

## EXPERIMENTAL VALIDATION OF LINEAR APERIODIC ARRAY FOR GRATING LOBE SUPPRESSION

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**Abstract**—In this paper, a deterministic strategy to generate the aperiodicity, based on three geometric taper distributions is studied and validated. The method is applied to study arrays with average inter-elements spacing larger than a wavelength, exhibiting a reduction of the grating lobe level and requiring lower aperture size against a periodic structure with same directivity. Finally, a microstrip patch aperiodic array has been designed, manufactured and measured for an experimental validation of the concept, obtaining good agreement between simulated and measured radiation patterns. This manufactured antenna demonstrates experimentally the reduction of the grating lobes with a similar level to the side lobe.

### 1. INTRODUCTION

Uniform spaced arrays have been widely studied and used in many applications. In particular, works on array synthesis methods, based on deterministic procedures [1, 2] or on heuristic search methods [3, 4], are addressed. Usually, these techniques are focused on the array factor synthesis, assuming ideal isotropic radiators separated a distance close to half of a wavelength. However, some applications could require the integration of active circuits in the array feeding network to achieve electronic beam control. In this case, periodic arrays with element separation close or over a wavelength produce grating lobes (GL) with degradation in the array performances. Thus, other topologies must be used, which are encompassed with the name of aperiodic or non-uniform spaced arrays. These arrays exhibit some advantages against periodic arrays as the potential reduction in the number of radiation

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elements and complexity of the feeding network. Moreover, the GL in the periodic structure are transformed in “pseudo-grating lobes” (P-GL) in the aperiodic arrays, being the P-GL level lower than the GL level of the equivalent uniform spaced array. However, the complexity of the analysis of these structures is slightly increased.

In the case of an aperiodic array, all the elements can be fed with same amplitude and phase and the synthesis process should determine the placement of the radiating elements. Several strategies to determine the spacing between the elements in a non-uniform array have been reported. In [5], an analytical method to design unequally spaced arrays based on the use of Poisson’s sum formula was presented. Others aperiodic formulas are based on subarray synthesis [6], sparse array synthesis using heuristic algorithms [7–10], Legendre polynomials [11] or nature based algorithm [12]. Few works have been carried out on the reduction of GL. Genetic algorithms were applied to thinned arrays [13] or to large subarrays [14, 15]. In [16], the inter-elements spacings are obtained minimizing a cost functional, but for isotropic elements. All these works assume isotropic radiators (array factor synthesis) or dipole antennas as array radiating elements. To the author’s knowledge, a design of an aperiodic array using real radiating elements has not been reported and no experimental validation of these arrays has been carried out up to now.

In this work, an aperiodic array demonstrator is designed, manufactured and tested. The spacing between elements follows a very simple equation, which is based on an approximation of a reference continuous taper function by means of the density of the position of an uniformly excited discrete array. Thus, the element’s spacing must follow the relation:

$$\frac{\text{integral over an area}}{\text{integral over the aperture}} = \frac{\text{elements in the area}}{\text{elements in the aperture}} \quad (1)$$

The main advantage of this strategy is that uniform feeding amplitude is automatically achieved. This technique was introduced in [17] and [18] and recently, it has been used to synthesize rectangular shaped beams [19] or broadside antennas for satellite applications [20], both with isotropic elements. This method produce similar results as the algorithm presented in [21] where a weighted distance between the desired function is minimized.

The main goal of this paper is to design and manufacture a non-uniform array with average inter-element spacing greater than a wavelength but with an important reduction in the GL level. In Section 2, the introduced algorithm is described and extended to solve the problem of reducing the number of elements in an array with minimum distance between radiating elements and finite aperture size,

considering three different taper functions for the array factor. This technique is also applied to design different arrays with the same directivity and a distance between elements greater than a wavelength. The P-GL level remains  $-4$  dB below the main lobe peak. In Section 3, one of the array factors is used to design a real microstrip patch linear array at 24 GHz. This array requires a very simple feeding network and the P-GL level remains below  $-13$  dB. The antenna has been manufactured and the radiation pattern measured in an anechoic chamber, obtaining good agreement between simulations and measurements. In addition, an important reduction of P-GL level is achieved.

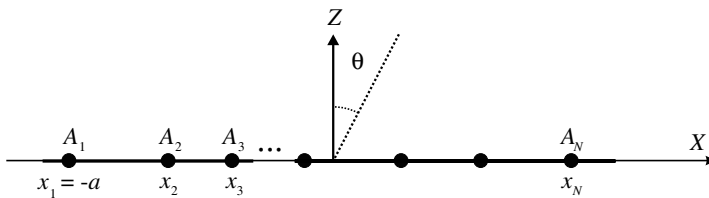
## 2. APERIODIC ARRAY STUDY

The far field,  $E(\theta)$ , radiated by an generical array of  $N$  radiators can be written as:

$$E(\theta) = \sum_{n=1}^{n=N} A_n e^{jkx_n \sin(\theta)} \tag{2}$$

where  $\theta$  is the observation angle,  $k$  the free space propagation constant,  $A_n$  and  $x_n$  are respectively the complex amplitude and the position of the  $n$ th element, with  $x_1 = -a$  for simplicity (see Figure 1). So,  $x_N + a$  can be considered as the total size of the aperture array. Let us denote the distance between two neighbor elements,  $n$ th and  $n + 1$ th, as  $d_n$ . Many applications usually require a minimum  $d_n$  and a maximum array aperture. Under these conditions, a periodic array cannot be the best solution, because grating lobes appears if the distance between elements is greater than  $\lambda/(1 + \sin \theta_0)$ , with  $\theta_0$  is the pointing direction [22]. In this case, the periodicity must be broken to reduce the GL levels.

An algorithm that emulates the taper distribution  $h(x)$  of a continuous aperture is used to generate the positions  $x_n$  of a non-



**Figure 1.** Geometry of an aperiodic and asymmetrical linear array with  $N$  radiating elements.

uniform array, following [17] and [18]. This procedure consists of three steps:

- A cumulative current function is defined as:

$$I_C(x) = \int_{-a}^x h(u)du \quad (3)$$

- The interval  $(-a, x_N)$  is divided into  $N$  intervals, each having the same area  $(1/N)$ . This is, a set of  $N + 1$  boundary points  $(b_0, b_1, \dots, b_{N+1})$  have to be calculated,

$$I_C(b_n) - I_C(b_{n+1}) = 1/N \quad (4)$$

$$d_n = b_{n+1} - b_n \quad (5)$$

- Each array element is placed at the median of each slice area.

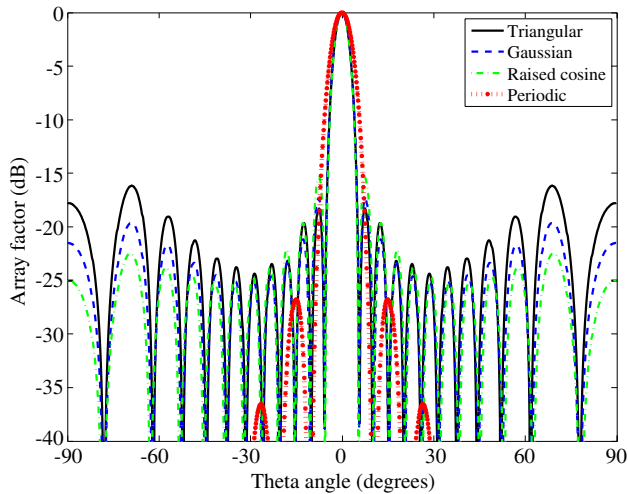
For the purpose of this work, this algorithm has been applied to a broadside array, symmetric respect to the  $Z$ -axis. All elements are fed with the same amplitude and phase ( $A_n = A$ ,  $n = 1, \dots, N$ ). Several geometric taper functions can be used but, in this case, three different distributions have been studied: triangular, gaussian and raised cosine.

To illustrate this algorithm, first, three finite size array ( $10.5\lambda$ ) with a minimum inter-element spacing ( $0.5\lambda$ ) have been calculated, where  $\lambda$  is the wavelength in free space. In Table 1, the positions of the elements of the three non-uniform arrays and the directivity are shown. The geometric triangular distribution is synthesized with 16 elements, while the gaussian and raised cosine distributions require 18 elements

**Table 1.** Positions (in  $\lambda$ ) of the radiating elements and the directivity (last row) of the three non-uniform arrays with minimum distance of  $0.5\lambda$ .

Positions	Triangular	Gaussian	Raised cosine
$x_{10} = -x_9$	0.28	0.26	0.28
$x_{11} = -x_7$	0.85	0.79	0.84
$x_{12} = -x_7$	1.46	1.32	1.41
$x_{13} = -x_6$	2.10	1.87	1.98
$x_{14} = -x_5$	2.78	2.44	2.58
$x_{15} = -x_4$	3.52	3.05	3.19
$x_{16} = -x_3$	4.34	3.70	3.83
$x_{17} = -x_2$	5.25	4.42	4.51
$x_{18} = -x_1$	-	5.25	5.25
Directivity	16.2 dB	16.3 dB	16.4 dB

and the periodic array is made up of 22. The array factor of a periodic array with triangular taper distribution is also plotted in Figure 2. As shown in the figure, the triangular distribution exhibits the larger side lobe level (SLL), because of the lower number of radiating elements, but it remains below  $-15$  dB [21].



**Figure 2.** Comparison between the array factors of the three non-uniform arrays and the periodic array, with minimum inter-element spacing of  $0.5\lambda$ .

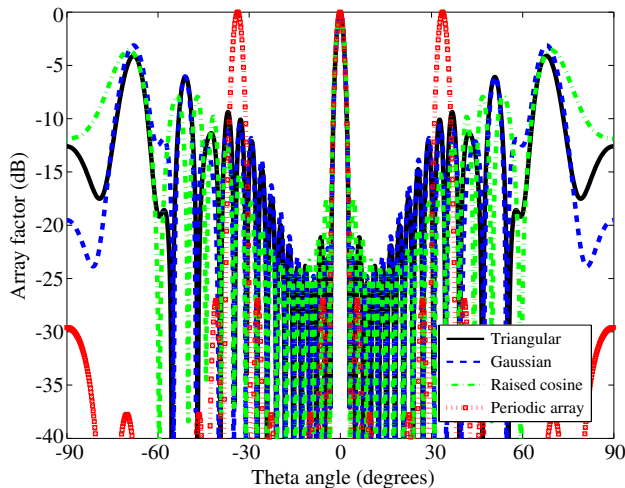
**Table 2.** Positions and mean interelement distance (in  $\lambda$ ) of the radiating elements of the three non-uniform arrays with minimum spacing of  $0.5\lambda$ .

Positions	Triangular	Gaussian	Raised cosine
$x_9 = -x_8$	0.49	0.52	0.51
$x_{10} = -x_7$	1.45	1.56	1.53
$x_{11} = -x_6$	2.57	2.64	2.57
$x_{12} = -x_5$	3.74	3.77	3.65
$x_{13} = -x_4$	5.02	5.00	4.78
$x_{14} = -x_3$	6.45	6.38	6.01
$x_{15} = -x_2$	8.12	8.02	7.38
$x_{16} = -x_1$	10.20	10.20	9.00
$\bar{d}$	1.36	1.36	1.20

A usual scenario in some applications is the requirement of a distance between elements greater than a wavelength, due to the requirement of room for the integration of active circuits. For this case, non-uniform arrays present very interesting characteristics. The three taper distributions have been studied with a minimum inter-element spacing of  $0.9\lambda$  but with the constraint of having the same directivity (14.5 dB) and the same number of elements (16). The different positions and the mean inter-element spacing ( $\bar{d}$ ) are set in Table 2. In all cases, the average distance is greater than  $\lambda$  and P-GL are expected. A linear periodic array with triangular taper distribution has also been calculated. To obtain the same directivity, the elements have to be spaced  $1.8\lambda$  and GL clearly appears at  $34^\circ$ . In Figure 3, all these array factors are shown. The P-GL levels appear around  $68^\circ$  and they are below  $-3$  dB in all cases, but for the triangular geometric distribution are slightly lower ( $-4$  dB). Also, let us note the great reduction of aperture size,  $20.4\lambda$  in the aperiodic structures against  $27\lambda$  in the periodic one.

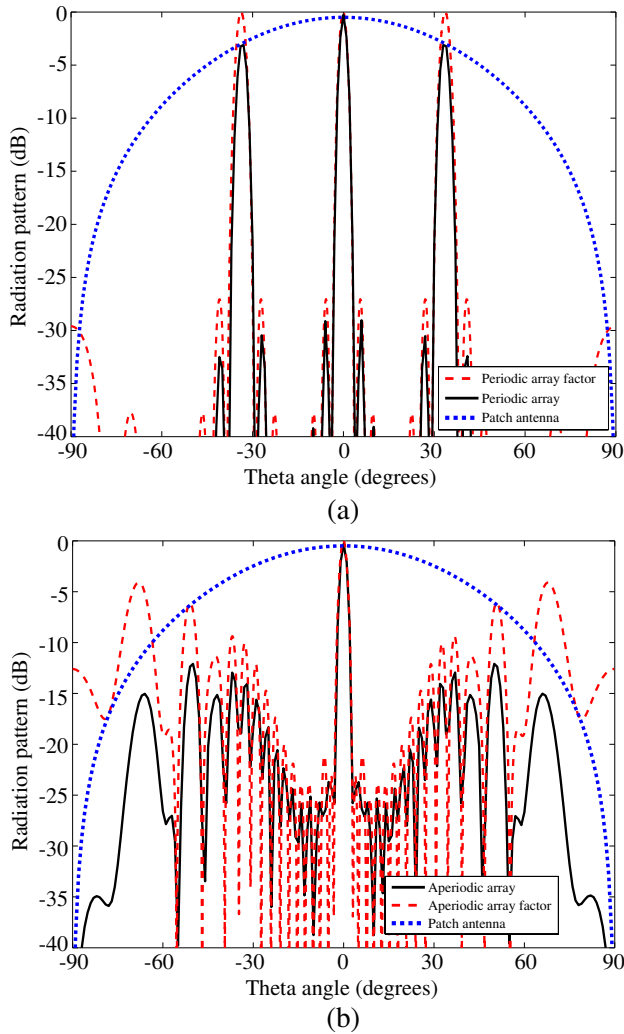
### 3. EXPERIMENTAL RESULTS

This last triangular geometric array factor has been studied using non-isotropic radiators. For this purpose, a direct fed microstrip patch



**Figure 3.** Comparison between the array factors of the three non-uniform arrays and the periodic array, with minimum inter-element spacing of  $0.9\lambda$ .

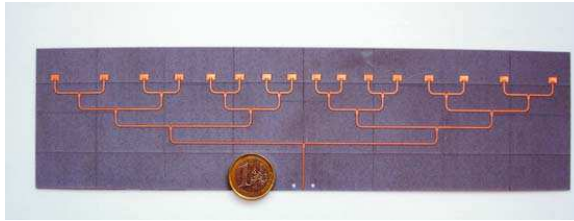
antenna at 24 GHz has been designed using a method of moment (MoM) commercial software [23]. The patch has been designed on a substrate thickness of 16 mils with dielectric permittivity of 3.55 and loss tangent of 0.003. The radiation pattern of this antenna has been



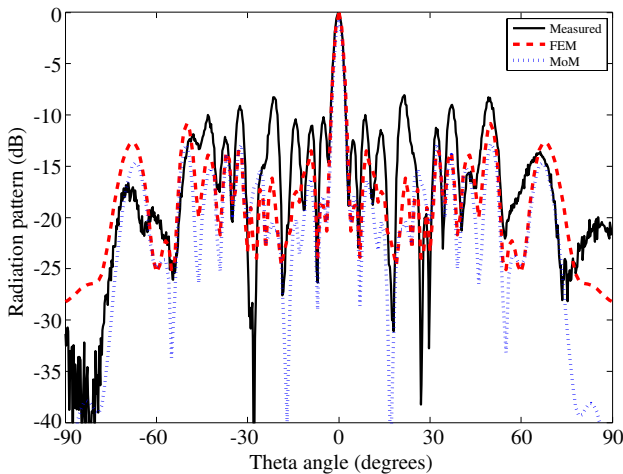
**Figure 4.** Comparison between the array factor and the radiation patterns of a single microstrip patch and an array of patches in (a) periodic structures and (b) triangular distribution structures, both with the same directivity.

compared with the aperiodic array factor and the radiation pattern of the periodic array with patch antennas. In Figure 4, it can be seen how the radiation pattern of a patch antenna decreases the GL level in the periodic array. However, this effect is more important in the non-uniform array, since the P-GL are located at upper angles, so the P-GL look like side lobes below  $-12$  dB.

A photograph of the manufactured array is shown in Figure 5. It can be seen that the 16 elements have been joint with the same power divider, adjusting the length of the feeding lines to have the same phase at each patch. That demonstrates the simplicity to design the network for aperiodic arrays. The manufactured antenna was measured in the anechoic chamber of the ANTEM Lab at the University of Oviedo [24]. The radiation of the antenna has been simulated with



**Figure 5.** Photograph of the manufactured aperiodic linear microstrip array.



**Figure 6.** Comparison between the radiation patterns of simulated and measured aperiodic arrays.



the MoM software and a Finite Element Method (FEM) commercial software [25]. Figure 6, the radiation patterns of the simulated and the manufactured antenna are shown. The main lobe and the P-GL match very well in both cases, and are below  $-10$  dB. However, SLL in the manufactured array increases, always below  $-8$  dB. That is, P-GL and side lobes have the same level.

#### 4. CONCLUSION

An aperiodic linear array has been synthesized, designed, manufactured and measured for the first time. The array is designed to reduce grating lobe level when the average inter-element spacing is greater than wavelength. In this work, a deterministic strategy to generate non-uniform spacing between array elements has been implemented and validated. This method is based on a continuous taper function with the density of the position of a uniformly excited discrete array. The non-periodic arrays exhibit a size reduction and a reduction in grating lobe level against a classic periodic array. A microstrip patch array with triangular inter-element space distribution has been designed and manufactured. In this antenna, the minimum and average inter-element spacing are  $0.95\lambda$  and  $1.36\lambda$  respectively, showing a grating lobe level similar to the side lobe level, which is lower than  $-13$  dB. The measured radiation pattern fits very well with simulations, demonstrating that this kind of non-periodic array can be a smart solution when there are constraints in the aperture size or minimum inter-element spacing. As a future work, the beam scanning and beam shaping capabilities of these arrays should be studied and experimentally validated.

#### ACKNOWLEDGMENT

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