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A numerical simulator for transmit-array antenna design and performance evaluation

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Abstract

This paper describes a hybrid simulation method devoted to quick design and simulation of transmit-array antennas operating in the Ka band. The simulated radiation patterns of a 30 dBi gain discrete lens antenna [1] computed with this simulator will be compared with full-wave simulations and measurements [2].

1. Introduction

Many applications nowadays use beam-reconfigurable antenna commands that provide fast and accurate beam-steering. Currently, the applications are mainly related to the space sector, from L-band to Ka-band, short-range and high-rate communication systems in V and W bands, radar and driving assistance. To meet these needs, the solution investigated by several authors is the use of planar arrays in transmission (transmit-arrays) [3, 4].

A transmit-array antenna consists of two arrays of radiating elements illuminated by a focal source. The two arrays are interconnected by intermediate circuits which serve to modify the phase quantization and the amplitude of the wave and thus to control the direction and the shape of the antenna radiation pattern. This lens can be moved along one direction (x) and the primary source is placed on one side of the lens (Figure 1).

The focal source illuminates the first array with a spherical wave front that will be reradiated by the second array with a plane wave front. The direction α(a) of the wave depends on the position of the source with respect to the array [1].

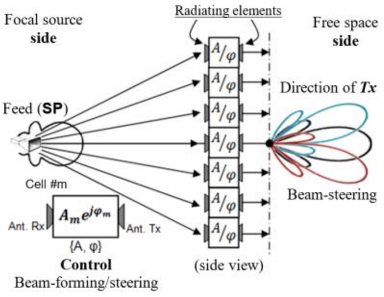

Figure 1: Principle of a transmit-array in transmit mode

A hybrid analytical tool has been developed for a quick design and computation of the performance of transmit-arrays. First the electromagnetic characteristics of the elementary cell and the focal source are obtained with commercial software (such as Ansoft HFSS, CST MWS or FEKO for example). The complex radiation pattern of the focal source is first used to determine the electric field distribution illuminating the receive antennas array (*Rx*). The complex radiation patterns and S-parameters of each elementary cell are then used to evaluate the radiation performances of the transmit-array. The simulator is also of interest to study the impacts of the different design parameters (focal length, cells size, phase quantization ...) on the transmit-array performances (directivity, gain, side lobes level, beam steering ...).

2. Equations governing the simulator

The main challenge of the transmit-array design is the ability to generate the appropriate phase-shift for each unit cell in order to transform the incoming spherical wave radiated by the focal source into a plane wave on the free-space side. The objective is to generate a given phase gradient depending on the main beam direction.

2.1. Perfect quantization

Consider a generic unit cells array illuminated by a focal source placed at (0, 0, -F) where F is the focal distance. The phase distribution of the incident electric field on the receive array is given by:

$$\Phi_{inc}(x,y) = -k_0\sqrt{(x-a)^2+y^2+F^2} \qquad \text{(Eq. 1)}$$

where a represents the shifting distance of the focal source along the x axis. The transmit-array is designed so as to introduce the required phase correction $\Phi_{lens}(x,y)$ to transform the spherical phase front into a plane wave front. The phase correction provided by the lens is then defined by:

$$\Phi_{lens}(x,y) = k_0\sqrt{x^2+y^2+F^2} - k_0\, x\, sin(\alpha_0) \qquad \text{(Eq. 2)}$$

The phase distribution in the second array level (free space side) is given by:

$$\Phi_{out}(x,y) = \Phi_{inc}(x,y) + \Phi_{lens}(x,y)$$

$$\begin{aligned}\Phi_{out}(x,y) &= -k_0\sqrt{(x-a)^2+y^2+F^2} \\ &\quad +k_0\sqrt{x^2+y^2+F^2} - k_0\, x \sin(\alpha_0)\end{aligned} \qquad \text{(Eq. 3)}$$

For the central position $a = 0$ (reference point), the phase of the reradiated wave is:

$$\Phi_{out}(x,y) = -k_0\, x \sin(\alpha_0) \qquad \text{(Eq. 4)}$$

This phase corresponds to a α_0-orientation of the beam in elevation as desired.

$\Phi_{lens}(x,y)$ defines the perfect compensation, but in reality it is very complex to realize it. In order to simplify the design process, it is recommended to get the optimal compromise between the phase quantization and the transmit-array performances.

2.2. N-bit quantization

The principle of this compensation is to provide the elementary cells with a number of phase states allowing them to create a more or less precise phase shift as a function of the number N of bits chosen [5]. The link in terms of number of bits, phase states (PE) and phase shift is given in the table below. For this case, a maximum range between 0° and 360° and a variable k which is a natural integer between 0 and 2^N -1 have been chosen.

Table 1: Link between the number of bits, phase states and phase shifts

N number of bits	Number of PE	Phase shifts
$N \in \mathbb{N}^*$	2^N	$k \times \frac{360}{2^N}$
1	2	0° - 180°
2	4	0° - 90° - 180° - 270°
3	8	0° - 45° - 90° - 135° - 180° - 225 ° - 270° - 315°

3. Effects of the overall system

This tool is better adapted for a periodic array and it allows to evaluate the radiation in free space side, that is, in the red area of the figure 2, when θ ∈ [- 90°; 90°]. Outside this range, it is a reflect-array effect instead of a transmit-array.

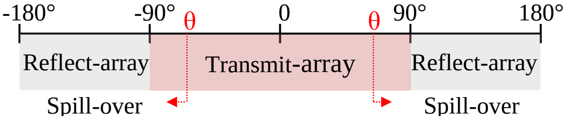

Figure 2: Different effects of the overall system

4. Simulation of a 30 GHz lens antenna [1]

The full wave simulation of the Fresnel lens presented in [1] requires considerable computation effort. Indeed, the lens is composed by 77 columns and 57 rows of unit cells of in-plane width P=2.5 mm. The dimensions of the lens is 192.5 mm x 142.5 mm (19.25λ x 14.25λ at 30 GHz) corresponding to a maximum directivity of 35.4 dBi and the electromagnetic problem to be solved is non-periodic. The single band lens we would like to calculate with the hybrid analytical tool is composed of 4389 phase-shifting cells chosen among 63 different constitutive unit cells. These unit cells are composed by five metallized layers of concentric squared patches on four substrate layers of Rogers Duroid 5880 (ε_r=2.2 and tan δ = 0.0009). The periodic simulation methods are therefore unusable here, whereas conventional full wave simulators require very important computing times and RAM memory.

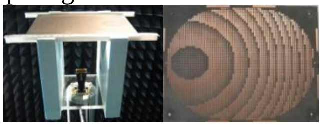

Figure 3: Single band 30 dBi lens antenna [1] (DOI:10.1109/TAP.2015.2484419)

The lens is illuminated with a standard 14.5 dBi horn antenna oriented such that the E-field is parallel to the shortest side of the horn. The horn is positioned at the focal distance F=100 mm below the lens and the analysis is done at 30 GHz (Figure 3). The 30 dBi full lens problem including the horn source is calculated with the hybrid tool. The gain diagrams obtained are considered acceptable compared to measurements, and simulations using CST MWS (Finite Difference Time Domain solver), ANSYS HFSS (Finite Element solver) and ONERA FACTOPO (Finite Element Tearing and Interconnecting solver) softwares [6] (Figure 4). Indeed, the main lobe position and level is well captured by all the methods but the hybrid tool does not take into account the lens's edges diffractions which induce very low side lobes (corresponding to grazing incidences).

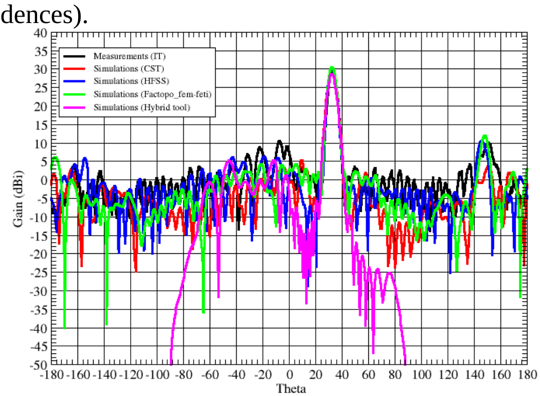

Figure 4: Measured and simulated gain radiation patterns with a centered horn source

5. Conclusions

The hybrid simulator developed in this study calculates efficiently the performances of transmit-arrays without taking into account the lens's edge diffractions. In the future, the simulator will be used to optimize the design of transmit-array antennas with limited ratio F/D in the aim of improving the compactness. The tool will be improved to take into account spill-over losses in the gain diagrams.

References

[1] E. B. Lima, S. A. Matos, J. R. Costa, C. A. Fernandes, and N. J. G. Fonseca, « Circular Polarization Wide-Angle Beam Steering at Ka-Band by In-Plane Translation of a Plate Lens Antenna », IEEE Trans. Antennas Propag., vol. 63, no 12, p. 5443‑5455, Dec. 2015.

[2] A. Barka, S. Matos, J. R. Costa, and C. A. Fernandes, « Assessment of FETI DDM methodologies for the simulation of high gain Ka-band transmit arrays », in 2017 International Symposium on Antennas and Propagation (ISAP), 2017.

[3] S. Ye, X. Liang, W. Wang, R. Jin, J. Geng, T. S. Bird, and Y. J. Guo, "High-Gain Planar Antenna Arrays for Mobile Satellite Communications," IEEE Antennas and Propag. Mag., vol. 54, No. 6, pp. 256 - 268, Dec. 2012.

[4] J. R. Costa, C. A. Fernandes, G. Godi, R. Sauleau, L. Le Coq, and H. Legay, "Compact Ka-Band Lens Antennas for LEO Satellites", IEEE Trans. Antennas and Propag., vol. 56, pp. 1251 - 1258, May 2008.

[5] H. Kaouach, L. Dussopt, R. Sauleau, and T. Koleck, « Design and demonstration of 1-bit and 2-bit transmit-arrays at X-band frequencies », in 2009 European Microwave Conference (EuMC), 2009, p. 918‑921.

[6] F. Roux and A. Barka, « Block Krylov Recycling Algorithms for FETI-2LM Applied to 3-D Electromagnetic Wave Scattering and Radiation », IEEE Transactions on Antennas and Propagation, vol. 65, no 4, p. 1886‑1895, April. 2017.