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Characteristic Analyses of a Five- Element Planar UWB Antenna Array

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Abstract

In this paper, a five- element UWB planar array has been investigated, and the results of a computer simulation are presented. Fixed spacing between radiators was included in simulations. Characteristics of array factor, array electric field, field pattern, and the directivity were shown and discussed in this work. The array factors for different cases have been derived and simulated using industry standard simulation software. The most important characteristic is its scanning mechanism. By setting the values of $\theta_0 = 30^0$ and $\phi_0 = 45^0$, it can be shown that we can approximately fulfill this feature. The simulations for the 3 – dimensional real-array array factor, array electric field, field pattern, and the directivity as a function of both the elevation angle (θ) and the azimuth angle (ϕ) are also shown in this work with performance improvements through using this particular structure. It is noted that large number of antenna elements contribute to higher directivity and large number of sidelobes in the AF pattern. Lower directivity can be achieved by setting inter - element spacing less than half wavelength but at the expense of mutual coupling effects. Thus, inter- elements spacing equal or larger than half wavelength is suitable to get higher directivity for large antenna array applications. Therefore, this structure with MIMO capability operating in UWB band is a good candidate for the indoor communications.

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I. Introduction

Ultra- wideband (UWB) is a radio technology which has been used in applications that require a very low energy level for short-range, high-bandwidth communications over a large portion of the radio spectrum [1]- [3]. The United States Federal Communications Commission (FCC) authorizes the unlicensed use of ultra-wideband (UWB) antenna radiation in the frequency range from 3.1 GHz to 10.6 GHz with low power spectral density [4]. The traditional applications for UWB are in non-cooperative radar imaging(e.g., ground penetration radar systems, wall imaging systems, through- wall imaging systems, surveillance systems, and medical systems), while target sensor data collection, precision locating and tracking are the most recent applications for UWB [5]. The transmission of UWB signal differs from spread spectrum in that there is no interference with conventional narrowband and carrier wave signals in the same frequency band. Besides, the short duration of the pulses in the UWB automatically creates a very large bandwidth without using the spreading codes [6]. Since UWB spectrum is used for transmitting information which is spread over a large bandwidth (>500 MHz), it should be able to share the spectrum with other users. Since UWB generation is based on the use antenna array, an important area of research is to study the role of arrays itself in generating the radiation [7]. Array theory [8], which is the subject of study in this paper, applies to both narrowband antenna arrays and UWB antenna arrays. Each beam in the array is formed by applying a distinct set of weights (i.e., amplitude and phase adjustments) to the signal records. An active array may form simultaneous multiple beams (e.g., Multiple Input Multiple Output (MIMO) wireless communications applications) when the signals from the elements of an array are digitally recorded.

UWB smart arrays (e.g., MIMO applications) [9], require UWB antenna elements. A common form of an array is a planar array. UWB antenna element spacing (e.g., may be much smaller than the lowest frequency wavelength) in UWB arrays is fundamentally different than narrowband antenna element spacing (e.g., on the order of the center frequency wavelength) in narrowband arrays. The Ultra-wideband innovation combined with MIMO methods has turned out to be an answer for the restriction of short- range communications, especially when low power transmission is required. in this scheme, the antenna design is set to guarantee that the mutual coupling among the individual elements should be less than -15 dB. This can be accomplished by setting the radiators at least half a wavelength apart from each other; however, this leads to the enlarging of MIMO antenna dimensions. Therefore, many compensation and optimization techniques have been used to mitigate the mutual coupling between the antenna elements [10]. The applications of the UWB smart antenna arrays include tracking radar, search radar, remote sensing, communications, etc.

Many UWB single antenna constructions have been described in the literature [10-11]. These antennas are characterized by the omnidirectional radiation patterns and have a moderate gain. When a directional radiation pattern or higher value of antenna gain is needed, UWB arrays can be utilized in radio systems [12-15]. Two planar elliptical antennas, microstrip, and stripline that have been used in ultra-wideband radio communication systems, are presented in [16]. The analysis of planar ultra-wideband microstrip and stripline antennas is presented in [17]. Besides, planar two-element UWB antenna for radio communication systems is analyzed in [18]. Also, Garbaruk M. et al. in [19] describes the structure and characteristics of a planar symmetrical two-element ultra- wideband antenna for applications that work within the frequency range of 6 - 8.5 GHz.

In this paper, we present a new planar UWB- MIMO antenna array structure to enhance the performance of modern wireless communication systems. Therefore, this structure with MIMO capability operating in UWB band is a good candidate for the indoor communications. Compared to the recent designs [20]- [23], the proposed array provides an improvement in the scanning mechanism throughout the entire UWB band as explained later in section IV. The characteristics analyses of a five- element planar UWB antenna arrays are investigated. We present the results of a computer analysis of planar UWB antenna arrays consisting of 5×5 radiators. Our focus is on a fixed spacing antenna array that working within a frequency range 3.1-10.6 GHz. We shall consider and show the characteristics of array factor, array electric field, field pattern, and the directivity. The array factors for different cases have been derived and simulated using industry standard simulation software. By setting the values of $\theta_0 = 30^0$ and $\phi_0 = 45^0$, it can be shown that we can approximately achieve the array scanning mechanism. So far, it is supposed that the array characteristics, are derived for the isotropic sources, and they have omnidirectional radiation patterns. Therefore, we shall focus on the non-isotropic arrays, the elements are not isotropic or isolated sources, and we can see much better improvement in the array performance. These good performances could be at the expense of many negative impacts, like mutual coupling, if the number of antenna elements increases. Finally, the simulation results for the 3 – dimensional array factor, array electric field, field pattern, and the directivity as a function of both the elevation angle (θ) and the azimuth angle (ϕ) are also shown in this work. It is also noted that the maximum directivity of 80 dB is also reported in this work. It can be observed that large number of antenna elements contribute to higher directivity and large number of sidelobes in the AF pattern. Lower directivity can be achieved by setting inter - element spacing less than half wavelength but at the expense of mutual coupling effects. Therefore, inter- elements spacing equal or larger than half wavelength is suitable to get higher directivity for large antenna array applications.

II. Methodology

Analysis of planar array as isotropic sources have been studied before; however, studies of planar sources are very fewer and far between [24]- [28]. Planar array analysis can be formed by positioning individual radiators along a rectangular grid. These grids could also be square in shape and contribute to the versatility of the configuration by providing additional symmetrical patterns with lower side lobes. They can also be used to scan the main beam of the antenna toward any point in space.

Important parameters in antenna array design include array factor, array electric field, field pattern and directivity.

The array factor (AF) of the planar arrays can be derived using the principles of the linear arrays (equations 1 through 16) [29]. The AF of a linear array of M elements along the x-axis is:

$$AF = \sum_{m=1}^{M} I_{ml}\, e^{j(m-1)(kd_x sin\theta cos\phi+\beta_x)} \qquad (1)$$

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where I_{ml} is the excitation coefficient of each element and $sin\theta cos\varphi$ is the directional cosine with respect to the x-axis. It is assumed that all elements are equally-spaced with an interval of d_x and a progressive shift β_x.

A rectangular array will be formed by placing N such array next to each other a distance d_y apart in the y- direction with a propagation phase β_y , as shown in Fig. 1.

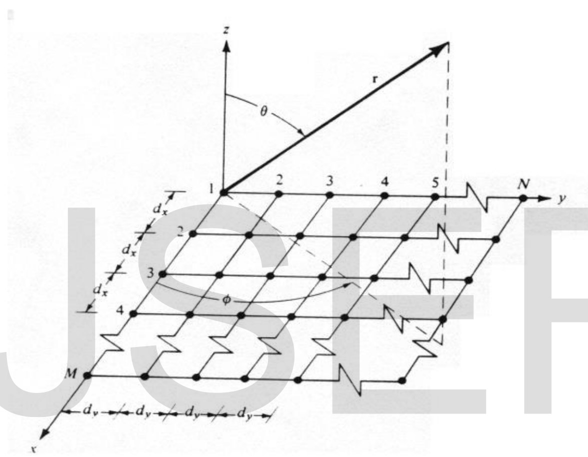

Fig. 1: Planar array geometry

It will be also assumed that the normalized current distribution along each of the x-directed array is the same, but the absolute values correspond to a factor of I_{ln} $(n = 1, \dots, N)$. Then, the AF of the entire array will be:

$$AF = \sum_{n=1}^{N} I_{ln} \Big[\sum_{m=1}^{M} I_{ml} e^{j(m-1)(kd_x \, sin\theta \, cos\phi + \beta_x)} \Big] e^{j(n-1)(kd_y \, sin\theta \, sin\phi + \beta_y)} \qquad (2)$$

or

$$AF = S_{xm}\ S_{yn} \tag{3}$$

where

$$S_{xm} = \sum_{m=1}^{M} I_{ml}\ e^{j(m-1)(kd_x \sin\theta \cos\phi + \beta_x)} \tag{4}$$

$$S_{yn} = \sum_{n=1}^{N} I_{ln}\ e^{j(n-1)(kd_y \sin\theta \sin\phi + \beta_y)} \tag{5}$$

It can be shown from equation (3) that the pattern of a rectangular array is the product of the array factors of the linear arrays in the x and y directions [29].

For a uniform array, the amplitude excitation coefficients of the array in the y −direction are proportional to those in the $x -$ direction ($I_{ml} = I_{ln} = I_0$) for all m and n, equation (2) can be expressed as, [29]

$$AF = I_0\ \sum_{m=1}^{N} e^{j(m-1)(kd_x \sin\theta \cos\phi + \beta_x)}\ \sum_{n=1}^{N}\ e^{j(n-1)(kd_y \sin\theta \sin\phi + \beta_y)} \tag{6}$$

The normalized array factor can then be obtained as:

$$AF_n(\theta,\phi) = \left\{\frac{1}{M}\ \frac{\sin\left(\frac{M}{2}\psi_x\right)}{\sin\left(\frac{\psi_x}{2}\right)}\right\}\ \left\{\frac{1}{N}\ \frac{\sin\left(\frac{N}{2}\psi_y\right)}{\sin\left(\frac{\psi_y}{2}\right)}\right\} \tag{7}$$

where

$$\psi_x = kd_x \sin\theta \cos\phi + \beta_x \tag{8}$$

$$\psi_y = kd_y \sin\theta \sin\phi + \beta_y \tag{9}$$

The major lobe (principal maximum) and grating lobes of the terms:

$$S_{xm} = kd_x \sin\theta \cos\phi + \beta_x \tag{10}$$

$$S_{yn} = kd_y \sin\theta \sin\phi + \beta_y \tag{11}$$

are located at angles such that:

$$kd_x \sin\theta_m \cos\phi_m + \beta_x = \pm 2m\pi, \quad m = 0,1, \dots \tag{12}$$

$$kd_y \sin\theta_m \sin\phi_m + \beta_y = \pm 2n\pi, \quad n = 0,1, \dots \tag{13}$$

The principal maxima correspond to m = 0, n = 0.

In general, β_x and β_y are independent from each other. But, if it is required for some particular applications that the main beams of S_{xm} and S_{yn} intersect (which is usually the case), then the common main beam is in the direction:

$$\theta = \theta_0 \quad \text{and} \quad \phi = \phi_0 , \qquad m = n = 0 \tag{14}$$

If the principal maximum is specified by (θ_0, ϕ_0) , then the progressive phases β_x and β_y must satisfy:

$$\beta_x = kd_x \sin\theta_0 \cos\phi_0 + \beta_x \tag{15}$$

$$\beta_y = kd_y \sin\theta_0 \sin\phi_0 + \beta_y \tag{16}$$

For the antenna presented in this work some of the equations cited above need to be modified, as discussed in the following section.

III. Simulation Parameters

Fig. 2 shows the geometries of the planar square array being simulated. The proposed geometry and its parameters are described as follows: The array is operated at UWB frequency range from3.1 GHz to10.6 GHz . A sampling at the middle of the frequency band (6.8 GHz) has also been performed to compare the response at three frequencies. The wavelengths of the array ($\lambda's$) were also calculated. The array is located on xy- plane and consists of M elements in the $x-$ axis and N elements in the $y-$ axis, with the normal along $z-$ axis. In the simulation $M = N = 5$, as compared to the previous value of $M = N = 2$ [19]. The spacing between parameters

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is set to be d_x in x −direction and d_y in the y −direction, such that $d_x = d_y = (\lambda - high)/2$, where$\lambda - high = f - high/v$. Some of the variable parameters have already been described earlier in section II; these include the excitation amplitude (I_0), phase excitation (β_x) and (β_y), elevation angle (θ), and azimuth angle (ϕ). The directivity maximums are oriented along $(\theta = \theta_{0)}$ and $(\phi = \phi_0)$ respectively.

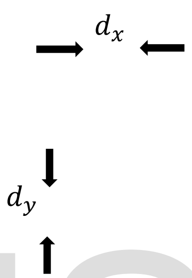

Fig. 2: Planar array geometry

IV. Simulated Results

Based on [29], the array factor plots for different situations were simulated using industry standard simulation software and the results were noted in a tabular form for three specific frequencies, designated as low, sampling, and high frequency. The spacing between elements were calculated as, $d_x = d_y = v/(2 \times \mathrm{f} - \mathrm{high})$, where v is the speed of light. In addition, the number of the elements in the x and y coordinates are similar (square grid), thus M =N = 5.

Fig. 3 shows the array factor plot as a function of θ angle, the elevation angle, using equation (6), where $\theta_0 = 0^0$, $\phi_0 = 0^0$, and $\phi = 0^0$. The same results can be obtain using the normalized version of the formula given in equation (7).

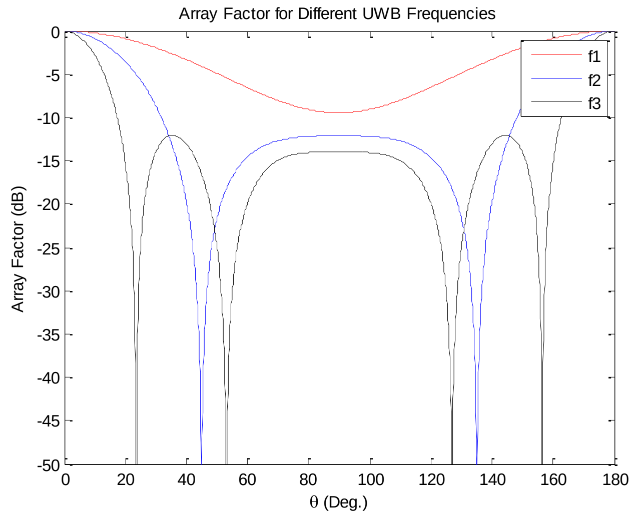

Fig. 3: The array factor plot as a function of θ angle,

where $\theta_0 = 0^0$, $\phi_0 = 0^0$, and $\phi = 0^0$.

Fig. 4 shows the array factor plot as a function of theta angle using equation (6) when where $\theta_0 = 0^0$, $\phi_0 = 0^0$, and $\phi = 45^0$. The same results can be obtained using the normalized formula of equation (7).

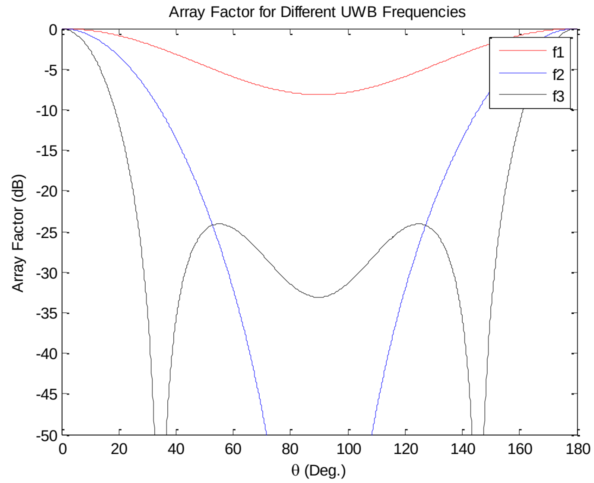

Fig. 4. The array factor plot as a function of θ angle,

where $\theta_0 = 0^0$, $\phi_0 = 0^0$, and $\phi = 45^0$.

Fig. 5 shows the array factor plot as a function of theta angle using equation (6) when $\theta_0 = 30^0$, $\phi_0 = 45^0$, and $\phi = 0^0$. The same results can be obtained using the normalized formula of equation (7).

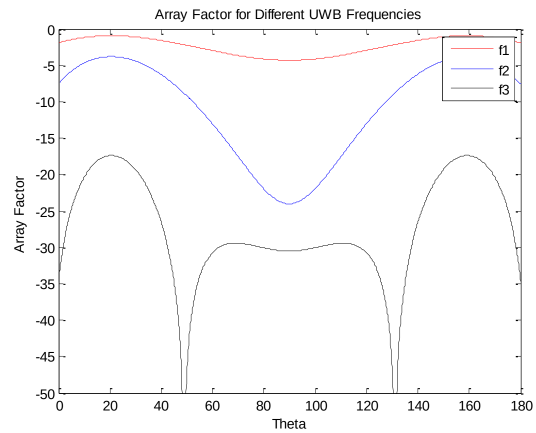

Fig. 5: The array factor plot as a function of θ angle,

where $\theta_0 = 30^0$, $\phi_0 = 45^0$, and $\phi = 0^0$.

Fig. 6 shows the array factor plot as a function of theta angle using equation(6) when $\theta_0 = 30^0$, $\phi_0 = 45$, and $\phi = 45^0$. The same results can be obtain using the normalized formula of equation (7).

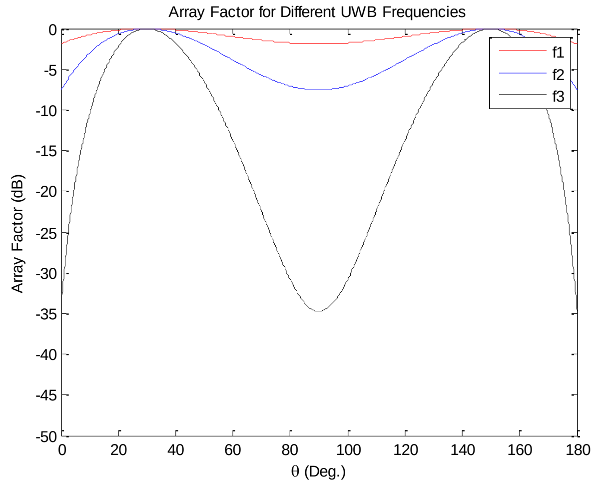

Fig. 6: The array factor plot as a function of θ angle,

where $\theta_0 = 30^0$, $\phi_0 = 45^0$, and $\phi = 45^0$.

As we can see from these results (summarized in Table I), the most important characteristic is the scanning mechanism, which is optimized at $\theta_0 = 30^0$ and $\phi_0 = 45^0$. This optimized feature together with the MIMO- UWB planar array structure can have applications in indoor wireless communications.

Table (1) simulated parameters

Sim #	M	N	$d_x(m)$	$d_y(m)$	β_x	β_y	ϕ	θ_0	ϕ_0
1	5	5	0.0141	0.0141	0	0	0	0	0
2	5	5	0.0141	0.0141	0	0	45	0	0
3	5	5	0.0141	0.0141	-1.1107	-1.1107	0	30	45
4	5	5	0.0141	0.0141	-1.1107	-1.1107	45	30	45

V. Antenna Array Performances

Analyses of MIMO- UWB planar array antenna show performance improvements**,** specifically in radiation pattern and directivity. However, these improvements could be at the expense of lower directivity and mutual coupling, and also if the number of antenna elements increase and the inter element spacing decrease, are equal or less than half wavelength.

1) Array Element Radiation Pattern

So far, it is supposed that the array factor formulas, equations (6) and (7), are derived for the isotropic sources and they have omnidirectional radiation patterns. In the real arrays, the elements are not isotropic or isolated sources. For an equally spaced array of a number of antenna radiators, the radiation pattern of the antenna can be found according to the pattern multiplication theorem [30]:

$$Array\ pattern = Array\ element\ pattern\ \times Array\ factor\ (AF)$$

2) Array Electric Field

Consider a 5 × 5 element array, the electric field of a single element is defined as

$$E(single\ element) = \begin{cases} cos\theta & \theta \leq \pi/2 \\ 0 & \theta > \pi/2 \end{cases}$$

The electric field for the total array

$$E(\theta, \phi) = E(single\ element) \times AF(\theta, \phi)$$

According to equation (6), the electric field for the total array is

$$E(\theta, \phi) = cos\theta\ \times\ I_0\ \sum_{m=1}^{N} e^{j(m-1)(kd_x\ sin\theta\ cos\phi + \beta_x)}\ \ \sum_{n=1}^{N}\ e^{j(n-1)(kd_y\ sin\theta\ sin\phi + \beta_y)}$$

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and the electric field of the total array for the normalized equation (7) is

$$E(\theta,\phi) = cos\theta \times \left\{\frac{1}{M} \frac{sin\left(\frac{M}{2}\psi_x\right)}{sin\left(\frac{\psi_x}{2}\right)}\right\} \left\{\frac{1}{N} \frac{sin\left(\frac{N}{2}\psi_y\right)}{sin\left(\frac{\psi_y}{2}\right)}\right\}$$

3) Array Field Pattern

The normalized field pattern is then

$$F(\theta,\phi) = \frac{E(\theta,\phi)}{E(\theta_m,\phi_m)}$$

Similarly, for equation (6), the normalized field pattern is

$$F(\theta,\phi) = \frac{cos\theta}{E(\theta_m,\phi_m)} \times I_0 \sum_{m=1}^{N} e^{j(m-1)(kd_x\, sin\theta\, cos\phi+\beta_x)} \sum_{n=1}^{N} e^{j(n-1)(kd_y\, sin\theta\, sin\phi+\beta_y)}$$

and the normalized field pattern for equation (7) is

$$F(\theta,\phi) = \frac{cos\theta}{E(\theta_m,\phi_m)} \times \left\{\frac{1}{M} \frac{sin\left(\frac{M}{2}\psi_x\right)}{sin\left(\frac{\psi_x}{2}\right)}\right\} \left\{\frac{1}{N} \frac{sin\left(\frac{N}{2}\psi_y\right)}{sin\left(\frac{\psi_y}{2}\right)}\right\}$$

4) Directivity

On the other hand, a very important quantitative characteristic of an antenna is the directivity. this characteristic describes how much it concentrates energy in one direction. Directivity is tied more directly to the pattern function. First, the beam solid angle is defined as

$$\Omega_A = \iint |F(\theta,\phi)|^2 \, d\Omega$$

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$$\Omega_A = \iint |F(\theta,\phi)|^2 \, sin\theta \, d\theta \, d\phi$$

where

$$d\Omega = sin\theta \, d\theta \, d\phi$$

so that the directivity is

$$D = \frac{4\pi}{d\Omega}$$

Directivity as a function of pattern angle is expressed as

$$D(\theta,\phi) = D \, |F(\theta,\phi)|^2$$

so that

$$D(\theta,\phi) = \frac{4\pi \; |F(\theta,\phi)|^2}{\iint |F(\theta,\phi)|^2 \, sin\theta \, d\theta \, d\phi}$$

The simulations for the 3 – dimensional array factor, array electric field, field pattern, and the directivity as a function of both the elevation angle(θ) and the azimuth angle(ϕ) are shown in the figures below.

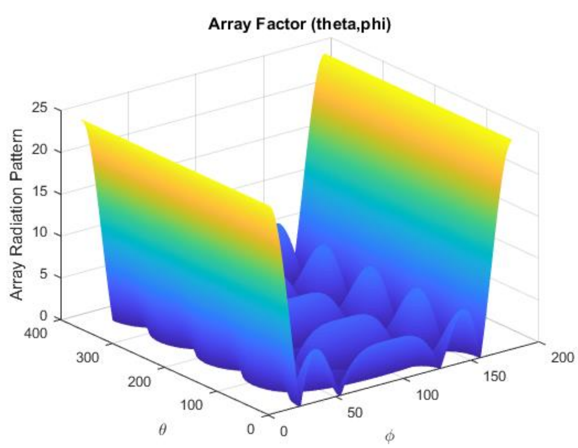

Fig. 7: 3 -D plot for the array radiation pattern (θ, ϕ)

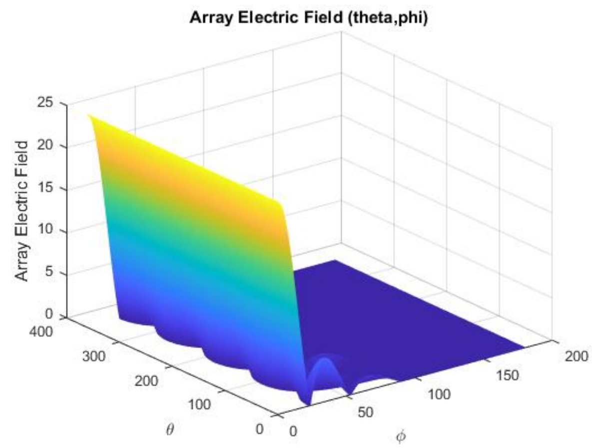

Fig. 8: 3 -D plot for the array electric field (θ , ϕ)

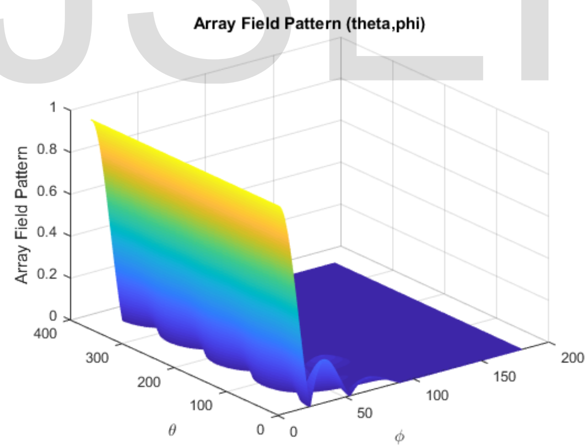

Fig.9: 3 -D plot for the field pattern (θ , ϕ)

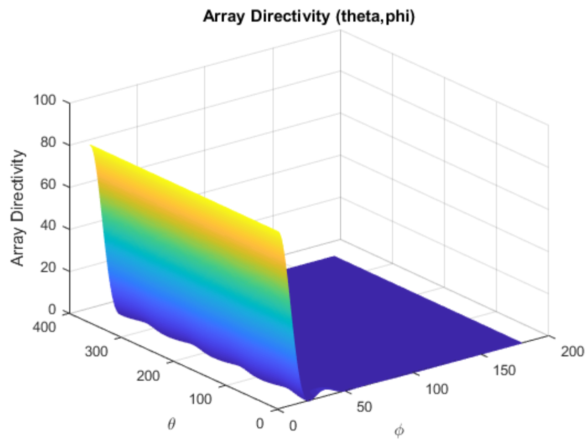

Fig. 10: 3 -D plot for the array directivity (θ , ϕ)

As can be seen from the simulated results (Fig. 7-10), by using the five-element UWB planar array, a much better array performance can be achieved. Although we have accomplished these improved results, it is at the expense of such negative impacts as mutual coupling; antenna element increases and a decrease in inter element spacing.

VI: Conclusion

In this paper, a planar MIMO UWB antenna array for possible use in indoor wireless communications is proposed. Specifically, a UWB planar array with fixed spacing antenna and designed to work within a frequency range 3.1-10.6 GHz has been proposed and analyzed. Results of simulation of a five- element planar ultra-wideband antenna arrays were presented, where the characteristics of network parameters, like radiation patterns, array electric field, field pattern, and directivity were considered. The array factors for different cases were derived and simulated using industry standard simulation software. Results at $\theta_0 = 30^0$ and $\phi_0 = 45^0$ indicate that the array has a wide versatility in its radiation characteristics, the most crucial aspect being its scanning mechanism. The 3 – D simulations with non-isotropic sources, array factor, array electric field, field pattern and the directivity as a function of both the elevation angle(θ) and the azimuth angle(ϕ) show improved performance as compared to other structures. A large number of antenna elements also contribute to higher directivity but with a larger number of side lobes in the AF pattern. Setting inter - element spacing less than half wavelength results in lower directivity and mutual coupling. However, with inter- elements spacing equal or larger than half wavelength the directivity increases even for large antenna array. As a result, it is possible to design UWB antenna with particular configuration and orientation to support the ever increasing demands of wireless communications.

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