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Radiation Pattern Analysis and Phase Shifter for Base Station Mobile Communication Circular Array Antenna at 900MHz Frequency by Using 4NEC2X Software

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تحليل نمط الإشعاع ومحول الطور لهوائي المصفوفة الدائرية للاتصالات المتنقلة للمحطة الأساسية بتردد 900 ميجاهرتز باستخدام برنامج 4NEC2X

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ABSTRACT

Background:

This paper presents the utilization of phase shifters to manipulate and control the radiation patterns in Uniform Circular Array (UCA) antennas. UCAs, known for their 360-degree coverage and symmetrical radiation patterns, are enhanced by incorporating phase shifters, enabling dynamic beam steering and pattern shaping.

Materials and Methods:

A uniform circular antenna array operating at 900 GHz frequency has been intended for use in base stations using 4NEC2X simulation software.

Results:

A single-element dipole antenna having a 2.14 dBi gain is used as a base for constructing a uniform 0.5 λ spacing circular array. The number of elements gradually increased from 2 to 12, raising the gain to 12.3 dBi. HPBW decreased both in vertical and horizontal plans from 80º to 60º and 360º to 20º respectively this implies that the circular array antenna's directivity is enhanced. The eight-element array beam scanning was performed from 0º to 360º without any distortion in radiation pattern, gain, and directivity, contradictory with the linear array.

Conclusions:

The studied case and simulation output illustrate the impact of the element numbers and phase shifter configurations on properties of the radiation pattern of the uniform circular array can be obtained when increasing the number of elements, the gain increases too and scanning the main beam without any change and distortion

Keywords:

Uniform circular array; half wavelength dipole antenna; Phase Shifter; Gain; 4NEC2X

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INTRODUCTION

An antenna with only one element has limited performance. In order to achieve specific properties such as strong directivity, narrow beam width, low side lobes, point-to-point, and preferred coverage pattern, a system of electrically and geometrically configured radiating elements called an antenna array must be assembled [1]. Traditional antenna types such as dipoles, monopoles, and folded dipoles have been superseded by arrays of antennas in recent years. In comparison to dipole antennas, arrays have a narrower beam width, lower SLL, and greater directivity [2]. In the 1940s, the idea of an antenna array was initially presented for use in military purposes [3]. The mentioned advancement holds great importance in the field of wireless communications due to its enhancement of the reception and transmission patterns of antennas employed in such systems. The attributes of the array mostly rely on the number of elements, the type of element employed, the spacing between elements, and the shape of the array [4]. Antenna array beamforming primarily aims to successfully transmit or receive a signal in a desired spatial direction [5, 6]. Modern sectored cell systems, such as commercial cellular networks, typically employ the uniform linear array (ULA) as their primary antenna technology. In contrast, the uniform circular array (UCA) has recently attracted a lot of attention for use in omnidirectional cell communication systems, particularly in ground-based military communications. For a long time, circular arrays of antennas have been the go-to for applications involving angle of arrival, where the ideal configuration for the array is one with inter element spacing equal to half wavelength. This pertains to signals that are either received through radio, optical, or acoustic means. To scan a beam through 360◦ without fluctuation in gain and pattern shape, circular arrays can be used because of their far-field radiation pattern symmetry, which is not the case with linear arrays [7]. The usage of a circular adaptive antenna array at the mobile station for a communication system operating at 900 MHz frequency and scanning main beam is investigated in this study using 4NEC2 software, which solves the impedance matrix considering the mutual coupling between antenna elements [8]. For different geometrical configurations of antenna arrays and varied amounts of phase shift applied between antennas elements, many numerical simulations have been conducted [9].

GEOMETRY AND ARRAY FACTOR

Imagine a circular ring with a radius of a, containing N isotropic radiators, positioned in the x-y plane. The coordinate system's origin is situated at the central point of the array. The determination of the array factor can be achieved by treating the elements as isotropic sources. To find the overall field, multiply the array factor of the isotropic sources by the field of the single element, even if the elements themselves are not isotropic sources. Only arrays with exactly the same members are subject to this condition, which is called the pattern multiplication rule. Figure (1) shows the array factor of N-isotropic elements, which may be calculated using the following series of equations [10]:

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There are two components to an array's representation: the array pattern and the array geometry. Antenna elements' actual placement inside the array, also known as its configuration, is defined by array geometry. It is possible to have both uniform and non-uniform arrangements of array elements inside each geometry. Next, we have the pattern that the array represents. Every element in the array is considered to have an isotropic pattern by default. Because of the interplay between these factors, the array pattern, a property of array geometry, is generated [11].

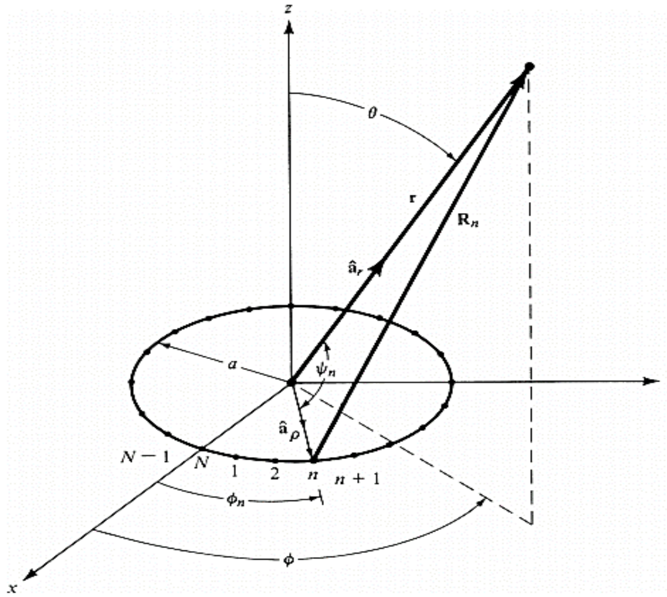

Fig. (1) The x-y plane layout of an N-element circular antenna array. [12]

The array's normalized field is expressed as [13, 14].

$$E_n(r,\theta,\phi) = \sum_{n=1}^{N} a_n \frac{e^{-jkR_n}}{R_n} \dots\dots\dots\dots\dots\dots\dots\dots (1)$$

In this case, R_n is the distance between the field observation point and the nth element. In general

$$R_n = (r^2 + a^2 - 2\,a\,r\cos\psi_n)^{\frac{1}{2}} \dots\dots\dots\dots\dots\dots\dots\dots (2)$$

For all values of r greater than a, it becomes

$$R_n \simeq r - a\cos\psi_n = r - a\,(\hat{a}_\rho . \hat{a}_r) = r - a\sin\theta\cos(\phi - \phi_n) \dots\dots\dots\dots\dots\dots\dots\dots (3)$$

where

$$\hat{a}_\rho . \hat{a}_r = (\hat{a}_x\cos\phi_n + \hat{a}_y\sin\phi_n).(\hat{a}_x\sin\theta\cos\phi + \hat{a}_y\sin\theta\sin\phi + \hat{a}_z\cos\theta)$$

$$= \sin\theta\cos(\phi - \phi_n) \dots\dots\dots\dots\dots\dots\dots\dots (4)$$

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Accordingly, the first equation is simplified. With the presumption that $R_n \simeq r$ for amplitude variations, in order:

$$E_n(r,\theta,\phi) = \frac{e^{-jkr}}{r}\sum_{n=1}^{N} a_n e^{jka\sin\theta\cos(\phi-\phi_n)} \dots\dots\dots\dots\dots\dots\dots\dots (5)$$

Where

a_n = Represents the element's excitation coefficient of the nth element to be considered.

$\phi_n = 2\pi\left(\frac{n}{N}\right)$ = angular position of nth element on x-y plane

The excitation coefficient of the nth element can be expressed in a general manner.

$$a_n = I_n e^{j\alpha_n}$$

Where

I_n = the excitation of the nth element in terms of amplitude.
α_n = phase excitation of the nth element in relation to the array center

When equations 1 and 2 are combined together:

$$E_n(r,\theta,\phi) = \frac{e^{-jkr}}{r}\left[AF(\theta,\phi)\right] \dots\dots\dots\dots\dots\dots\dots\dots (6)$$

Where

$$AF(\theta,\phi) = \sum_{n=1}^{N} I_n e^{j[k\,a\sin\theta\cos(\phi-\phi_n)+\alpha_n]} \dots\dots\dots\dots\dots\dots\dots (7)$$

A set of N elements organized in a circular array spaced equally is represented by the array factor (AF) in Equation (4). To guide the main beam's peak in the direction given by (θ_0, ϕ_0), the nth element's phase excitation can be changed.

$$\alpha_n = -\,k\,a\,\sin\theta_o\cos(\phi_o-\phi_n) \dots\dots\dots\dots\dots\dots\dots (8)$$

$$a = \frac{Nd}{2\pi} \dots\dots\dots\dots\dots\dots\dots (9)$$

Using the above equation the phase shifter progress between the array elements can be found.

N = number of elements in circular array

a = radius of circular array

d = angular separation between two adjacent elements

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k = wave number = $\frac{2\pi}{\lambda}$

λ = wavelength of the signal

θ = An angle formed by the positive z-axis and the zenith.

ϕ_o = The angle determined by extending the positive x-axis to the azimuth.

ϕ_n= The nth element's angular position ϕ_n on the resting plane is provided by

$$\phi_n = \frac{2\pi n}{N} \dots\dots\dots\dots\dots(10) \quad n = 1,2,3,\dots\dots\dots\dots N$$

DESIGN AND SIMULATION RESULTS

Some fundamental features of radiation are addressed in this study of a uniform circular array for difference number of elements and phase shift for scanning beam at different angle has been analyzed through the 4NEC2X software with 0.5λ spacing between the elements [15]. The length (L) and the wire radius (R) of a single half wavelength dipole antenna array have been determined using the formulae below [16, 17].

$$L = 0.475\,\lambda = \frac{143}{\mathrm{f(MHz)}}\ (m) \dots\dots\dots\dots(11)$$

$$R = \frac{D}{2} = 0.001\,\lambda \dots\dots\dots\dots\dots\dots\dots\dots(12)$$

$$\lambda = \frac{c}{f} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots(13)$$

The variables at play here are the operating wave's wavelength (λ) and frequency (f), the speed of light (c), and the elements' wire diameter (D).

As shown in Figure (2), a dipole is a simple antenna configuration that consists of two straight collinear wires. The half-wavelength dipole, with dimensions L = λ/2, is among the most used types of antennas. The reason behind this is that it meets the requirements for the matching process, as the characteristic impedance of certain transmission lines used nowadays is 75 ohms, which is pretty near to its radiation resistance of 73 ohms [18].

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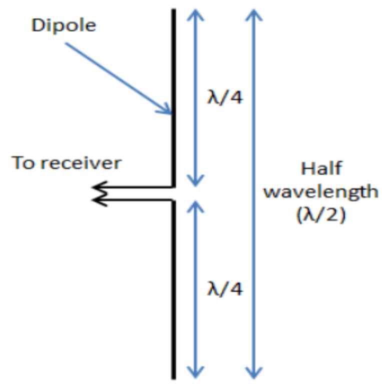

Fig. (2) A basic dipole antenna [17]

The half wave length dipole antenna has been designed and analyzed for 900 MHz operating frequency. The 4NEC2X software gave a 2.14 dBi gain, HPBW (vertical plane) 80 degree, HPBW (Horizontal Plane) 360 degree, 1.4 VSWR and no front to back ratio, no side lobe level. This information is taken as a reference for designing a circular array.

For designing a circular antenna array, the x and y coordinates can be found using the equations a = $\frac{Nd}{2\pi}$ and $\phi_n = \frac{2\pi n}{N}$ with the aid of the figure (3), below as

X=a cos ϕ_n

Y=a sin ϕ_n

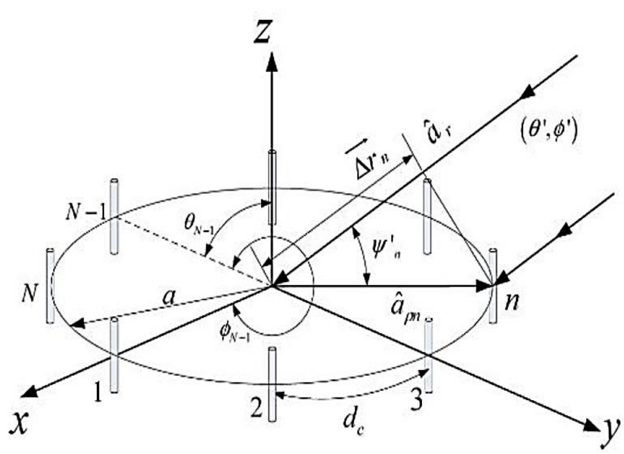

Fig. (3) Circular array geometry with N dipole elements [19]

In this study, the uniform circular half wavelength dipole array antenna operating at 900 MHz has been analyzed for base station mobile communication [20] as the following:

The elements were distributed in the x-y plane and the length of dipole aligned directly on the z-axis. L and R did not change in value by using equation (11 and 12) for each of the several configurations of circular arrays investigated here, knowing that depending on the specific design, configuration, and intended application case for typical base station array antennas used

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in cellular or wireless communication systems, the gain can range from around 10 dBi (decibels relative to isotropic) to 20 dBi or more [21].

Number of Elements Effect on the Performance of uniform circular array

The first planned study is to look at how the radiation characteristics, such as gain, half power beam-width, number of side lobes, and radiation pattern, are affected by the number of elements. We used the 4NEC2X simulators to do the design simulations and optimization processes with 0.5λ spacing between elements, and the results are in Table (1).

Table 1: Some radiation characteristics vary with the number of elements in an array with a separation of 0.5 λ.

No. of element	Gain (dBi)	HPBW (vertical plane) degree	HPBW (horizontal Plane) degree	F/B ratio	No. of SLL
2	5.88	76	152	7.13	3
4	8.23	72	64	14.6	3
6	9.97	68	44	9.41	5
8	10.6	64	32	4.29	7
10	11.6	60	24	3.66	9
12	12.3	60	20	6.99	9

It is evident from these results that the radiation properties of the array are greatly affected by the number of elements. With 12 elements, the gain of the array antenna reaches 12.3 dBi, which is a significant increase over the previous value. Increasing the number of elements causes the half power beam-width (HPBW) to decrease in both the vertical and horizontal planes, making the beam more directed, as illustrated in figure (4). Furthermore, as the number of elements increases, there is a corresponding increase in the number of side lobes. There are all well appeared in the next figure which is called antenna (power or radiation) pattern for the antenna.

The relationship between the gain and the number of elements is illustrated in figure (5) below. For the array of 12 elements, the gain is measured to be 12.3 dBi.

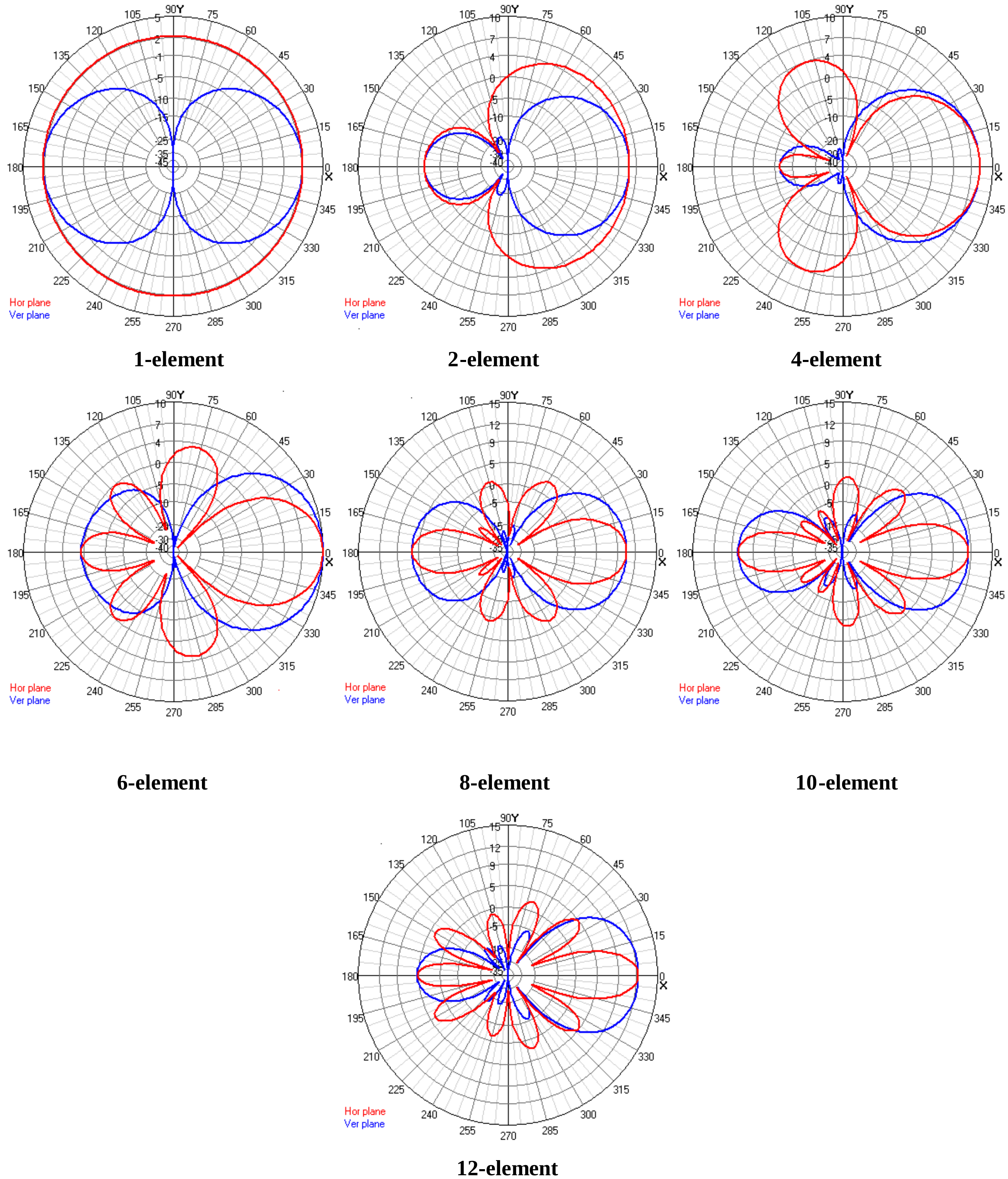

Fig.(4) Radiation pattern in both the vertical and horizontal axes as a function of element number for uniform circular array dipole antenna.

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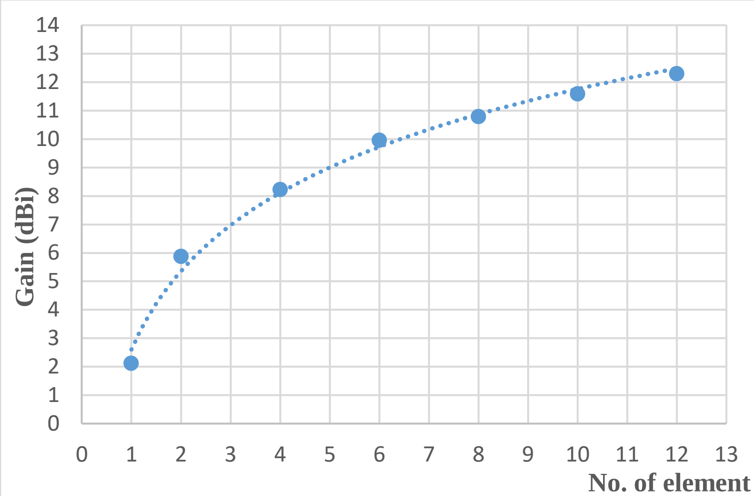
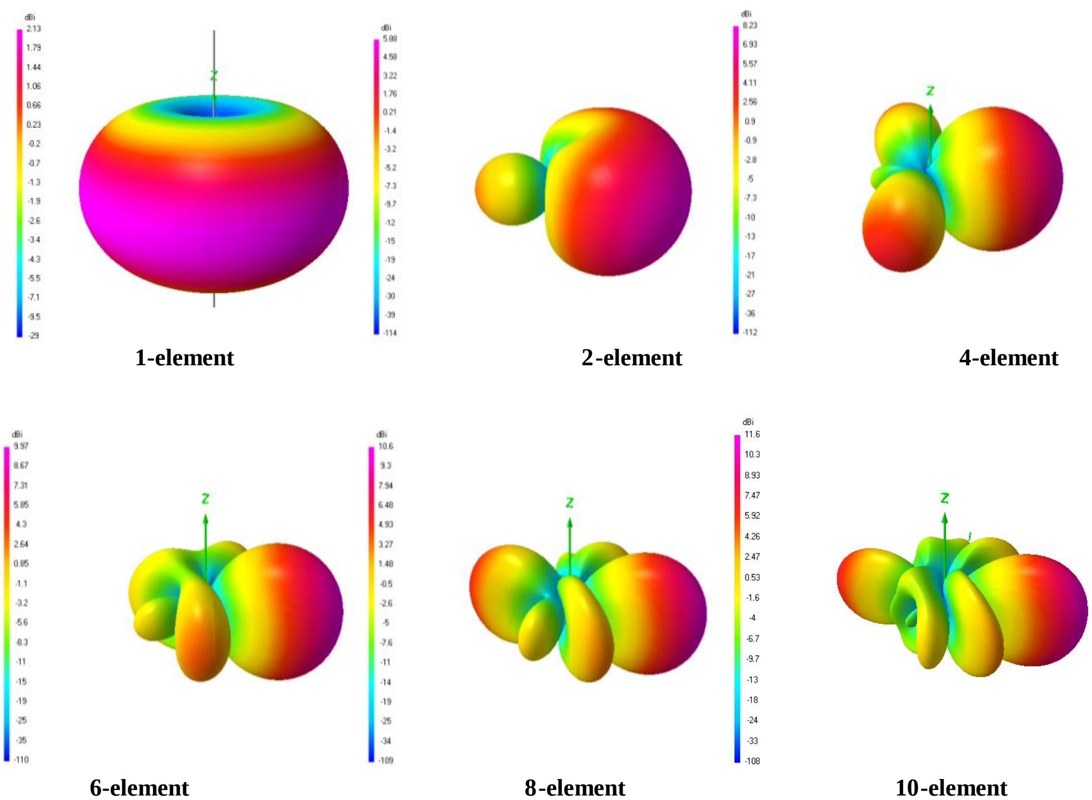


Fig. (5) Graph showing gain as a function of element count with a 0.5λ spacing

Figure (6) below shows the same variation in 3D form.



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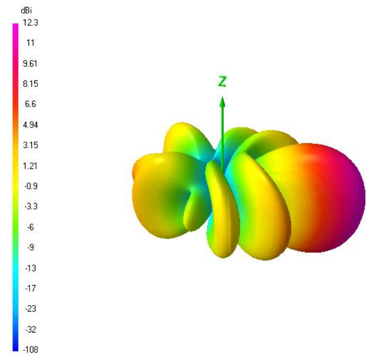

12-element

Fig. (6) 3D Relationship between radiation pattern and number of elements with a spacing of 0.5λ

Phased (Scanning) Array

Linear Array Antenna Main Beam Scanning

The goal of directing the main lobe of the radiation pattern at an angle different than the broadside and end-fire directions is to be achieved in various applications. The pattern's scan angle determines this directed angular position. By applying a phase difference to the antenna array's elements, the scanned pattern can be obtained. To achieve an orientation of the greatest radiation from the array at angle θ_0, it is necessary to modify the progressive phase excitation β between each element such that [22].

$$\psi = \beta + kd\cos\theta_0 = 0 \dots\dots\dots\dots\dots\dots (14)$$

$$\beta = -kd\cos\theta_0 \dots\dots\dots\dots\dots\dots\dots\dots\dots (15)$$

By manipulating the progressive phase difference among the elements, it is possible to focus the maximum radiation in a particular direction, resulting in the formation of a scanning array (of a 2D array antenna designed as shown in figure (7)). In figure (8) below shows the 8-element uniform linear array for difference angle phase scanning from 0 degree to 360 degree.

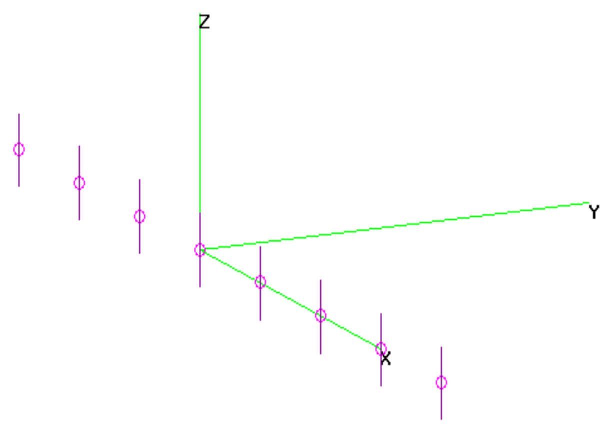

Fig. (7) Antenna design using 4NEC2X, with elements aligned along the x-axis and parallel to the z-axis.

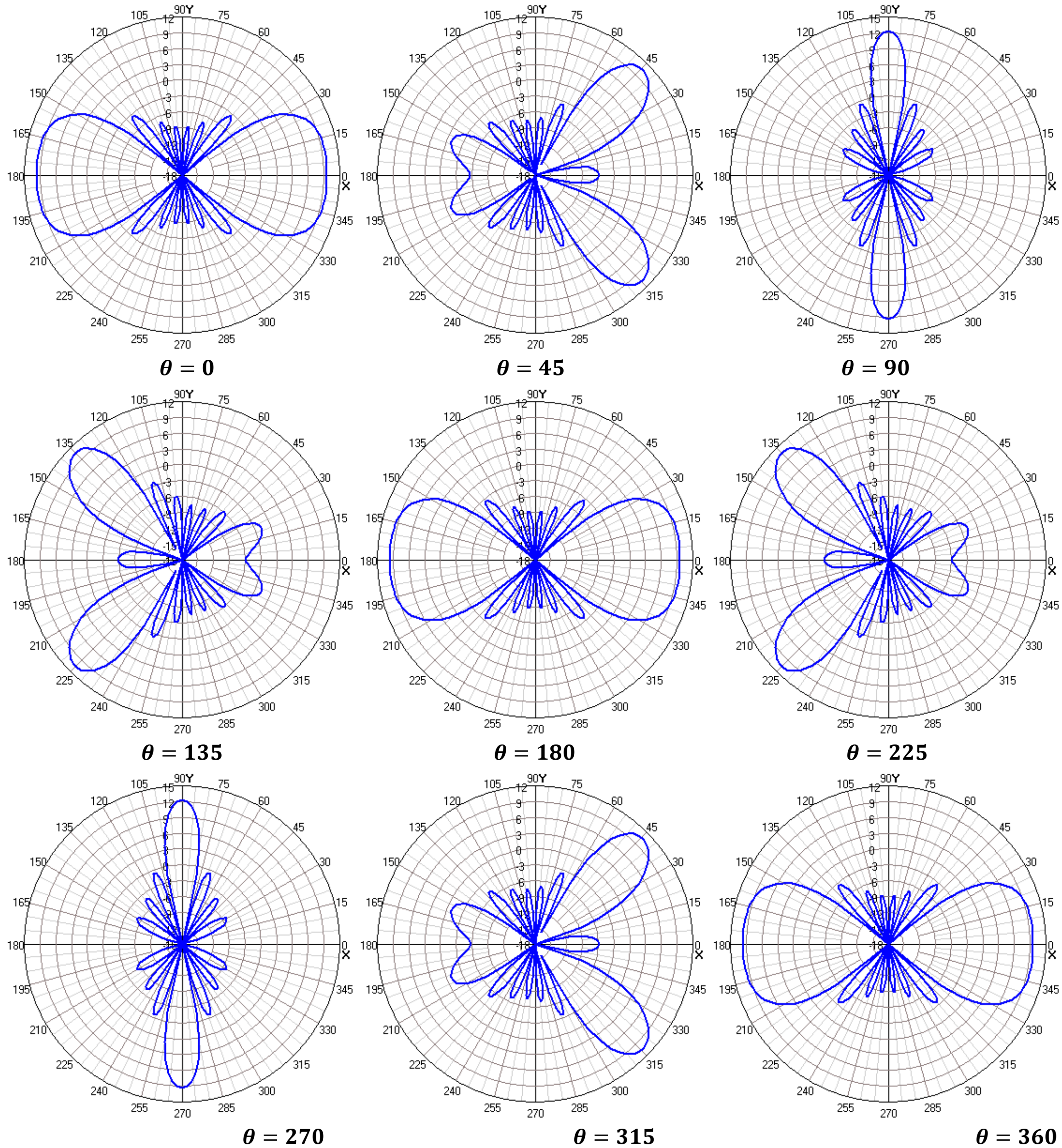

Fig. (8) Radiation pattern of phase scanning 0, 45, 90, 135, 180, 225, 270, 315 and 360 degree (8-element and λ/2 spacing).

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Circular Array Antenna Main Beam Scanning

The capacity of this antenna to steer the radiation pattern without changing location is one of its key features, we take into account a circular array of eight identical dipole antenna elements that are evenly distributed in a circle with radius a in the xy plane, as depicted in Figure (9). The radius is selected so that the elements are spaced at a distance of λ/2. (a=Nλ/4π), and use $\alpha_n = -\,k\,a\,sin\,\theta_o\,cos(\phi_o - \phi_n)$ to find the phase angle between adjusting element [23].

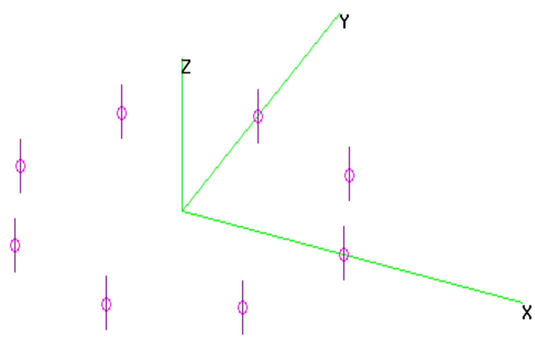

Fig. (9) Antenna design using 4NEC2X, with elements aligned along the x-y plane and parallel to the z-axis.

Figure (10) shows different radiation patterns that belong to different scanning angle, for 8-elements circular array with uniform spacing of 0.5 λ.

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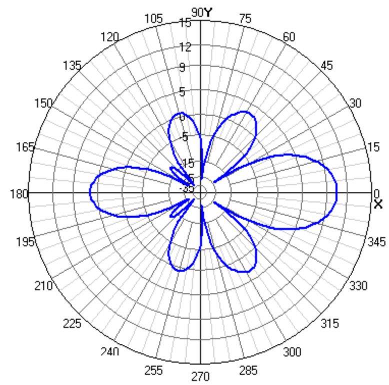
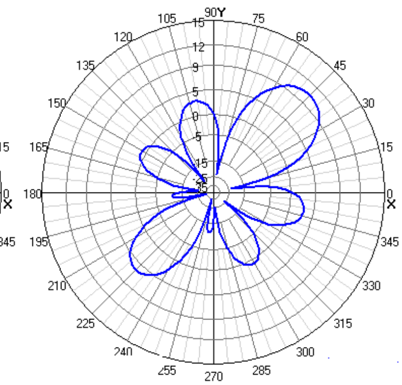
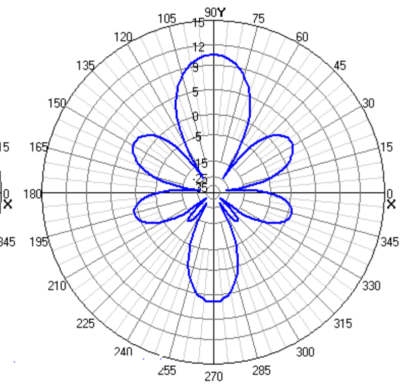


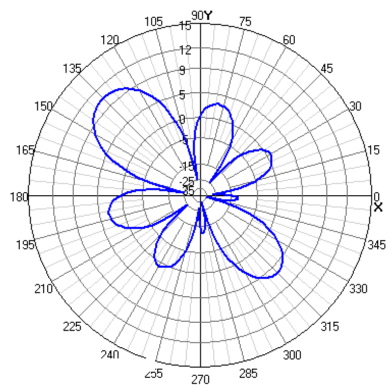
$\boldsymbol{\theta = 0}$



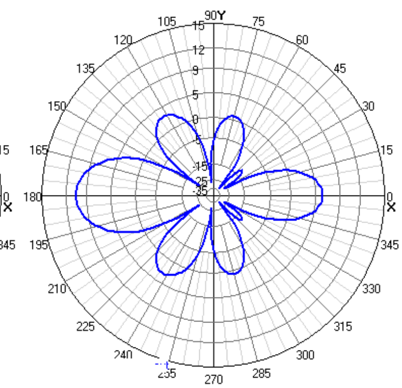
$\boldsymbol{\theta = 45}$



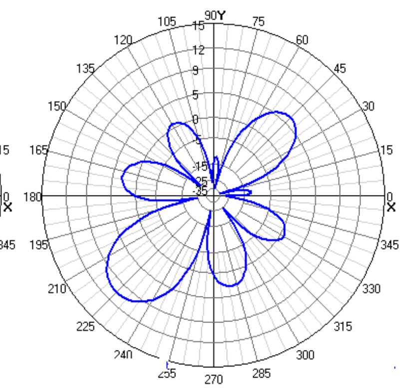
$\boldsymbol{\theta = 90}$



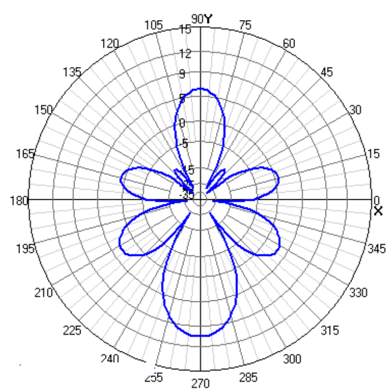
$\boldsymbol{\theta = 135}$



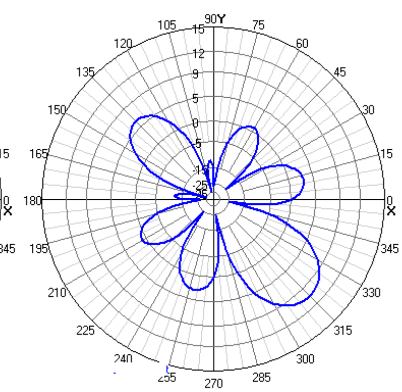
$\boldsymbol{\theta = 180}$



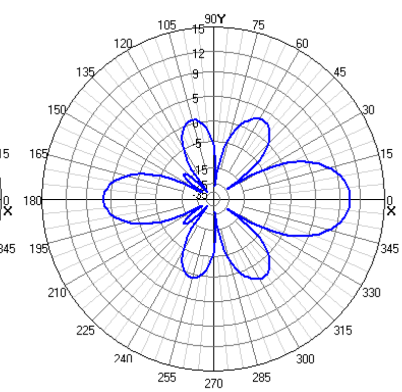
$\boldsymbol{\theta = 225}$



$\boldsymbol{\theta = 270}$



$\boldsymbol{\theta = 315}$



$\boldsymbol{\theta = 360}$

Fig. (10) Radiation pattern in horizontal plane of phase scanning 0, 45, 90, 135, 180, 225, 270, 315 and 360 degree (8-element and λ/2 spacing) for uniform circular dipole array.

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Conclusion

Finally it can be concluded that, the circular array antenna is considered a highly suitable option because of its capability to electronically scan a beam over a 360-degree range without any change and distortion in radiation pattern. Increasing the number of the elements in the circular array, decreases the beamwidth of major lobe that leads to increase in the directivity and the gain. The gain of a single element, half wavelength dipole antenna, increases from 2.14 dBi to 12.3 dBi for a 12-element circular array with the degradatiom of HPBW as shown in table (1). Through simulation and analysis using 4NEC2X software, the performance of the Circular Array Antenna with phase shifters can be evaluated in terms of beam steering range, beamwidth, sidelobe levels, and overall radiation efficiency. Figure (8) and (10) show the difference between linear and circular array antenna when the beam scaninng in desire direction. The circular array phase shifting design is quite accepted due to its fixed pattern shap, directivity and gain while the scanning the beam without changing the antenna position.

Conflict of interests

There are non-conflicts of interest

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الخلاصة

مقدمة

يعرض هذا البحث استخدام مبدلات الطور للتحكم في أنماط الإشعاع في هوائيات المصفوفة الدائرية الموحدة (UCA). تم تعزيز UCAs، المعروفة بتغطيتها بزاوية 360 درجة وأنماط الإشعاع المتناظرة، من خلال دمج مبدلات الطور، مما يتيح توجيه الحزمة الديناميكية وتشكيل النمط.

طرق العمل

تم تصميم مجموعة هوائيات دائرية موحدة تعمل بتردد 900 جيجا هرتز للاستخدام في المحطات الأساسية باستخدام برنامج المحاكاة 4NEC2X.

الاستنتاجات

يُستخدم هوائي ثنائي القطب أحادي العنصر له كسب قدره 2,14 dBi كقاعدة لإنشاء صفيف دائري منتظم بتباعد 0,5 λ. زاد عدد العناصر تدريجيا من 2 إلى 12، مما رفع الكسب إلى 12.3 ديسيبل. انخفض HPBW في المخططين الرأسي والأفقي من 80 درجة إلى 60 درجة ومن 360 درجة إلى 20 درجة على التوالي مما يعني زيادة اتجاهية المصفوفة الدائرية للهوائي. تم إجراء مسح شعاع المصفوفة المكونة من ثمانية عناصر من 0^{o} إلى 360^{o} دون أي تشويه في نمط الإشعاع والكسب والاتجاهية، وهو ما يتعارض مع المصفوفة الخطية.

الكلمات المفتاحية:

مجموعة دائرية موحدة، هوائي ثنائي القطب نصف الطول الموجي، محول الطور ، الكسب، 4NEC2X