present case is computationally slower than in-house ad hoc tools, it allows to flexibly analyse arbitrary reflectarray unit cells. In addition, the HFSS scripting API allows to generate scripts that can handle thousands of elements, allowing an unattended simulation of the full array. It also takes into account reflectarray elements belonging to the dielectric frame without metallizations as well as the real angle of incidence to correctly characterise the crosspolar pattern. Future work would involve automatic generation of samples for surrogate modelling and the possibility of optimizing reflectarray antennas with arbitrary unit cells in super-computers directly using the HFSS FEM solver.

ACKNOWLEDGMENT

This work was supported in part by the Ministerio de Ciencia, Innovación y Universidades under projects TEC2017-86619-R (ARTEINE) and IJC2018-035696-I; 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.

The authors would like to thank Prof. J. A. Encinar for providing the MoM-LP software.

REFERENCES

[1] D. R. Prado, M. Arrebola, M. R. Pino, and F. Las-Heras, "Improved reflectarray phase-only synthesis using the generalized intersection approach with dielectric frame and first principle of equivalence," *Int. J. Antennas Propag.*, vol. 2017, pp. 1–11, May 2017.

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

[3] C. Wan and J. A. Encinar, "Efficient computation of generalized scattering matrix for analyzing multilayered periodic structures," *IEEE Trans. Antennas Propag.*, vol. 43, no. 11, pp. 1233–1242, Nov. 1995.

[4] R. Florencio, R. R. Boix, J. A. Encinar, and G. Toso, "Optimized periodic MoM for the analysis and design of dual polarization multilayered reflectarray antennas made of dipoles," *IEEE Trans. Antennas Propag.*, vol. 65, no. 7, pp. 3623–3637, Jul. 2017.

[5] "HFSS," Ansys Inc., Pittsburgh, Pennsylvania, USA.

[6] A. K. Bhattacharyya, *Phased Array Antennas: Floquet Analysis, Synthesis, BFNs, and Active Array Systems*. Hoboken, NJ, USA: John Wiley & Sons, 2006.

[7] 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.

[8] A. C. Ludwig, "The definition of cross polarization," *IEEE Trans. Antennas Propag.*, vol. 21, no. 1, pp. 116–119, Jan. 1973.

[9] R. J. Mailloux, *Phased Array Antenna Handbook*, 2nd ed. Norwood, MA, USA: Artech House, 2005.

[10] J. A. Encinar, "Design of a dual frequency reflectarray using microstrip stacked patches of variable size," *Electron. Lett.*, vol. 32, no. 12, pp. 1049–1050, Jun. 1996.

[11] D. R. Prado, M. Arrebola, M. R. Pino, and F. Las-Heras, "Complex reflection coefficient synthesis applied to dual-polarized reflectarrays with cross-polar requirements," *IEEE Trans. Antennas Propag.*, vol. 63, no. 9, pp. 3897–3907, Sep. 2015.

[12] E. Plaza, G. Leon, S. Loredo, and F. Las-Heras, "A simple model for analyzing transmitarray lenses," *IEEE Antennas Propag. Mag.*, vol. 57, no. 2, pp. 131–144, Apr. 2015.