Comparative Study of the Radiation Performance between Uniform and Non-uniform Excitation of Linear Patch Antenna Array for UWB Radar Applications

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Abstract: In this paper, we proposed four identical elements linear rectangular patch array antenna for ultra wide band applications. We considered the response of the array for uniform and non uniform amplitude excitations such as broadside, binomial and Dolph-Tschebyscheff distributions. Variation of radiation patterns in vertical plane, return loss, arrays factor, half -power beam width, gain and directivity are critically investigated. The rectangular patch antenna considered had to be small enough to fit on the communication device, it is characterized by the substrate thickness $h = 1.5 \text{ mm}$, the relative permittivity $\varepsilon_r = 4.4$, loss $\tan \delta = 0.02$ and fed by $50 \Omega$ microstrip line. We can see also that the gain and directivity maximal of the arrays can reach to $G = 12.4353 \text{ dB}$ and $D = 12.6951 \text{ dB}$ with a band wide can reach 72%, who can justify that we can manipulate these arrays in ultra wide band radar applications. The performance of the proposed arrays antenna has been studied by means of MATLAB.

Key-Words: Rectangular patch antenna, UWB, Array factor, Binomial, Dolph-Tschebyscheff, HPBW.

1 Introduction
Nowadays, Ultra Wideband (UWB) communication systems have the promise of very high bandwidth, reduced fading from multipath and low power requirements [1]. The Federal Communication Commission (FCC) specified some rules for UWB antenna implementations. It specified the antenna impedance bandwidth form 3.1 GHz to 10.6 GHz and any signal that occupies at least 500 MHz spectrum or occupy a fraction bandwidth of 20 % or greater can be used in UWB applications [2]. In general, the antennas for UWB systems should have sufficiently broad operating bandwidth for high-directivity and high-gain radiation in desired directions, the linear rectangular patch array antenna type is widely used due to its wide bandwidth, simple structure and low cost. The beam of an array can be shaped to become narrow and control the level of the side lobes by adjusting the current amplitudes in an array. The array excitation current distribution can be used to control the shape of the radiation pattern. The modes supported by the rectangular patch antenna can be found by treating the patch, ground plane and the material between the two as a rectangular cavity.

The merits of printed antenna such as light weight, small size and low profile make them an attractive candidate for UWB antenna development [3-8]. The radiation pattern of a single element is relatively wide and each element provides low values of gain [8]. In many applications it is necessary to design antennas with very directive characteristics and very high gains to meet the demands of long distance communication such as radar systems [9-11].

In this paper, we use four elements rectangular patch antenna placed linearly with uniform distance between each element. Firstly, each antenna is excited by uniform amplitude current and with the same phase shift between two successive elements, secondly, each antenna is excited by binomial function amplitude current and finally, each antenna is excited by Dolph-Tschebyscheff function amplitude current, in order to compare their performance in terms of the return loss, gain, directivity, HPBW, array factor and side lobes.

There are three popular models for the analysis of microstrip antennas - transmission line model, cavity model and full wave model. The transmission line model is the simplest. It gives a good physical...
insight but is less accurate. The cavity model, which is used in this work, is quite complex but gives good physical insight and is more accurate. The full wave model is the most complex. It is very accurate in the design of finite and infinite arrays or stacked structures [8].

2 Theoretical Study of Patch Antenna

The geometry of the single patch antenna was first designing and implementing the equations from the transmission line model approximation in which patch radiating element is viewed as a transmission line resonator with no transverse field variations [8]. The width and length of the patch antenna used in the array are calculated by using transmission line design equations [8].

The width of the patch is given by

\[ W = \frac{c}{2f_0} \text{ } \varepsilon_{ref}^{-\frac{1}{2}} \]  

(1)

For dominant mode TM_{010} with no fringing the actual length of the patch is determined as

\[ L = L_{eff} - 2\Delta L \]  

where \( \Delta L \) is the extended incremental length:

\[ \Delta L = 0.412\hbar \left( \varepsilon_{ref}^{0.3} + \varepsilon_{ref}^{0.285} \right) \left( W + 0.264 \right) \left( W + 0.8 \right) \]  

(3)

where \( \varepsilon_{ref} \) is the effective dielectric constant:

\[ \varepsilon_{ref} = \varepsilon_{r+1}^2 + \varepsilon_{r-1}^2 \left( 1 + 12 \frac{h}{W} \right)^{-1/2} \]  

and \( L_{eff} \) is the effective length of the patch:

\[ L_{eff} = \frac{c}{2f_0\sqrt{\varepsilon_{ref}}} \]  

(5)

The expression for approximately calculating the directivity \( D \) of the rectangular microstrip antenna is given by [17], [21]:

\[ D \approx 0.2W + 6.6 + 10\log_{10} \left( \frac{1.6}{\sqrt{W}} \right) \text{ } dB \]  

(6)

The antenna gain which is a product of directivity and efficiency can be approximated thus [18]:

\[ \text{Gain} = \eta \cdot \text{Directivity} \]  

(7)

where \( \eta \) is the efficiency of antenna

Half power beamwidth (HPBW) which is defined by IEEE as: "in a plane containing the direction of the maximum of a beam, the angle between the two directions in which the radiation intensity is one-half value of the beam" [8],[12]. The beam width of an antenna is a very important figure of merit and often is used as a trade-off between it and the side lobe level; that is, as the beam width decreases, the side lobe increases and vice versa. In addition, the beam width of the antenna is also used to describe the resolution capabilities of the antenna to distinguish between two adjacent radiating sources or radar targets.

For a linear array uniform amplitude and spacing, the half-power beam width \( \theta_H \) can be found once the angles of the first maximum (\( \theta_m \)) and the half-power point (\( \theta_h \)) are determined [8]:

\[ \theta_H = 2\left| \theta_m - \theta_h \right| \]  

(8)

\( \theta_m \) is the angle which the array factor is maximum [8], [12]:

\[ \theta_m = \cos^{-1} \left( \frac{\lambda}{2na} (-\beta + 2\pi m) \right) \]  

(9)

where, \( m = 0,1,2 \ldots \)

\( \theta_h \) is the angle of array factor at -3 dB [8]:

\[ \theta_h = \frac{\pi}{2} - \sin^{-1} \left( \frac{\lambda}{2\pi d} \left( -\beta + \frac{2.782}{N} \right) \right) \]  

(10)

where, \( d \) is the element separation, \( \beta \) is the phase excitation difference and \( \lambda \) is the wavelength.

For Dolph Tschebyscheff array the half-power beamwidth can be determined by [13]:

- calculating the beamwidth of a uniform array (of the same number of elements and spacing),
- multiplying the beamwidth of (8) by the appropriate beam broadening factor \( f \) computed using [8],[13]:

\[ f = 1 + 0.636 \left( \frac{2}{\varepsilon_{0} \cosh} \left[ \sqrt{(\cos^{-1}(\beta_{0}))^2 - \pi^2} \right] \right) \]  

(11)

So,

\[ \theta_{H-Dolph} = \theta_{H} \cdot f \]  

(12)

For Binomial array, as the design using a \( \lambda/2 \) spacing leads to a pattern with no minor lobes, approximate closed-form expressions for the half-power beamwidth for the \( d = \lambda/2 \) spacing only have been derived [14] in terms of the numbers of elements or the length of the array, and it is given by [8]:

\[ \theta_{H-Bin}(d = 0.5\lambda) = \frac{1.06}{\sqrt{N-1}} = \frac{0.75}{\sqrt{L/\lambda}} \]  

(13)

where \( L \) and \( N \) are the array length and number elements respectively:

\[ L = (N - 1)/d \]  

(14)

3 Array Patch Antenna
An antenna array (often called a "phased array") is a set of two or more antennas (fig.1). The signals from the antennas are combined or processed in order to achieve improved performance over that of a single antenna. The antenna array can be used to [1] :
- increase the overall gain,
- provide diversity reception,
- cancel out interference from a particular set of directions,
- "steer" the array so that it is most sensitive in a particular direction,
- determine the direction of arrival of the incoming signals,
- to maximize the Signal to Interference plus Noise Ratio (SINR).

### 3.1 Analysis of Linear Array

![Fig.1. Linear array antenna geometry](image)

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 (neglecting coupling). It’s equal to the field of a single element positioned at the origin multiplied by a factor which is widely referred to as the array factor [8-9].

\[
E_{\text{Total}} = [E_0, \text{Array Factor}] \tag{15}
\]

where, \(E_0\) : Field of a single element at reference point.

The array factor, in general, is a function of the number of elements, their geometrical arrangement, their relative magnitudes, their relative phases, and their spacing. The array factor will be of simpler form if the elements have identical amplitudes, phases and spacing.

#### 3.1.1 N-elements Linear Array : Uniform Amplitude and Spacing

Now that the arraying of \(N\) elements positioned along the z-axis has been introduced, let us assume that all the elements have identical amplitudes but each succeeding element has a \(\beta\) progressive phase lead current excitation relative to the preceding one, the array factor can be obtained by considering the elements to be isotropic sources.

The array factor is given by :

\[
AF = \sum_{i=1}^{N} I_i e^{j(i-1)\psi} \tag{16}
\]

with, \(\psi = kd \cos \theta + \beta\)

\(\beta\) : The excitation phase shift between two successive elements.
\(\theta\) : The angle of elevation between the z-axis and the point of calculating the distant field.
\(d\) : The distance between two successive elements.
\(I_i\) : The excitation amplitude of element \(i\). Since the array is excited by uniform signal amplitude, so : \(I_1 = \text{constante} \quad \forall i = 1, ..., N\)

Therefore

\[
AF = \sum_{i=1}^{N} e^{j(i-1)\psi} = \frac{1 - e^{j(N-1)\psi}}{1 - e^{j\psi}} = \frac{e^{j(N-1)\psi/2} (\sin(N-1)\psi/2)}{e^{j\psi/2}} \tag{17}
\]

If the reference point is the physical center of the array, the array factor can be written as

\[
AF = \left[ \frac{\sin(N-1)\psi/2}{\sin\psi/2} \right] \tag{18}
\]

The amplitude coefficients for 4-element \((M = 4)\) are :

\(a_i = 1 \quad \forall i = 1, ..., 4\)

#### 3.1.2 N-elements Linear Array : Non-Uniform Amplitude and Spacing

An array of an even number of isotropic elements \(2M\) is positioned symmetrically along the z-axis. The separation between the elements is \(d\), and \(M\) elements are placed on each side of the origin. Assuming that the amplitude excitation is symmetrical about the origin, the array factor for a non-uniform amplitude broadside (\(\theta = 90^\circ\)) array can be written as :

\[
(AF)_{(2M)} = 2 \sum_{i=1}^{M} a_i \cos \left( \frac{(2i-1)kd \cos(\theta)}{2} \right) \tag{19}
\]

Which in normalized form reduces to :
where \( a_i \) are the excitation coefficients of the array elements.

If the total number of isotropic elements of the array is odd \( 2M + 1 \) (where \( M \) is an integer), the array factor can be written as:

\[
(AF)_{2M+1} = 2 \sum_{i=1}^{M+1} a_i \cos((i - 1)kd \cos(\theta))
\]

The amplitude of the center element is \( 2a_1 \).

Which in normalized form reduces to:

\[
(AF)_{2M+1} = \sum_{i=1}^{M+1} a_i \cos((i - 1)kd \cos(\theta))
\]

Equations (20) and (22) can be written in normalized form as

\[
(AF)_{2M} = \sum_{i=1}^{M} a_i \cos((2i - 1)u)
\]

\[
(AF)_{2M+1} = \sum_{i=1}^{M+1} a_i \cos(2(i - 1)u)
\]

where, \( u = \frac{\pi d}{\lambda} \cos(\theta) \)

3.1.2.1 Dolph-Tschebyscheff Array

Another array, with many practical applications, is the Dolph-Tschebyscheff array. The method was originally introduced by Dolph and investigated afterward by others. The excitation coefficients of a Dolph-Tschebyscheff array can be derived using various documented techniques [8], [19] and others. One method, whose results are suitable for computer calculations, is that by Barbire [13]. The coefficients using this method can be obtained using:

- For Even elements (2M):

\[
a_i = \sum_{q=1}^{M-q} (-1)^{M-q} z_q [2q-1] (q+M-2)/(2(M-1)) \quad \text{for } i = 1, 2, \ldots, M
\]

where, \( i = 1, 2, \ldots, M \)

- For odd elements 2M+1:

\[
a_i = \sum_{q=1}^{M+q+1} (-1)^{M-q+1} z_q [2q-1] (q+M-2)/(2(M-1)) \quad \text{for } i = 1, 2, \ldots, M + 1
\]

where:

\[\varepsilon_i = \begin{cases} 2 & \text{si } i = 1 \\ 1 & \text{si } i \neq 1 \end{cases}\]

The coefficients \( z_q \) can be obtained using:

\[z_q = \frac{1}{2} \left[ \left( R_0 + \sqrt{R_0^2 - 1} \right)^{1/p} + \left( R_0 - \sqrt{R_0^2 - 1} \right)^{1/p} \right]
\]

where: \( p = (M - 1) \)

and \( R_0 \) is the ratio of major-to-minor lobe intensity.

The amplitude coefficients for 4-element (2M = 4) are:

\[a_1 = 2.1126 \quad \text{and} \quad a_2 = 1.7592\]

3.1.2.2 Binomial Array

The array factor for the binomial array is represented by (23)–(24) where the \( a_i \) are the excitation coefficients which will now be derived. To determine the excitation coefficients of a binomial array, J. S. Stone [8],[19] suggested that the function \((1 + x)^{(n-1)}\) be written in a series, using the binomial expansion, as:

\[(1 + x)^{(n-1)} = 1 + (n - 1)x + \frac{(n-1)(n-2)}{2!}x^2 + \frac{(n-1)(n-2)(n-3)}{3!}x^3 + \cdots \]

The positive coefficients of the series expansion for different values of \( m \) are:

\[
m = 1 \quad 1
\]
\[
m = 2 \quad 1 \quad 1
\]
\[
m = 3 \quad 1 \quad 2 \quad 1
\]
\[
m = 4 \quad 1 \quad 3 \quad 3 \quad 1
\]
\[
m = 5 \quad 1 \quad 4 \quad 6 \quad 4 \quad 1
\]
\[
m = 6 \quad 1 \quad 5 \quad 10 \quad 10 \quad 5 \quad 1
\]

The values of "\( m \)" are used to represent the number of elements of the array. For 4-element (2M = 4)

\[a_1 = 3 \quad \text{and} \quad a_2 = 1\]

4 Results and Discussion

The performance of the proposed arrays antenna uniform amplitude and spacing, Dolph Tschebyscheff and Binomial have been studied by means of MATLAB, for comparison purposes, results obtained with the measures of Array factor, directivity, gain and HPBW. For the simulations, the following parameters are used:

- A linear array consisting of 4 isotropic elements.
- Distance between elements \( d = 0.5\lambda \) at 5.5 GHz.
- Angle of radiation maximal \( \theta = 90^\circ \).
- \( \varepsilon_r = 4.4 \) dielectric constant (FR-4)
- \( h = 1.5 \text{ mm} \) height of the substrate.
- \( R_0 = 15 \text{ dB} \) is the ratio of major to minor lobe intensity.
- \( \eta = 0.94 \) efficiency of antenna.
- \( G_0 = 2.91 \text{ dB} \) gain of single antenna.
- \( D_0 = 3.10 \text{ dB} \) Directivity of single antenna.
Fig. 2: Return Loss of array antenna

where:
- $G_0$: Gain of Uniform array,
- $G_1$: Gain of Binomial array,
- $G_2$: Gain of Dolph-Tschebyscheff array.

Fig. 3. Directivity patterns in decibel scale for 6-element

where:
- $D_0$: Directivity of Uniform array,
- $D_1$: Directivity of Binomial array,
- $D_2$: Directivity of Dolph-Tschebyscheff array.

Fig. 4. Gain patterns in decibel scale for 6-element

The following table summarizes the parameters of each array and it gives the difference between the same parameters of these arrays:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Gain (dB)</th>
<th>Dir. (dB)</th>
<th>HPBW (deg)</th>
<th>BW (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uniform</td>
<td>12.4353</td>
<td>12.6951</td>
<td>17.1902</td>
<td>70</td>
</tr>
<tr>
<td>Binomial</td>
<td>10.7428</td>
<td>11.0026</td>
<td>27.1013</td>
<td>72</td>
</tr>
<tr>
<td>Dolph-Tsch</td>
<td>12.4004</td>
<td>12.6602</td>
<td>17.7769</td>
<td>71</td>
</tr>
</tbody>
</table>

For uniform amplitude and spacing array, it is shown that the bandwidth can reach 70%, the maximum radiation of directivity is oriented toward $\theta = 90^\circ$, it’s the desired direction of radiation, with other side lobes (4 lobe) oriented towards other directions. In many practical applications the side lobes are undesirable. The maximal directivity which showed in Fig.3 is equal to 12.6951 $dB$, the gain which showed in Fig.4 is approximately 12.4353 $dB$ with Half-power beamwidth of the main beam equal to 17.1902$^\circ$ shown in Fig.5.

For Dolph-Tschebyscheff array, it is shown that the bandwidth can reach 71%, the maximum radiation of directivity is oriented toward $\theta = 90^\circ$, but also there are other side lobes oriented towards other directions no desired. The maximal directivity shown in Fig.3 is equal to 12.6602 $dB$, and its gain which showed in Fig.4 is approximately 12.4004 $dB$, they are less than directivity and gain.
of uniform amplitude, and its Half-power beamwidth of the main beam shown in Fig.5 is equal to 17.776°, it is larger than uniform amplitude and spacing array Half-power beamwidth.

For Binomial array, it is shown that the band width can reach 72%, the maximum radiation of directivity is oriented toward θ = 90° with no side lobe, Hence the side lobes are completely eliminated using binomial amplitude excitation with λ/2 separation between the elements. this is the advantage of Binomial array than the others arrays like uniform amplitude and Dolph Tschebyscheff arrays that they have many side lobes. The maximal directivity shown in Fig.3 is equal to 11.0066 dB, and its gain which showed in Fig.4 is approximately 10.7428 dB, they are less than uniform amplitude and Dolph Tschebyscheff arrays directivity and gain, also the Half-power beamwidth of the main beam shown in Fig.5 is equal to 27.1013°, it is larger than the others arrays Half-power beamwidth.

5 Conclusion

Microstrip antennas are usually employed at UWB and higher frequencies because the size of the antenna is directly tied to the wavelength at the resonant frequency.

A single patch antenna provides a maximum directive gain of around 2 – 5 dB. But in order to synthesize the total pattern of an array, the designer is not only required to select the proper radiating elements but the geometry (positioning) and excitation of the individual elements. So we could see some simulations of antenna arrays studied before, for comparing the return loss, directivity, gain, HPBW and array factor between them.

We can conclude that the half-power beamwidth (HPBW) of uniform amplitude array yields is the smallest of the three distributions (uniform, binomial and Tschebyscheff). It is followed, in order, by the Dolph-Tschebyscheff and binomial arrays. Instead, uniform array usually possess the bigger side lobes followed, in order, by the Dolph-Tschebyscheff array possess the smallest and binomial array possess no side lobes.

As a matter of fact, binomial arrays with element spacing equal or less than λ/2 have no side lobe. It is apparent that the designer must compromise between side lobe level and beamwidth. Uniform amplitude array usually possess the big directivity and gain, followed, in order by the Dolph-Tschebyscheff and binomial arrays.

Acknowledgements

Authors like to express their thanks to the laboratory of renewable energy and intelligent systems (LERSI) for their continuous support and encouragement during this work.

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