Analysis of Antenna Synthesis Techniques for Radar Specifications

Julio Cesar S. Rosario and Jacqueline S. Pereira

Abstract—**The aim of this paper is to verify the performance of signal processing techniques in antenna synthesis. It is possible to reduce the quantity of elements in an antenna array with a slight alteration in the irradiation pattern applying signal processing techniques. Two synthesis methods are presented: the classical one and the signal processing one. Simulations for a radar antenna specifications are made, in order to compare the techniques performance.**

Keywords—Antenna Synthesis, Signal Processing, Element Quantity Reduction, Antenna Array.

I. INTRODUCTION

Antennas are transition structures between the guided field in devices such as waveguides or transmission lines and the free space [1],[2]. As the transmission systems become more and more complex, it is necessary to investigate methods to make better and more efficient antennas.

In a variety of applications, it is necessary to design antennas with high directivity in order to improve long distance communications. It can be achieved simply by enlarging an antenna element, or creating a group of radiating elements, the latter one does not make necessary to enlarge any individual element. The antenna formed by multiple elements is known as antenna array [2], and, in most of the cases, this elements are identical.Therefore, it was necessary to develop antenna synthesis methods to achieve the desired specifications with fewer elements. Based on this, this work is aimed to verify the performance of antenna array synthesis techniques based on signal processing, leading to a reduced number of elements in the array.

This work is organized as follows: in Section I, a brief description of the objectives and motivation of the wok is presented. In section II, some basic concepts are reviewed. Section III describes some antennas synthesis techniques. Performance simulations and comparisons between methods are provided in Section IV. Conclusions are made in Section V.

II. BASIC CONCEPTS

A. Antenna Array

A linear array is a group of elements (antennas) with special specifications and aligned in some determined direction [2]. The individual characteristics of each one of these components, when subjected to a group or array, makes different patterns from those they would have individually. An identical array, with the same input current's amplitude and some progressive phase difference is known as uniform array.

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The electric field irradiated by an antenna array can be written as the product of the electric field irradiated by only one element, called element factor, and a multiplier called array factor [2]. The element factor represents the amount of electric field due to the type of element selected to compose the array and the array factor depends on the geometry the array is disposed [2]. Is it possible, then, to control the irradiated wave characteristics changing the configuration of the array.

B. Planar Arrays

In many applications, the irradiation specifications are made in the horizontal and vertical planesimultaneously. In these cases, the specifications are treated independently, creating planar arrays [3]. The electric field that meets the vertical and horizontal planes specifications is shown in Eq. (1):

$$E(\varphi,\theta) = f(\varphi,\theta) S_x S_y \tag{1}$$

Where $f(\varphi,\theta)$ is the element factor; S_x is the electric field due to the array factor horizontally positioned that will meet the horizontal plane irradiation specifications and S_y is the electric field due to the array factor vertically positioned that will meet the vertical plane irradiation specifications.

III. ANTENNA SYNTHESIS TECHNIQUES

The theory in antennas synthesis is based in obtaining an array that will fit best some desired specifications. There are different methods to build antennas, some are based in electromagnetism theory [3],[4] and others in signal processing theory [5],[6],[7].

Among the methods based on electromagnetism, it is possible to point out the trigonometric and polynomial interpolation ones [3],[4], which consists in, given a desired power pattern, finding the antenna array that is capable to reproduce the pattern with some acceptable error [3]. This problem is conventionally solved expanding the function that determines the shape of the irradiation power in space in Fourier series and taking the series N first terms.

When using signal processing theory, it is possible to achieve antenna arrays with some null elements, known as sparce array [5], and reduce the quantity of elements, making the solution less complex and more economic [5]. These methods are based in the design of FIR filters, once their transfer functions are similar to the far electric field irradiated by an antenna [6], that can be expressed by Eq. (2), where $w[n]$ is the current of array's element number n, N is the number of elements of the array, d is the distance between the array's elements, λ is the wave length and θ is the angle between the irradiation direction and z-axis.

$$E(\theta) = \sum_{n=0}^{N-1} w[n].e^{j\left[\frac{2\pi d}{\lambda}\cos\theta\right]n} \tag{2}$$

Sparse arrays leads to an increase in the amount of energy emitted in the direction of the power second maximum, but an adequate choice of the elements to be removed reduces this effect [5]. In a variety of applications, different antennas arrays are utilized in the reception and transmission, having two different irradiation diagrams. In these cases, the information of interest is the effective aperture, that is given in Eq. (3).

$$E_{eff}(z) = \sum_{n=0}^{N-1} w_{eff}[n].z^{-n} \tag{3}$$

thatcan be expressed in terms of the transmitted and received electric fields, E_T and E_R, respectively, as in Eq. (4):

$$E_{eff}(z) = E_T(z) \times E_R(z) \tag{4}$$

with

$$E_T(z) = \sum_{n=0}^{L-1} w_T[n].z^{-n} \tag{5}$$

$$E_R(z) = \sum_{n=0}^{M-1} w_R[n].z^{-n} \tag{6}$$

$$w_{eff}[n] = w_R[n] * w_T[n] \tag{7}$$

where $w_R[n]$ and $w_T[n]$ are the expressions for the supplying currents of the element number n at both reception and transmission antennas, respectively; L and M are the total number of array elements in transmission reception, respectively. The values of L and M include zero supplying currents. Among these methods, it is possible to point out the linear aperture [7] and staircase aperture[7] methods.

IV. SYNTHESIS TECHNIQUES IMPLEMENTATION

In order to verify the performance and compare the antennas synthesis methods, the specifications of a monopulse radar antenna, described in [4] was utilized. These antenna specifications are showed here again, for convenience: half power badwidth of approximately 2.5 ° in horizontal plane and between 15° and 30° in vertical plane [4]. Simulations with MATLAB ® showed that, in order to meet these specifications, the array to be designed had to present 30 and 4 of directivity in the horizontal and vertical planes respectively and lateral lobe level of 13.5 dB in horizontal plane and 11.4 dB in vertical plane.

The simulated irradiation diagrams which meets the desired specifications, in horizontal and vertical planes are shown in Figures (1) and (2), respectively.

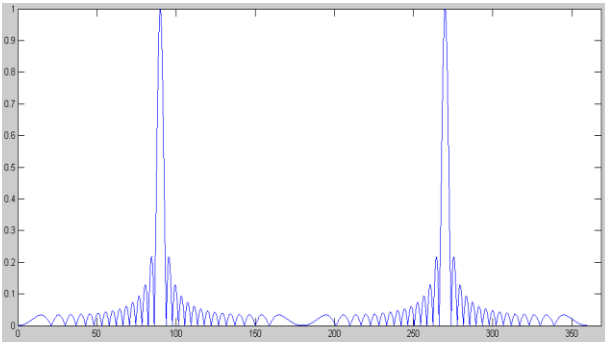

Fig. 1. Simulated horizontal irradiation diagram for radar specifications given in [4].

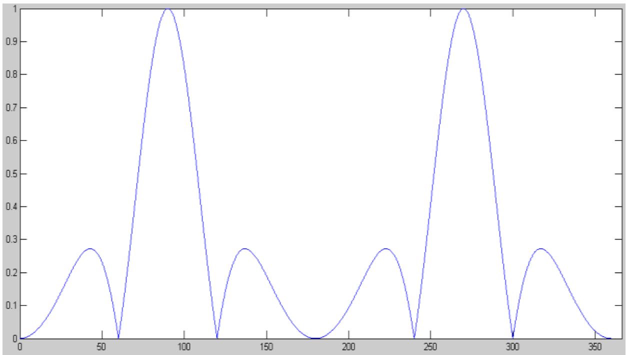

Fig. 2. Simulated vertical irradiation diagram for radar specifications given in [4].

In all simulations, in order to verify only the efficiency of the methods, isotropic irradiators [1] were considered, where the electric field due to the element factor is 1, making it possible to express the resulting electric field in space [6] as the product of the array factor in the horizontal and the array factor in the vertical. The performance of the polynomial interpolation and the linear aperture methods were verified.

A. Polynomial Interpolation

1) Horizontal Diagram

After some MATLAB® simulations, the result that presented the smallest mean square error in the main irradiation lobe and smaller amount of energy outside this lobe in relation to the model curve was a 24 degree Lagrange polynomial. A comparison between the desired irradiation diagram and the one obtained with polynomial interpolation can be seen in Figure (3)

It is possible to notice in Figure (3) that the irradiated electric field of the synthetized array has more irradiated energy out from its direction of maximum when compared to the desired one.

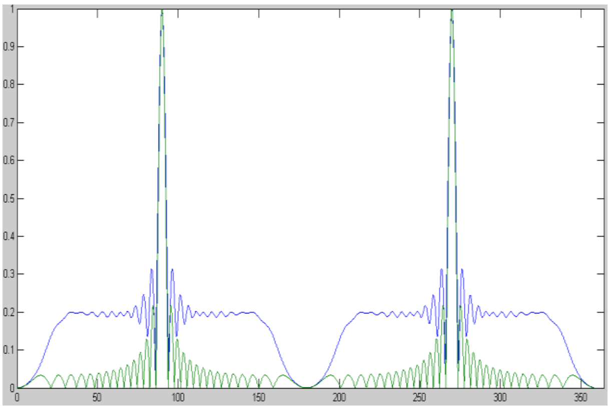

Fig. 3. Comparison between the horizontal irradiated electric field: desired (green) and obtained via polynomial interpolation (blue).

2) Vertical Diagram

MATLAB® simulations showed that the result that presents smaller mean square error in the main irradiation lobe and smaller amount of energy outside this lobe in relation to the model curve was a 3 degree Lagrange polynomial. A comparison between the desired irradiation diagram and the one obtained with polynomial interpolation can be seen in Figure (4)

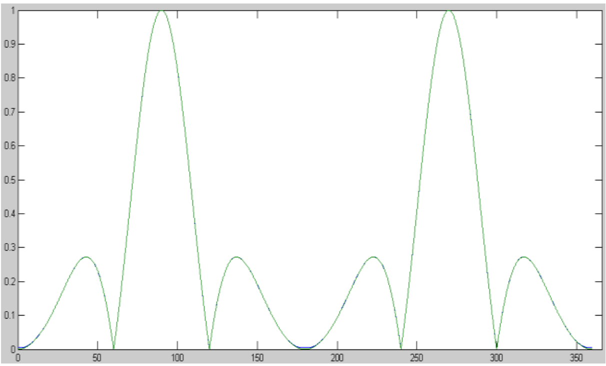

Fig. 4. Comparison between the vertical irradiated electric field: desired (green) and obtained via polynomial interpolation (blue).

The resulting array has a total number of elements equal to the product between the number of elements of the horizontal array and the number of elements of the vertical array [3]. In this case, the resulting array must have 100 irradiators in disposed in a grid in the *x*-*y* plane.

B. *Linear Aperture*

1) Horizontal Diagram

The first step in this method is to find the values of L and M in order to make the diagram of $E_{eff}(x)$ meet the desired specification. As the desired specification in bandwidth, it was necessary to find the smallest value of L with M=2 which the specification was met, once a reduction in the half power bandwidth is associated with the increase of L [8].

MATLAB® simulations showed that the smallest value of L which presented and $E_{eff}(x)$ with the smallest mean square error at the main lobe was 32. A comparison between the desired $E_{eff}(x)$ and the one obtained via linear aperture method is presented in Figure (5).

The irradiation diagrams of $E_T(x)$ and $E_R(x)$ can be analyzed in Figure (6).

The reception antenna irradiation diagram $E_R(x)$ has various amplitude maxima in the same position of the nulls of the transmission antenna irradiation diagram $E_T(x)$, then, when combined, the effective irradiation diagram of Fig. (5)is generated.The reception antenna array obtained is an sparse array, since this antenna has 26 elements, but only the elements 0, 1, 8, 9, 16, 17, 24 and 25 are supplied with a current of 0.5 and the other elements with zero value current. The transmission antenna has 8 non-zero elements, as the reception antenna, resulting in a final array of 16 elements.

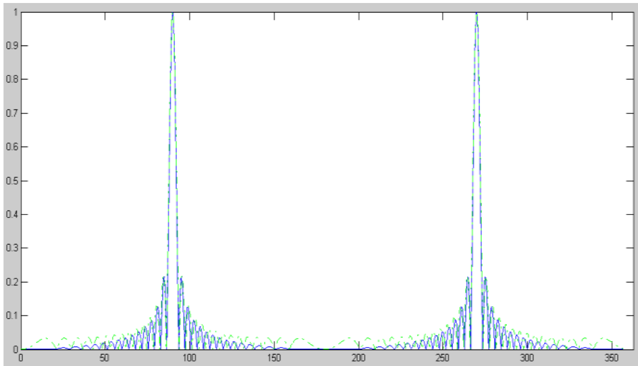

Fig. 5. Comparison between the horizontal irradiated electric field: desired (green) and obtained via linear aperture method (blue).

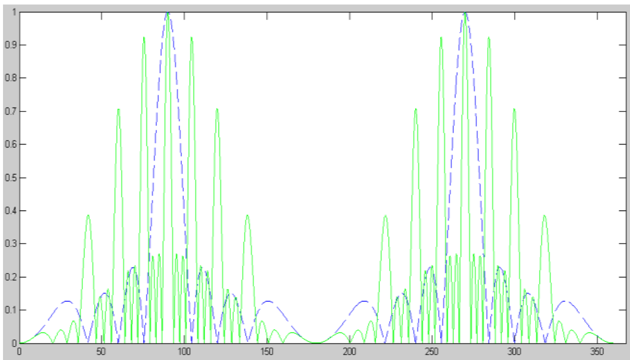

Fig. 6. Irradiated electric field: by the transmission array (green) and by the reception array (blue).

2) Vertical Diagram

For the vertical case, the smallest values of L and M were 4 and 1, respectively. Figure (7) shows the comparison between the desired and the obtained vertical irradiation diagram.

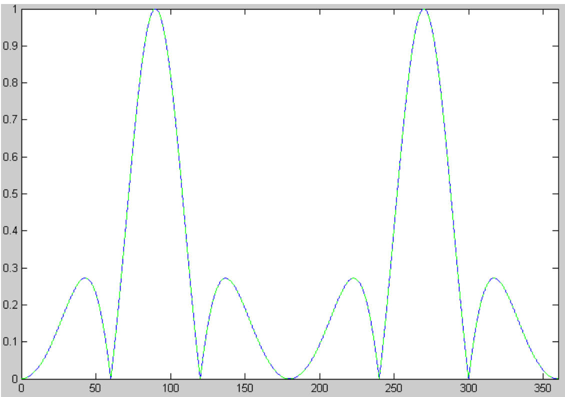

Fig. 5. Comparison between the vertical irradiated electric field: desired (green) and obtained via linear aperture method (blue).

Due to the fact that it is possible to make sparse arrays with this method, the total number of elements for this solution was 40: 32 in the transmission antenna and 8 in the reception antenna.

C. Comparisons BetweenTechniques

The results obtained in the simulations were summarized in Tables I and II.

TABLE I. COMPARISON BETWEEN THE METHODS IN HORIZONTAL DIRECTION

	Desired specification	Polynomial Interpolation	Linear Aperture
BW_{3dB}	1.7°	1.9°	1.6°
NLL	13.5 dB	9.9 dB	13.6 dB
Directivity	30	14.7	32.5

TABLE II.COMPARISON BETWEEN THE METHODS IN VERTICAL DIRECTION

	Desired Specification	Polynomial Interpolation	Linear Aperture
BW_{3dB}	13.2°	13.2°	13.2°
NLL	11.4 dB	11.4 dB	11 dB
Directivity	4	4	4

Analysing Tables I and II, it is possible to notice the the biggest difference between the results is the directivity in the horizontal plane. The final solution obtained via linear aperture in more directive than the one obtained via polynomial interpolation, which means that the first is more efficient in terms of power than the latter, since linear aperture has a larger gain in the transmission/reception of the signal. Comparisons based in other criterions, such as complexity of construction, are done in the sequence.

1) Complexity of Construction

The necessary number of elements for the polynomial interpolation array is 100, while it is 40 if the linear aperture is used. Besides this, since the supplying currents of the elements are completely independent, the polynomial interpolation array is more expensive, complex and error sensible than the linear aperture array because it is necessary to have various supplying sources or an input circuit much more complex in order to properly supply the necessary current to each element.

Due to this fact, the linear aperture array is more advantageous than the polynomial interpolation array.

2) Transmission and Reception Antennas Maxima Mismatch

This problem affects less the polynomial interpolation array than the linear aperture since the first array is designed to meet the desired specifications just in the transmission array and the antennas in transmission and reception has no relation between each other and can be different. Because of this fact, the effects of this problem in the polynomial array are irrelevant [8]. The linear aperture array is more sensible to this kind of problem, since its design is based in the relation between the transmission and reception antennas in order to simplify the final solution in terms of number of elements [7]. In this method, the nulls of the reception irradiation diagram are coincident with the unwanted lateral lobes of the transmission irradiation diagram. As the distance between the secondary maxima and the nulls increases, the sidelobe level in the effective irradiation diagram also increases, and can reach inacceptable error levels.

Figure (6) shows the simulated unwanted effects of a mismatch of approximately 3 degrees between the transmission and reception irradiation maxima in a linear aperture array and Table III presents the irradiation diagram characteristics for ideal and simulation cases. It can be noticed that when there is a mismatch between transmission and reception maxima the directivity and the attenuation of the sidelobes are reduced, degrading the solution.

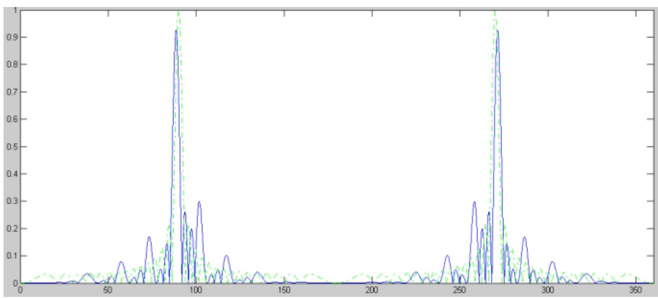

Fig. 6. Irradiated electric field with a mismatch of 3 degrees between the transmission and reception maxima: desired (green) and obtained via linear aperture method (blue).

TABLE III.IRRADIATION CHARACTERISICS OF AN IDEAL ARRAY AND AN ARRAY WITH A MISMATCH OF 3 DEGREES BETWEEN TRANSMISSION AND RECEPTION MAXIMA

	Ideal	With mismatch
BW_{3dB}	1.6°	1.6°
NLL	13.6dB	9.8 dB
Directivity	32.5	29

The linear aperture method adequately combines regions of high and low power in transmission and reception antennas to obtain the desired effective diagram, with nulls (or low power regions) from a diagram cancelling the unwanted maxima (or high power regions) of the other diagram. In case these regions do not adequately match, the desired effective irradiation diagram is not met, as seen in Figure (6). This type of problem can be minimized with a controller circuit at the reception signal system [9]. Basically, this circuit would adjust dynamically the current mismatch between the reception antenna's elements so that it is possible to find the right direction of maximum transmission power irradiation.

3)Interferences in Neighbouring Systems

When the horizontal irradiation diagrams are compared, it is possible to notice that more energy is irradiated out of the main lobe in the linear aperture array, but this can be compensated at the reception array and will not affect the system.However, when irradiating more power outside the region of interest, the noise level in the other systems is increased, since a system signal is a noise to another system. The increase in the noise power degrades the signal-to-noise ratio, generating interference [2].

4)Interferences From Neighbouring Signals

The polynomial interpolation method does not consider the reception antenna when finding a solution, only the transmission antenna is considered [4]. If there is any specific requirement at the reception antenna, the method should be applied twice, one considering the transmission and another considering the reception antenna and, since the construction of each antenna is independent, the mutual influence of the antennas is not considered in order to simplify the final solution.

On the other hand, the linear aperture method takes into consideration the reception antenna and its mutual influence with the transmission antenna to generate the final solution [6]. If there is any specific requirement in any antenna,transmission or reception, a maximum bandwidth at the transmission antenna is considered when selecting $E_T(x)$ and $E_R(x)$ as a function of $E_{eff}(x)$ to avoid noise interference from another system. From this aspect, the linear aperture method is more efficient.

V. CONCLUSIONS

The verification of the antennas synthesis techniques made it possible to evaluate the performance of antennas arrays designed based in two different methods - polynomial interpolation and linear aperture - for radar specifications, verifying the main differences and the kind of degradation the irradiated electric field presents for each technique, aiming at a reduction in the number of elements in the array.

The linear aperture technique is the one that presents a solution with fewer elements, with a smaller complexity and cost. On the other hand, the polynomial interpolation solution showed to be more robust, insensitive to transmission and reception antennas mismatch and interferences in neighbouring systems.

Based on these results and considerations, it was possible to point out some pros and cons of each method, in order to find solutions with small cost and complexity.

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