Comparative study and design of antenna array parameters

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Abstract

An array of antenna elements is a spatially extended collection of **N** similar radiators or elements, where **N** is a countable number bigger than 1, and the term "similar radiators" means that all the elements have the same polar radiation patterns, orientated in the same direction in 3-d space. The elements don't have to be spaced on a regular grid, neither do they have to have the same terminal voltages, but it is assumed that they are all fed with the same frequency and that one can define a fixed amplitude and phase angle for the drive voltage of each element. Arrays of antennas are used to direct radiated power towards a desired angular sector.

The number, type, geometrical arrangement, relative amplitudes and phases of the array elements depend on the angular pattern that must be achieved, the influence that each parameter of the above has on the overall radiation characteristics will be the subject of this research paper.

Many results were obtained such as, the array directivity increases with the number of elements, the number of side lobes and the side lobe level increase with the number of elements, a larger element spacing results is a higher directivity. However, the element spacing is generally kept smaller than λ/2 to avoid the occurrence of grating lobes. finally the effect of element's type (isotropic , dipole, …etc.) on the array radiation pattern were studied ,specifically if elements are dipoles on an infinite ground planes the overall array does indeed not radiate in directions were the antenna element doesn’t radiate, the overall array’s radiation pattern has thus a perfect front to back ratio.

Keywords: Arrays of Antennas, Angular Pattern, Radiation Characteristics, Array Directivity, Side Lobes.

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1. Introduction

The radiation characteristics of single-element antennas were discussed and analyzed in scientific antennas literature, Usually the radiation pattern of a single element is relatively wide and each element provides low values of directivity (gain). In many applications it is necessary to design antennas with very directive characteristics (very high gains) to meet the demands of long distance communication. This can only be accomplished by increasing the electrical size of the antenna.

Enlarging the dimensions of single elements often leads to more directive characteristics. Another way to enlarge the dimensions of the antenna, without necessarily increasing the size of the individual elements, is to form an assembly of radiating elements in an electrical and geometrical configuration. This new antenna, formed by multi elements, is referred to as an antenna array. In most cases, the elements of an array are identical. This is not necessary, but it is often convenient, simpler, and more practical. The individual elements of an array may be of any form (wires, apertures, etc).

The total field of the array is determined by the vector addition of the fields radiated by the individual elements. This assumes that the current in each element is the same as that of the isolated element. This is usually not the case and depends on the separation between the elements. To provide very directive patterns, it is necessary that the fields from the elements of the array interfere constructively (add) in the desired directions and interferes destructively (cancel each other) in entire remaining space. Ideally this can be accomplished, but practically it is only approached. In an array of identical elements, there are five control parameters that can be used to shape the overall pattern of the antenna. These are

1. The geometrical configuration of the overall array (linear, circular, Rectangular, Spherical, etc.).
2. The relative displacement between the elements.
3. The number of individual elements in antenna array.
4. The excitation phase of the individual elements.
5. The relative pattern of the individual elements.

The influence that each parameter of the above has on the overall radiation characteristics will be the subject of this research paper.

2. Two - Element array

Placing the elements along a line forms the simplest and one of the most practical arrays. To simplify the presentation and give a better physical interpretation of the techniques, a two-element array will first be considered. The analysis of an **N** element array will then follow. Two-dimensional analysis will be the subject at first. [1] In Fig. (1) The elements are fed with currents I_o and I_1, which we will assume to be of equal magnitude but out of phase, i.e.

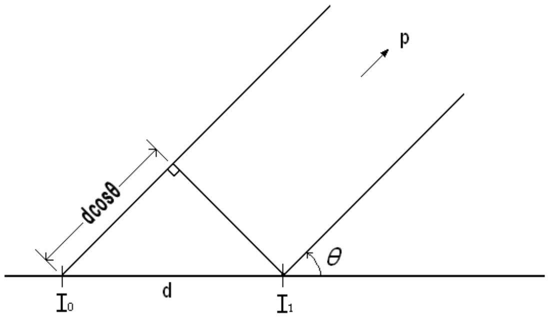

Fig. (1): Two-element array

$$I_1 = I_0 \angle \alpha \qquad (1)$$

If *P,* the point of observation, is well into the far field, the path-length difference to *P* from the elements will be approximately equal to *d* cosθ where *d* is the element spacing.

In the position shown the phase of the radiation at *p* from element (1) will lead that from element (0) by ψ. Where

$$\psi = \beta d \cos\theta + \alpha \qquad (2)$$

β (=2π/λ) is the phase constant of the transmitted wave.
Given that the field at *P* due to element *0 is* E_0. Then the total field E_P is given by.

$$E_p = E_0 \left[1 + \exp(j\psi)\right] \qquad (3)$$

$$= E_0 \left[\exp\left(-\frac{1}{2} j\psi\right) + \exp\left(\frac{1}{2} j\psi\right)\right] \exp(j\psi/2) \qquad (4)$$

Which has a magnitude

$$E = 2E_0 \cos\frac{1}{2}\psi \qquad (5)$$

i.e.

$$E = 2E_0 \cos\frac{1}{2}(\beta d \cos\theta + \alpha) \qquad (6)$$

$$E = 2E_0 \cos\left(\frac{\pi d}{\lambda} \cos\theta + \frac{\alpha}{2}\right) \qquad (7)$$

Thus, for any given separation and phase difference, the radiation pattern, which is the variation of *E* with θ, can be found. Major changes at the polar diagram can be produced by varying *d*/λ and α. [2]

3. Linear Arrays

Several elements in line create a linear array. In this section we restrict our attention to the simplest form of array, in which ***N*** equally spaced elements are fed with currents of equa1 magnitude, and the phase difference between adjacent elements is constant.

Form Fig. (2) the field at some distant point *P* is

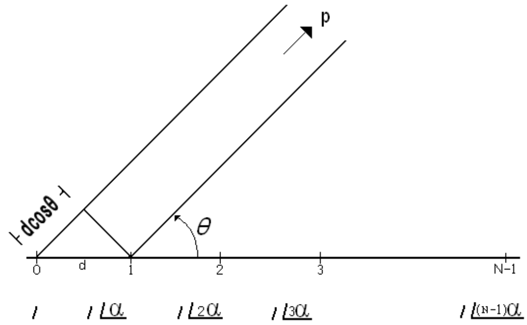

Fig.(2) Uniform linear array of *N* elements

$$E_p = E_o\left[1+\exp(j\psi)+\exp(j\psi 2)+\ldots\exp\left[j(N-1)\psi\right]\right] \quad (8)$$

Where, as before, E_0 is the field at *P* due to radiation from element 0, and ψ is the phase difference at *P* due to radiation from element 1 compared with that from element 0, i.e.

$$\psi = \beta d\cos\theta + \alpha \quad \textbf{(9)}$$

To find the magnitude of E_p we can use the relationship

$$1+\exp(j\psi)+\ldots\exp\left[j(N-1)\psi\right] = \frac{1-\exp(jN\psi)}{1-\exp(j\psi)} \quad \textbf{(10)}$$

Then, the magnitude of Eqn. (8) is

$$E = E_0\left|\frac{1-\exp(jN\psi)}{1-\exp(j\psi)}\right| \quad \textbf{(11)}$$

$$\boldsymbol{E} = E_0\left|\frac{\sin N\psi/2}{\sin\psi/2}\right| \quad \textbf{(12)}$$

The quantity (sin nψ/2)/(sin ψ/2) is known as the array factor because it determines the shape of the radiation pattern. It has a minimum, as we could verify by using L Hospital's Rule. When ψ = 0, i.e. when

$$\beta d \cos\theta = -\alpha \qquad \textbf{(13)}$$

By choosing α correctly we can place the maximum where required. Consider two cases. [2]

A: Broadside array

The maximum is normal to the line of the elements, in the direction *θ*=π/2, The radiation from the elements must be in phase in this direction, and form Eqn. (9) this requires, as we would expect that the elements are fed in phase, i.e. α = 0.

B: End-Fire array

In this case the maximum is placed along the line of the elements, i.e. in the direction *θ = 0*. Here the radiation from adjacent elements will add in one direction, and subtract in the reverse direction, again we are not surprised to find from Eqn. (9) that the phase relationship between adjacent elements is

$$\alpha = -\beta d \qquad \textbf{(14)}$$

So that the phase difference in the currents between, for example, elements 0 and 1 is cancelled by their separation.

The directions of radiation pattern of these two cases are shown in Fig. (3).

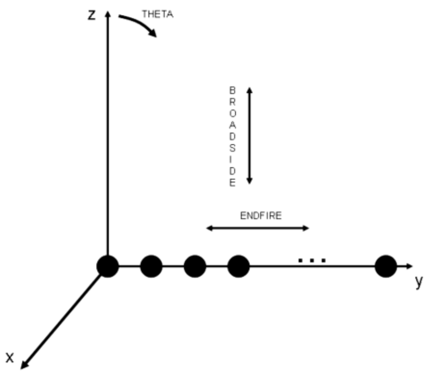

Fig.(3) Topology of a linear array

In both these cases, and for any linear array, increasing the number of elements, which is similar to making the array physically longer, reduces the width of the main lobe.

To find the shape of the radiation pattern of a particular array it is often sufficient to establish the direction of the maximum, from Eqn. (12), and to find the position of the nulls. These null directions, where the field at P is zero, can be determined much more easily, than the directions of the maxima of the secondary lobes. From Eqn. (12) we can see that a zero field occurs when the array factor is zero i.e. when

$$\frac{N\psi}{2} = \pm k\pi \tag{15}$$

$$\frac{1}{2}N(\beta d\cos\theta + \alpha) = \pm k\pi \tag{16}$$

where k **=** 1, 2, 3….

A detailed evaluation of the array factors necessary if a complete radiation pattern is required. Often, however, it is sufficient to estimate the minor lobes by calculating one or two values for sample angles between adjacent nulls.

4. Array Factor

For an array of N elements, the array factor is given by

$$AF(\psi, \theta) = \sum_{n=1}^{N} I_n e^{j(\zeta_n + \delta_n)} \tag{17}$$

Where I_n is the magnitude, δn is the phase of the weighting of the N_{th} elements and ζ_n is the relative phase of the incident wave at the N_{th} elements.

The normalized array factor is given by

$$f(\psi, \theta) = \frac{AF(\psi, \theta)}{\max|AF(\psi, \theta)|} \tag{18}$$

This would be the same as the array pattern if the array consists of ideal isotropic elements.

The array factor depends on the number of elements, the element spacing, amplitude and phase of the applied signal to each element. The number of elements and the element spacing determine the surface area of the overall radiating structure. This surface area is called aperture. A larger aperture results in a higher gain. The aperture efficiency quantifies how efficient the aperture is used.

The influence of these parameters will be further explained with the aid of a linear array of isotropic radiating elements. An isotropic radiating element radiates an equal amount of power in all directions, i.e. it has a directivity of 1 (0 dB) and a gain of 1 (0 dB) if the efficiency were 100%. In the outline bellow the array factor is normalized to the array directivity. This results in more intuitive and realistic radiation pattern plots. [3]

5. Results

5.1: Influence of the number of elements on the array factor

The array directivity increases with the number of elements. Fig. (4) shows the directivity of 3 arrays, with 2 (red), 5 (green) and 10 (blue) elements. The element spacing is 0.4 times the wavelength (λ) for all the arrays in Fig.(4).Note the presence of side lobes next to the main lobes: this is typical for arrays. The number of side lobes and the side lobe level increase with the number of elements. It is important to note that due to the array factor definition there are 2 main lobes. There is a main lobe at theta 0° (positive z axis) and a main lobe at theta 180°/-180° (negative z axis).

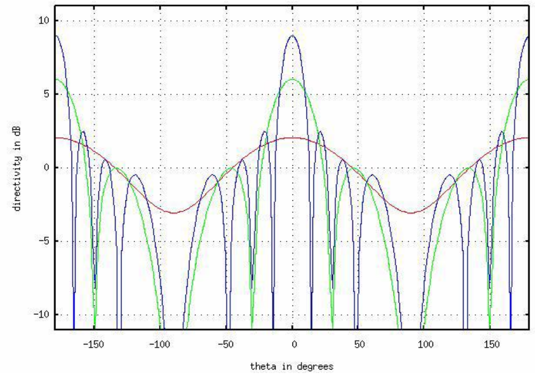

Fig.(4) Directivity of a 2 (red), 5 (green) and 10 (blue) element array with 0.4 λ element spacing.

5.2: Influence of the element spacing on the array factor

The element spacing has a large influence on the array factor as well. A larger element spacing results is a higher directivity. However, the element spacing is generally kept smaller than λ/2 to avoid the occurrence of grating lobes. A grating lobe is another unwanted peak value in the radiation pattern of the array. Fig.5,6 and 7. Show the array factors of a 5-element array with
various element spacing.

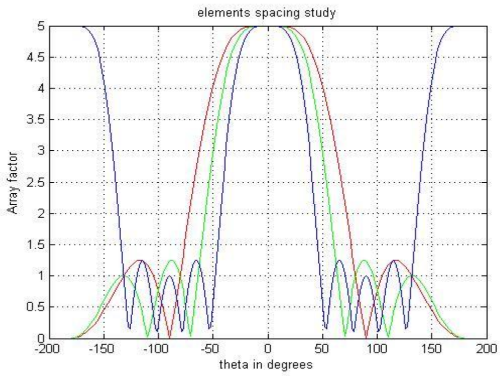

Fig.(5) Directivity of a 5 elements array with 0.2 (red), 0.3 (green) and 0.5 (blue) times λ element spacing

Increasing the element spacing towards λ results in an increased directivity and grating lobe effect with maximum grating lobe amplitude equal to the main lobe magnitude at an element spacing λ as shown in Fig. (6).

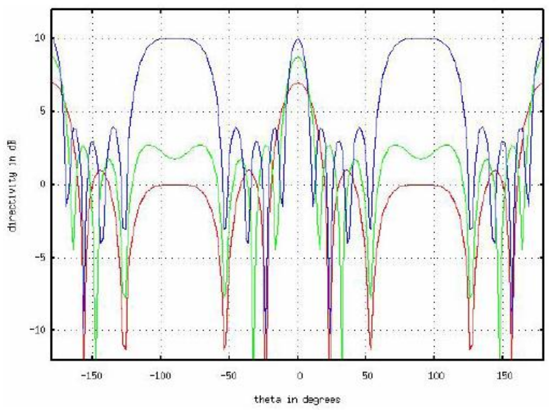

Fig.(6) Directivity of a 5 elements array with 0.5 (red), 0.75 (green) and 1 (blue) times λ element spacing

An element spacing beyond λ becomes impractical and results in multiple unwanted Grating lobes as depicted in Fig. (7).

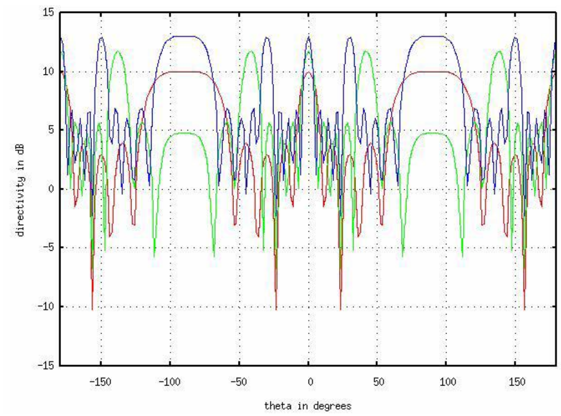

Fig.(7) Directivity of a 5 elements array with 1 (red), 1.5 (green) and 2 (blue) times λ element spacing

5.3: Influence of the radiating element properties on the overall radiation pattern

A number of examples of total radiation patterns are given below in order to give an idea of the effect of the radiating element radiation pattern on the overall array radiation pattern. Fig.(8) shows the radiation pattern of an isotropic element (red), the array factor and the combined radiation pattern (both green). In this case the overall radiation pattern is the same as the array factor since an isotropic element radiates the same amount of power in all directions.

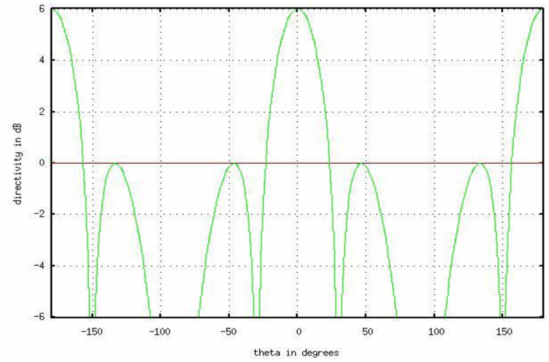

Fig.(8) Directivity of an isotropic source (red) in a 5 elements array (green) with 0.4 λ element spacing

Fig. (9) shows the radiation pattern of a dipole (red), the same array factor as in Fig.(8) (Green) without dipoles and the overall radiation pattern of the array with dipoles (blue). The overall radiation pattern is clearly different from the array factor i.e. the directivity has increased with the dipole's directivity and the overall radiation pattern is slightly modified due to the dipole's radiation pattern.

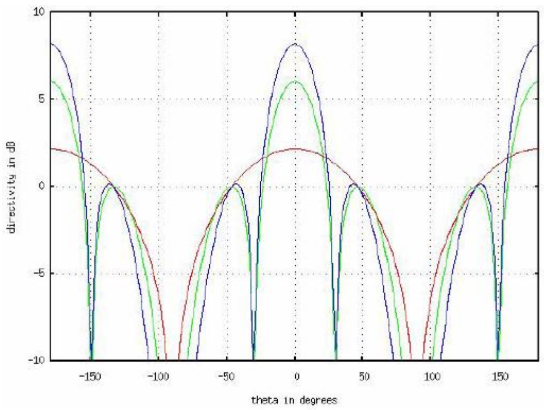

Fig.(9) Directivity of a dipole in a 5 elements array with 0.4 λ element spacing

Fig.(10) shows the radiation pattern of a dipole on an infinite ground plane (red), the same array factor as in Fig.(9) (green) without dipoles and the overall radiation pattern of the array with dipoles on an infinite ground plane (blue).

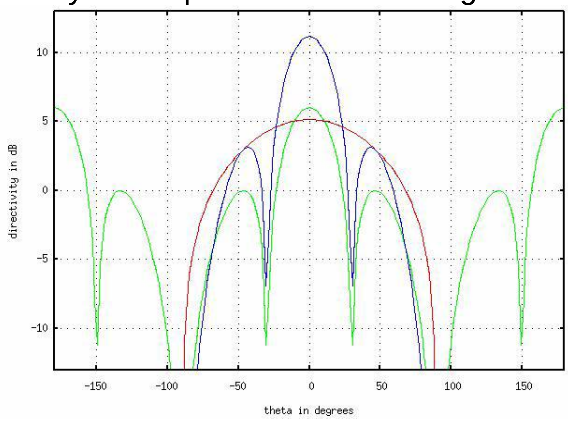

Fig.(10) Directivity of a dipole on infinite ground in a 5 elements array with 0.4 λ elements spacing

The dipole has a radiation lobe in the positive z-axis only (broadside and because of the ground plane) and thus the directivity of the dipole has increased with 3 dB (because of that ground plane). Note that the overall array does indeed not radiate in directions were the antenna element doesn't radiate, i.e. no radiation in the negative z direction any more. The overall array has thus a perfect front to back ratio; This makes sense because we have used an infinite ground plane.

6.Concluction

1-For a given array size, increasing the number of elements concentrates the power in the main lobe so the beam width decreases, the power ratio between the main beam and side lobes will be increased and the directivity will be increased.

2-For a uniform weight distribution, increasing the number of elements for a given size makes the pattern approach the sin x/x form obtained in case of continuous aperture.

3-Increasing element spacing results a high directivity, the element spacing generally kept smaller than **λ/2** to avoid the occurrence of grating lobes, that's in end fire arrays, while in the case of broadside arrays the spacing must be kept smaller than **λ**.

4-If the radiating element is an isotropic radiator then the overall radiation pattern is the same as the array factor.

5- If the radiating element is dipole on an infinite ground, the overall array has a perfect front to back ratio.

References

[1] - Constantine A.Balanis Copyright © Antenna Theory(Analysis and design)" 1982, 1997, Second Edition, by john Wiely and Sons, Inc Engineering Telecommunication".

[2] - Dunlop and D. G. Smith Copyright©1994, Third Edition by Chapman and Hall.

[3] - " Antenna Theory and design" Robert S.Elliott Copyright © 1981. by johnWiely and Sons, Inc.

دراسة مقارنة وتصميم معاملات مصفوفة الهوائيات

م.م علي رزوقي حسين*

المستخلص

تعرف مصفوفة الهوائيات على انها مجموعة من عناصر الهوائيات (مشعات متماثلة) التى يتم ترتيبها بالفراغ وباى عدد صحيح N اكبر من واحد . هذه العناصر ليس من الضروري ان تكون بفاصلة منتظمة ولايجب ان تغذى بنفس قيمة الجهود الطرفية , ولكنها جميعا تغذى بنفس التردد وبالامكان التحكم بقيمة (الاتساع) وزاوية الطور لفولتية كل عنصر من العناصر .

تستخدم مصفوفات الهوائيات لتوجيه القدرة المشعة نحو القطاع الزاوي المطلوب . ان عدد ,نوع ,الترتيب الهندسي للعناصر ,والسعة والطورالنسبيين لاشارات العناصر المختلفة, كل ذلك يتحدد بطبيعة النمط الاشعاعي المراد تحقيقه. ان تاثير كل من هذه العوامل على النمط الاشعاعي الكلي للمصفوفة هو موضوع هذه الورقة البحثية.

نتائج عديدة تم الحصول عليها ومنها ان توجيهية النمط الاشعاعي تزداد مع زيادة عدد العناصر والمسافة الفاصلة بين العناصر (حجم الهوائي) . لكن اكبر مسافة عملية بين العناصر هي بقيمة λ/2 والا ظهرت مايسمى بالحزم الجانبية المتشابكة داخل النمط الاشعاعي . تم كذلك اثبات التناسب الطردى بين مستوى الحزم الجانبية وعدد عناصر المصفوفة. اخيرا تم دراسة تاثير نوع الهوائي العنصر للمصفوفة على نمط اشعاعها ومن اهم النتائج هى عند الرغبة بالحصول على اعلى نسبة اشعاع امامي قياسا بالاتجاه الخلفى يجب استخدام الهوائى ثنائى القطب المثبت على سطح ارضى لانهائي كعنصر للمصفوفة.

* وزارة التعليم العالي والبحث العلمي