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Design of Adaptive Planar Microstrip Patch Array Operating at 28 GHz for 5G Smart Mobile System

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Abstract

Smart antenna system has been studied extensively for the fifth generation of wireless communication systems, because it has made a system better performance of higher capacity and coverage as well as of power-saving. The present paper introduces a design of planar microstrip patch antenna array for a smart mobile system operating at 28 GHz. The present smart antenna has an adaptive radiation pattern that adjusts its main beam automatically to the desired direction by following the signal environment. This is based on the processing of an algorithm called the Least Mean Square (LMS) resulting in a change in the magnitude and phase of the feeding current for each element in the antenna array. From the obtained results, the main beam can be steered 180 degrees in the phi (azimuth) plane at a constant theta (elevation) angle. The planar antenna array was designed and simulated using CST Microwave Studio and MATLAB software that is used to find the required exciting current for each element. It is found that the antenna bandwidth is greater than 1 GHz while its gain is about 21 dB.

Keywords: Smart antenna, Planar array, LMS Beamforming, Adaptive radiation pattern, Microstrip patch.

1. INTRODUCTION

Nowadays, the term communication is going to grow in the world, different applications and features have been presented day by day. Since the mobile communication request is always rising, the requirement for high data rates, better coverage, high capacity, and high quality of services are relied upon to keep on increasing quickly, thus a more efficient use of a radio spectrum. The newest technology of mobile communications 5G, has advantages of improving capacity, coverage, connectivity, energy-efficient, and has the lowest cost as contrasted to the 4G [1]. To confront those requirements of 5G communications in various application situations, it is certainly, the use of smart antenna technology is needed.

At present, to improve the performance of wireless communication systems, smart antennas are the most attractive choice; proposing their applications to mobile systems. As the requirements for a large number of users are increasing, the smart antennas have been solving the problem of limited bandwidth channels [2]. Nonetheless, the traditional antenna system that uses a single antenna transmits and receives data in equal directions. The feature of this antenna is a multi-directional pattern that distributes energy in all directions, this energy is regarded as the source of lost power for interference between different users or different base stations in different cells [3].

The block diagram of smart antenna systems was illustrates in figure 1 which consisting of an antenna array unit, with a signal processing unite which is the process of estimating the Direction of Arrival (DOA) and beamforming algorithm to automatically adjust the main beam direction in the response to signal environment, so that the antenna system essentially increases the required signal strength and prevents the interference signals by beamforming the required signal according to the Direction of Arrival (DOA) and nullifying strength against the unrequired signals [4]. Smart antenna systems are two classifications: beam switch system and adaptive antenna arrays [5]. A switched-beam antenna is a type of smart antenna in its simplest form, where it consists of several static beams in prearranged a direction that is used to serve the users. On the other hand, the smart antenna technology, that is the most advance type, is known as adaptive beamforming, which is consist of antenna arrays with smart signal processing capability to automatically adjust the beam pattern according to the changing signal environment. In addition to direct maximum radiation according to the direction of the desired mobile user, it makes nulls at interfering directions at the same time.

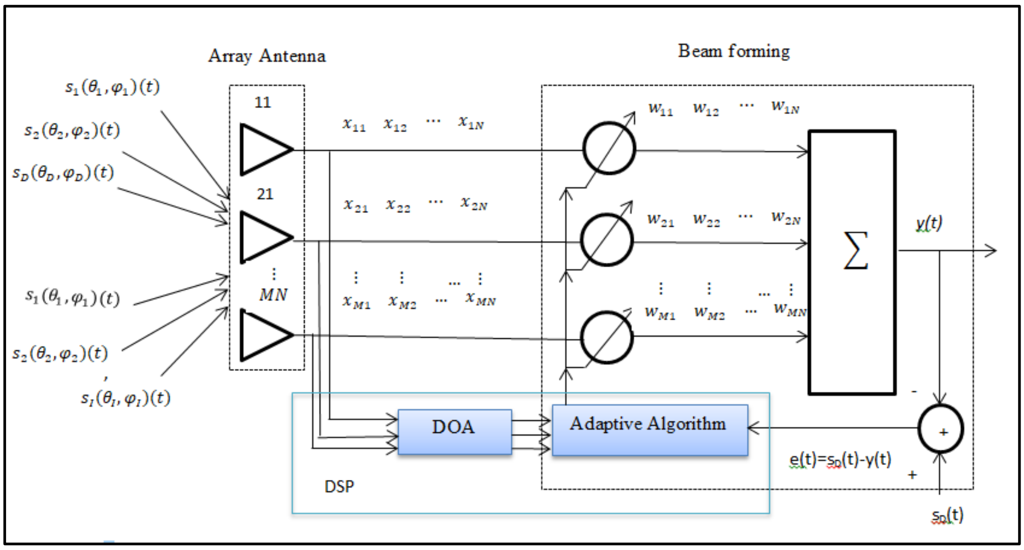

Figure 1: Smart antenna system [6].

Adaptive array antennas are regarded as one of the most common types of smart antenna arrays which are also known as digital antenna arrays and most newly, MIMO antenna arrays. With the algorithms of digital signal processing utilized to determine the signal direction of arrival (DOA), and for every component of the array, use them to compute the amplitude and phase of the feeding current which are important to guide the main beam of the antenna to the mobile goal [7]. The adaptive antenna system finds the signal direction of arrival based on various methods like: Multiple Signal Classification (MUSIC) and speculation of signal parameters via an algorithm called rotational invariance techniques (ESPRIT) [8],[9]. They include determining the array spatial spectrum, and from the peaks of that spectrum computing the DOA.

The radiation pattern of the array is creating by beamforming techniques, by changing the amplitude and phase of the exciting signal to every array components to guide the main beam to the required target and nulling the pattern of the undesired goals. This can be achieved using a simple Finite Impulse Response (FIR) tapped delay line filter. To get the optimum beamformer the FIR filter could be changing the weights adaptively and reduced the Mean Square Error (MSE) between the required and existing signals [10]. The common algorithm that is used in the present work is the Least Mean Square (LMS) method. The first development of this algorithm was in 1960 by Widrow and Hoff [11],[12]. Using the set of Wiener Hopf equations with the stochastic gradient method, this developed procedure was later known as the least-mean-square (LMS) method.

In Kong et al (2011) [13] The LMS algorithm is used to design the uniform linear array and rectangular planner array and then to prefer the method of designing heterotypic antenna. In this way, the size of the antenna is much smaller and the performance of the antenna is good in terms of system gaining and Signal to Interference Ratio (SIR). The experimental result proved that the 4x4 antenna array was further suitable for the environment that has a high interference.

In Fadl et al (2013) [14] the C-band (4-8)GHz circular microstrip patch antenna array is studied with the designing beamforming algorithm which is used in the smart antenna system. The DOA of desired and interference signal was precisely assessed by Matrix Pencil (MP) method, and by applying the LMS method the main beam is directed to the desired signal while the nulls is directed to the interference signal.

Nadu (2015) [15] presented two parts, the first demonstration was designing various rectangular microstrip patch components which were appropriate for beamforming techniques at the operating frequency of (1.8-2.4) GHz. The designed module was consist of eight linear arrays which can achieve a 15dB gain and directivity of greater than 58% as constructed to the conventional patches. In the second part of the beamforming procedure, the author suggested an NLVFF-RLS algorithm for concentration of the user power direction and negation of the interferer power direction.

Mercy (2017) [16] presented the design of a smart antenna for cellular networks using a microstrip single patch antenna and a linear microstrip patch antenna array of (1x3) to meet triple ISM frequency band of 2.45GHz, 4.5GHz, and 7.1GHz. Thus due to these multiband frequencies, the smart antenna designed can be used for multiple applications

Supratha & Robinson (2018) [17] analyzed the design of four elements of the microstrip patch array antenna to use it in mobile phone applications at the frequency of 28GHz. The implementation of the designed antenna was using economical FR-4 substrate material which has a good performance with the gain and efficiency. Furthermore, the result of this study demonstrated that in the frequency range of 22-34GHz the S11 has a response bellow -10dB.

The present paper aims to introduce a design of a planar array consisting of 64 microstrip patches operating at frequency of 28.7 GHz. This array antenna has an adaptive radiation pattern based on the LMS beamforming algorithm. The proposed antenna can be used on the top of the BTS tower for the 5G system.

2. ANTENNA DESIGN

2.1 Single Element Design

In this section, a rectangular microstrip patch element as a basic element of the proposed array is designed and analyzed for operating frequency of 28.7 GHz. The antenna element is designed on a Rogers CLTE-MW substrate material. For design purposes, 10 mils substrate of a dielectric constant ($\epsilon_r = 3.1$) and 0.0015 of a delta tangential are selected. This selection is more adequate for 5G applications [18]. For preliminary design, the following calculations for the single element dimensions are considered [19].The resonance length can be determined by:

$$L_p = \frac{1}{2fr\sqrt{\varepsilon_{reff}}\sqrt{\mu_o\varepsilon_o}} - 2\Delta L \qquad (1)$$

Where f_r is the resonant frequency, c is the free-space velocity of light ($3x10^8$ *m/s*) and ε_r is the dielectric constant of substrate while:

$$\Delta L = 0.412h\,\frac{(\varepsilon_{reff} + 0.3)(\frac{W_p}{h} + 0.264)}{(\varepsilon_{reff} - 0.258)(\frac{W_p}{h} + 0.8)} \qquad (2)$$

Where h is the substrate thickness and

$$\varepsilon_{reff} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2\sqrt{1 + \frac{12h}{W_p}}} \qquad (3)$$

Now, to determine the patch width (W_p), the following equation can be used:

$$W_p = \frac{1}{2f_r\sqrt{\mu_o\varepsilon_o}}\sqrt{\frac{2}{\varepsilon_r + 1}} = \frac{c}{2f_r}\sqrt{\frac{2}{\varepsilon_r + 1}} \qquad (4)$$

At a certain resonance frequency f_r, the priliminary values of length L_p and width W_p can be found and these valuse are considerd to analyise the input and output characteristics of this antenna using CST Microwave Studio prgramm. Referred to figure 2, optimization of antenna characteristics is performed to find the optimum dimensions of the single element. These dimensions are illustrated in Table 1 for single element. These dimensions are then used for the array design with optimum inter-element spacing.

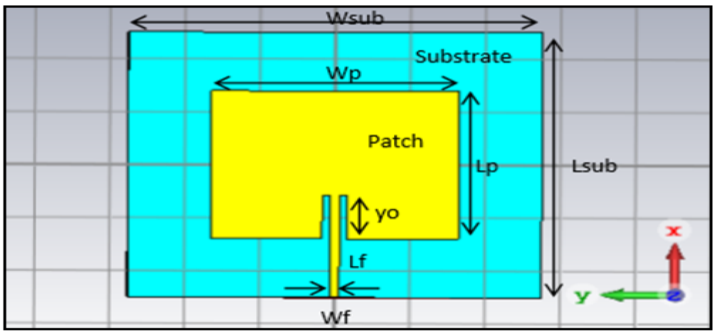

Figure 2: The structure of the patch element.

Table 1: Final dimensions of the patch element

Parameters	Value(mm)
Patch Width (W_p)	3.3
Patch length (L_p)	2.8
Substrate Width (W_{sub})	5.5116
Substrate Length (L_{sub})	5.0116
Feeding Width (W_f)	0.13
Feeding Length (L_f)	2
Insertion feeding (y_o)	0.832
Patch thickness (t)	0.035

2.2 Array Design

In a planar array, $M \times N$ elements are placed in a planar or rectangular grid where M represents No. of rows in the x-direction while N is No. of columns in the y-direction as shown in Figure 3 [19].

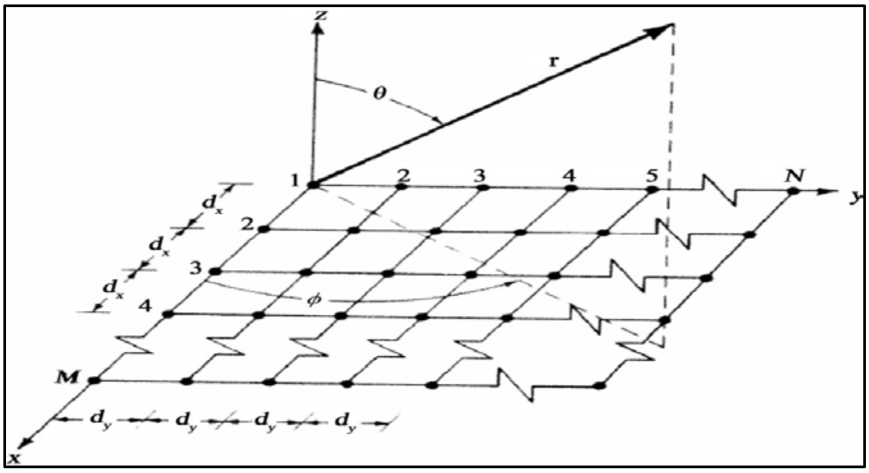

Figure 3: Geometry of the uniform planar array[19].

The principle of multiplication pattern is used to determine the field pattern of the entire array. The array factor of planar array is given by [19]:

$$AF(\theta,\varphi)_{M\times N} = AF_x\, AF_y$$

$$AF(\theta,\varphi)_{M\times N} = \sum_{n=1}^{N}\sum_{m=1}^{M} w_{mn}\, e^{j[(m-1)(\psi_x+\beta_x)+(n-1)(\psi_y+\beta_y)]} \qquad (5)$$

Where:

$\psi_x = kd_x \sin\theta \cos\varphi$ and $\psi_y = kd_y \sin\theta \sin\varphi$.

$\beta_x = -kd_x\, sin\,\theta_d\, cos\,\varphi_d$ and $\beta_y = -kd_y\, sin\,\theta_d\, sin\,\varphi_d$ are phase delays which are used to steer the main beam to desired angle (θ_d, φ_d), d_x, d_y are the distances between elements in x & y directions, respectively. $k = {2\pi}/{\lambda}$ is the propagation constant in free space, and w_{mn} is the complex weights of excitation current for the individual element.

The total electric field for the actual planar microstrip patch antenna array can be obtained by multiplying the electric field of single patch element by the array factor as follow [20]:

$$E_{total}(\theta,\varphi) = AF(\theta,\varphi) * E(\theta,\varphi) \tag{6}$$

Where

$$E(\theta,\varphi) = E_\theta(\theta,\varphi) + E_\varphi(\theta,\varphi) \tag{7}$$

And

$$\begin{pmatrix} E_\theta \\ E_\varphi \end{pmatrix} = \begin{pmatrix} e_\theta R \frac{\sin\psi_a}{\psi_a} \cos\psi_b \cos(\mathrm{kt}\cos\theta)\sin\varphi \\ e_\varphi R \frac{\sin\psi_a}{\psi_a} \cos\psi_b \cos(\mathrm{kt}\cos\theta)\cos\varphi\cos\theta \end{pmatrix} \tag{8}$$

$$\begin{pmatrix} \psi_a \\ \psi_b \end{pmatrix} = \begin{pmatrix} k_o \frac{L_p}{2} cos\,\varphi\, sin\,\theta \\ k_o \frac{W_p}{2} sin\,\varphi\, sin\,\theta \end{pmatrix} \tag{9}$$

$$R = j\left(\frac{E_z}{\pi t}\right)\left(\frac{e^{-jk_o r}}{r}\right) \tag{10}$$

The designed array was analyzed and simulated using CST Microwave studio, and it consists of 8x8 patch elements (M=8, N=8) placed in a rectangular grid. Figure 4 shows the studied array antenna with an inter-element distance of 0.5λ in both x & y directions.

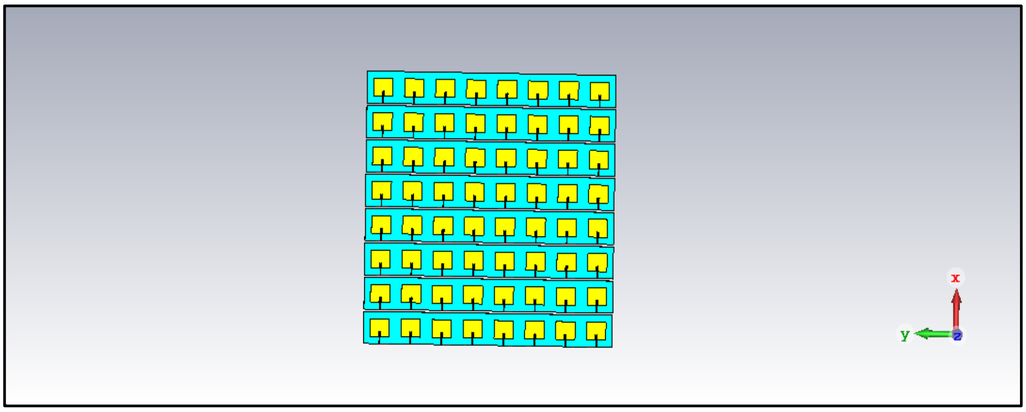

Figure 4: Geometry of 8x8 microstrip patch antenna array.

3. ADAPTIVE BEAMFORMING ALGORITHM

3.1 Beamforming Assumption

Let the proposed array be composed of $M \times N$ elements, and let it receives D narrowband source signals $s_d(t)$ from desired users arriving at directions $((\theta_1, \varphi_1), (\theta_2, \varphi_2),\ldots,(\theta_D, \varphi_D))$ as shown in Figure 1. The array also receives I narrowband source signals $s_i(t)$ from undesired (or interference) users arriving at directions $((\theta_1,\varphi_1),(\theta_2,\varphi_2),\ldots, (\theta_I,\varphi_I))$. The desired users signal vector $X_D(t)$ can be represented as [21]:

$$X_D(t) = \sum_{d=1}^{D} a(\theta_d, \varphi_d)\, s_d(t) \qquad (11)$$

Where $a(\theta_d, \varphi_d)$ is the M × N array steering vector which represents the array response at direction (θ_d, φ_d) which is given by:

$$a(\theta_d, \varphi_d) = \left[e^{-j((m-1)\beta_x + (n-1)\beta_y)}\right] \qquad 1 \le m \le M, 1 \le n \le N \qquad (12)$$

Where β_x and β_y were indicated in equation (5) .The desired users signal vector $X_D(t)$ of equation (10) can be rewritten as:

$$X_D(t) = A_D\, S(t) \qquad (13)$$

Where A_D is three dimensional matrixes (M × N × D) of the desired users signal direction vectors and is given by:

$$A_D = [a(\theta_1, \varphi_1), a(\theta_2, \varphi_2), \dots \dots, a(\theta_D, \varphi_D)] \qquad (14)$$

And $S(t)$ is the D × 1 matrix of desired users source waveform vector defined as:

$$S(t) = [s_1(t) \quad s_2(t) \quad \dots \quad s_D(t)]^T \qquad (15)$$

We also let to define the undesired (or interference) users signal vector $X_I(t)$ as:

$$X_I(t) = A_I\, I(t) \qquad (16)$$

Where A_I is the three dimensional matrixes (M × N × I) of the undesired users signal direction vectors and is given by:

$$A_I = [a(\theta_1, \varphi_1), a(\theta_2, \varphi_2), \dots \dots, a(\theta_I, \varphi_I)] \qquad (17)$$

And $I(t)$is the I × 1 matrix of undesired (or interference) user's source waveform vector defined as:

$$I(t) = [i_1(t) \quad i_2(t) \quad \dots \quad i_I(t)]^T \qquad (18)$$

The overall received signal vector X(t) is given by the superposition of the desired users signal vector $X_D(t)$, undesired (or interference) users signal vector $X_I(t)$, and an M×N vector n(t) which represents the white Gaussian noise for each element of the designed array. Hence, $X(t)$ can be written as:

$$X(t) = X_D(t) + X_I(t) + n(t) \qquad (19)$$

Where $n(t)$ can be represented by matrix vector as:

$$n(t) = \begin{bmatrix} n_{11} & n_{12} & \dots & n_{1N} \\ n_{21} & n_{22} & \cdots & n_{2N} \\ n_{31} & n_{32} & \cdots & n_{3N} \\ \vdots & \vdots & \cdots & \vdots \\ n_{M1} & n_{M2} & \cdots & n_{MN} \end{bmatrix}^T \qquad (20)$$

In the case that we consider all sources at the same time, the signal at the mn^{th} element will be [5]:

$$x_{mn}(t) = \sum_{d=1}^{D} a(\theta_d, \varphi_d)\, s_d(t) + \sum_{i=1}^{I} a(\theta_i, \varphi_i)\, s_i(t) + n_{mn}(t) \quad (21)$$

Then the total array output will be:

$$y(t) = \sum_{n=1}^{N} \sum_{m=1}^{M} w_{mn}\, x_{mn}(t) \quad (22)$$

3.2 LMS Algorithm

The LMS algorithm is a method of adaptive weighted beamforming of radiant weights. The weight vector for the array is started with such that it is updated frequently for optimal weight. The signals received by these array elements are multiplied with the weight vector as demonstrated in figure 1. These weighted signals are added to obtain the beamformer output [22].

For the beamformer, the comparison between the output from the array antenna Y(**n**) and the desired signal S_d(**n**) that must be in similar to the reference signal, is strongly taken into consideration for the error minimization between the desired signal and the reference signal. At time **n**, where **n** (bold letter) is the overall number of snapshots occupied, the output Y(**n**), is determined by a summation of the signals at the M × N antenna which is presented as [23]:

$$Y(\mathbf{n}) = W^H X(\mathbf{n}) \quad (23)$$

Where W represents the complex weights vector while $X(\mathbf{n})$ represents the received signal vector given in (19). Therefore the error signal is expressed as:

$$e(\mathbf{n}) = S_d(\mathbf{n}) - W^H X(\mathbf{n}) \quad (24)$$

The beamformer normally uses the error signal $e(\mathbf{n})$ to adjust the complex weights vector W in an adaptive way to reduce the Mean Squared Error (MSE). Using the steepest descent method the LMS algorithm calculates and updates recursively the weights vector W. Successive corrections to the weights vector W are achieved resulting in minimum mean square error. The weights vector W may be started arbitrarily and updated based on the given LMS equation:

$$W(\mathbf{n}+1) = W(\mathbf{n}) + \mu X(\mathbf{n})\, e^*(\mathbf{n}) \quad (25)$$

Where $W(\mathbf{n}+1)$ defined as the weights vector to be calculated at iteration **n**+1 while μ represents the size of the LMS step that relates to the convergence rate, where describes how quickly the LMS reaches a steady state. The size of an adaptive step must be within the range defined as [23]:

$$0 < \mu < \left(\frac{1}{\lambda_{max}}\right) \quad (26)$$

Where λ_{max} represents the maximum Eigenvalues of the correlation matrix R_{xx} which is given by following equation [23]:

$$R_{xx} = E\{X(n)\, X^H(n)\} \qquad (27)$$

Where E{.} is defined as ensemble average and $(.)^H$ represents the Hermitian transposition operator.

4. RESULTS AND DISCUSSION

4.1. Simulation of Single Element and Array

The proposed antenna of dimensions given in Table 1 has been constructed in CST Microwave Studio. The simulated results for the reflection coefficient are shown in figure 5. It can be seen that the antenna element can achieve the bandwidth from 28.209 GHz to 29.237 GHz for $|S_{11}|$<-10dB, for the resonant frequency of 28.7GHz. For the whole array of 8x8 elements, the same input characteristics (S_{11}) are obtained.

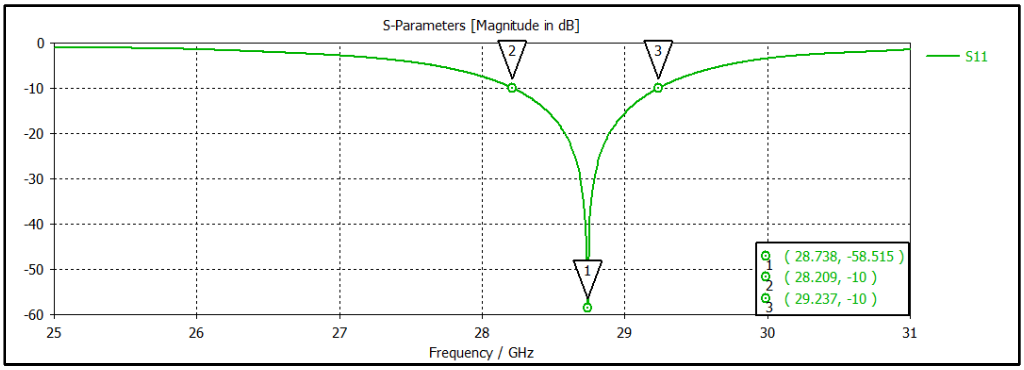

Figure 4: The reflection coefficient of the single patch element.

The radiation pattern of an antenna is important for determining the output characteristics which include beamdwidth, beam shape, directivity and radiated power. So in figure 6, 3D radiation pattern of single patch antenna element is plotted. Figure 7, shows the radiation pattern for 8x8 array elements with a uniform amplitude and phase. The main lobe is more directive than single element pattern.

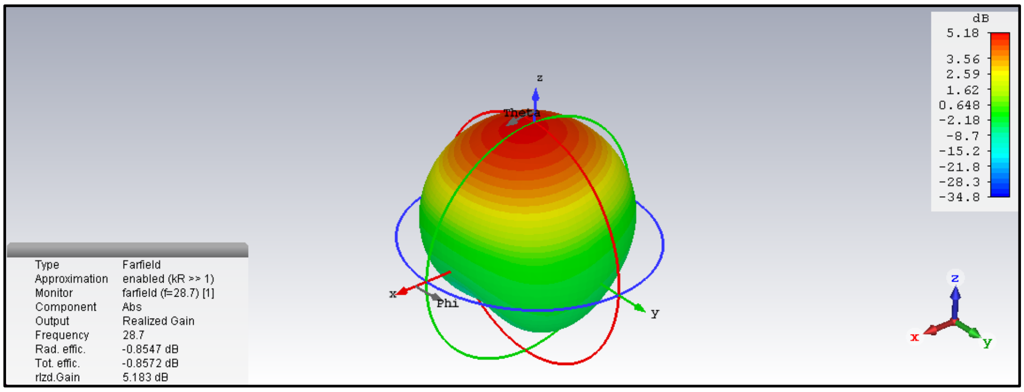

Figure 6: Far-field Radiation Pattern for single element.

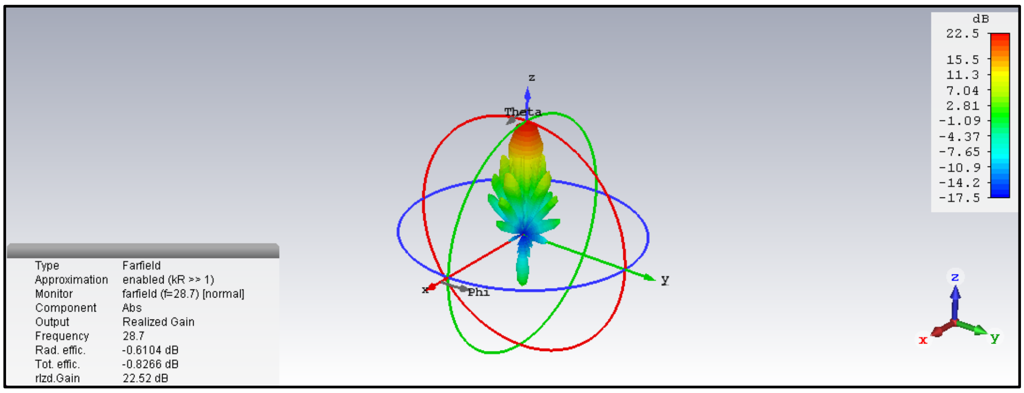

Figure 7: Far-Field Radiation Pattern for the uniform array.

4.2. Simulation of Adaptive Beamforming

To evaluate the performance of adaptive beamforming that is using the LMS algorithms to form the pattern when the smart antenna system uses a planar antenna array in its input, we consider a planar antenna array with 8×8 elements and half-wavelength element spacing in x and y directions (d_x=d_y=λ/2). The impinging desired signal on the array is supposed from the one direction $\theta_{d_1} = 45^o, \varphi_{d_1} = 30^o$. Two interferers' signals are supposed to impinge the array from the directions $\theta_{i_1} = 10^o, \varphi_{i_1} = 20^o$, and $\theta_{i_2} = 30^o, \varphi_{i_2} = 10^o$, in the white Gaussian noise channel. The iteration number has been set to 500 iterations and the step size of the LMS algorithm is chosen as $\mu = 0.001$. The simulation based on MATLAB program showed the possibility of forming the radiation pattern in the angle of the desired direction and suppressing the angles of undesired directions as follows.

Figure 8 represents the beamforming pattern at the phi-plane for a constant theta-angle ($\theta_{d_1} = 45^o$). The x-axis shows the phi-plane angle (in degrees), while, the y-axis shows the total normalized radiation pattern electric field. The figure also shows that the main lobe of radiation is shaped towards the desired angle $\varphi_{d_1} = 30^o$, while the lower side lobes appear in other directions. From the result, the HPBW (φ_{az}) is approximately equal to 20°.

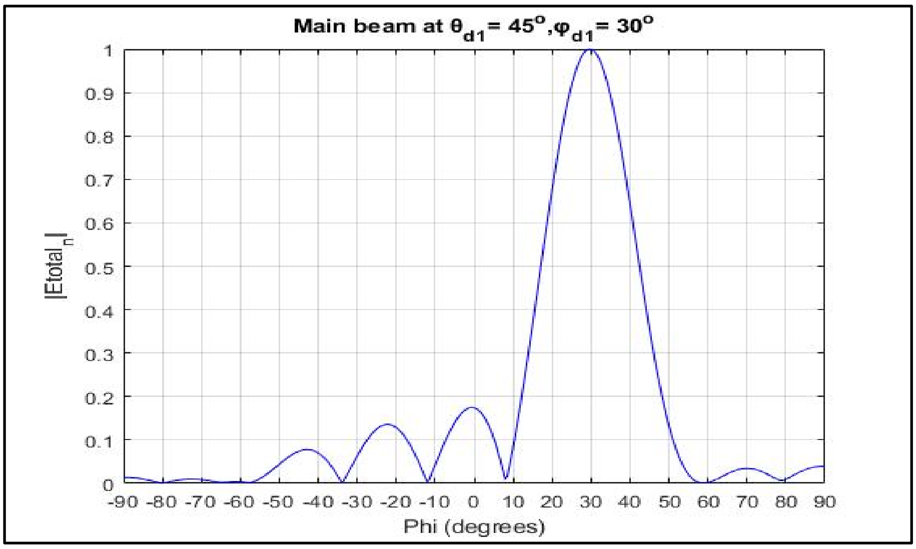

Figure 8: Radiation pattern for 8X8 antenna array in phi (Azimuth)-plane.

Figure 9 shows the radiation pattern at the theta-plane for a constant phi-angle ($\varphi_{d_1} = 30^o$), where the main lobe of radiation is at the desired theta-angle ($\theta_{d_1} = 45^o$). The x-axis shows the theta-plane angle (in degrees), while the y-axis shows the total normalized electric field. The HPBW (θ_{el}) is approximately equal to 18^o, and the array directivity (D) is approximately equal to 21.7dB. Figure 10 illustrates the progression of amplitudes and phases of the feeding currents that are used to excite the planar array elements.

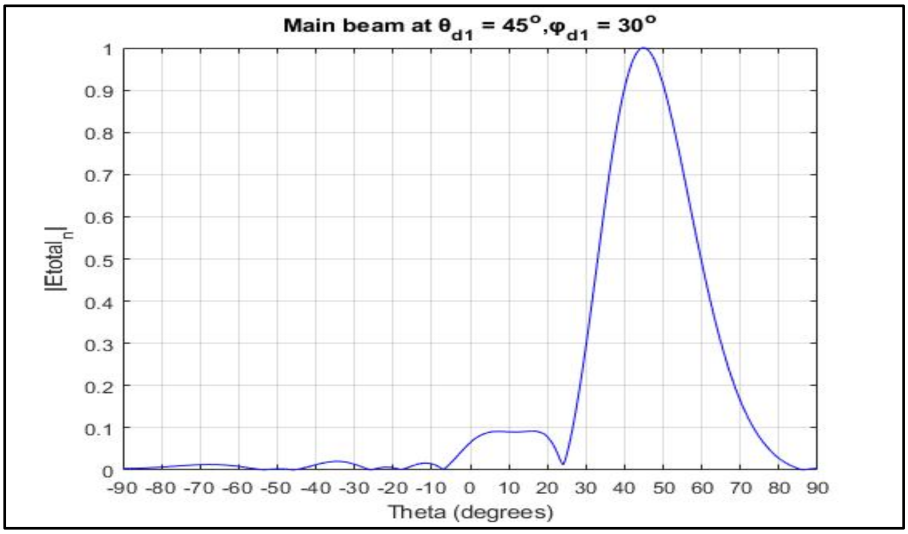

Figure 9: Radiation pattern for 8X8 antenna array in theta (Elevation) - plane.

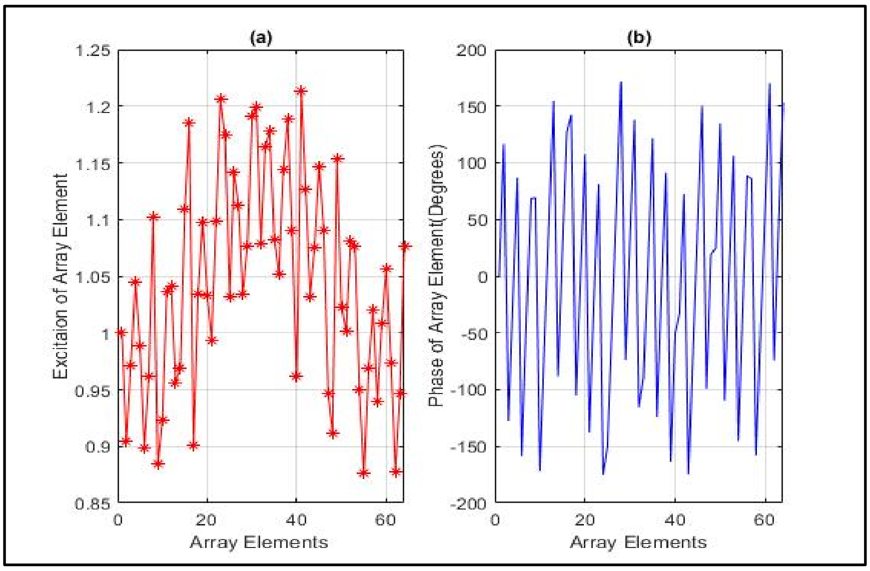

Figure 10: (a) The distribution of the amplitude. (b) The distribution of the phase of the excitation currents for planar array elements.

Using the weights of exciting current to each array element, that obtained by the LMS algorithm, the antenna is capable to direct narrow beams towards the desired user. The complex weights consist of amplitude and phase which are manually fed to the CST simulator. The array is therefore capable of steering narrow beams towards desired users at the exact resonant frequency as shown in figure 11. It is found that the antenna gain is 20.9 dB.

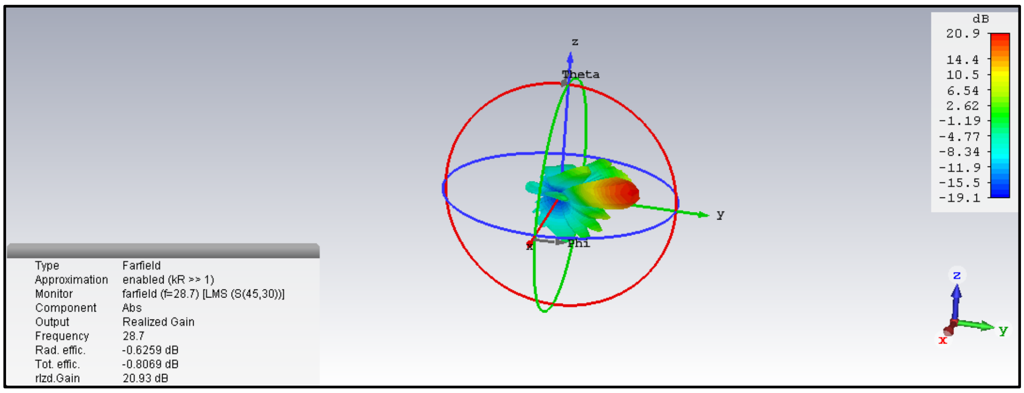

Figure 11: 3D Radiation Pattern of the 8x8 antenna array of different weights with steered main beam at angles.

Figure 12 shows the mean square error (MSE) related to the iteration number, it is observed that the value of the MSE decreases while the amount of iterations increases. It is noted that the LMS algorithm needs 20 iterations to reach a minimum error value between the reference and actual outputs, and then the algorithm stabilizes. Furthermore, Figure 13 shows the obtained array output and the desired signal tracks after 20 iterations.

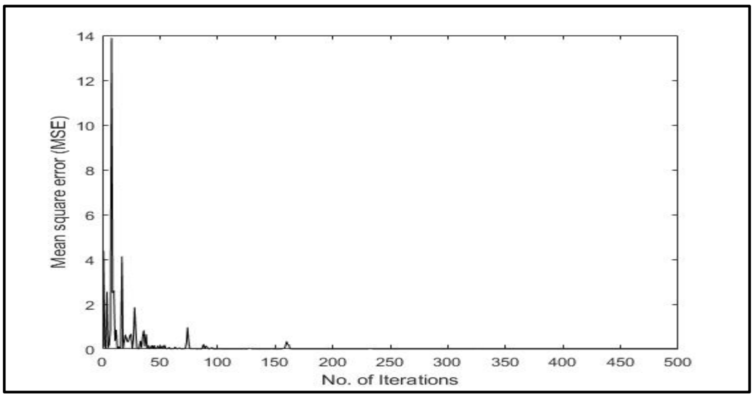

Figure 12: Mean square error Vs No. of iteration.

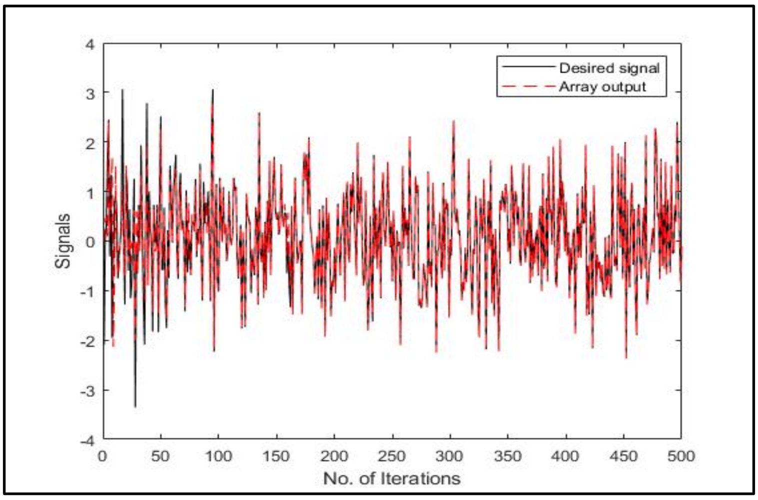

Figure 13: Comparison of desired signal and actual array output

Finally, to obtain the steering radiation pattern, figure 14 shown that the total field radiation pattern capable of steering in the phi (Azimuth)-plane from 0° to 180° at the constant theta-angle (θ_d=40°). Therefore, it could be needed two sectors at the base station to cover 360°. Figure 15 also shows the total field radiation pattern coverage at the theta (Elevation)-plane for a constant phi-angle (φ_d=40°). It is observed that there is a covering angle of 60° in the elevation plan without beam interference.

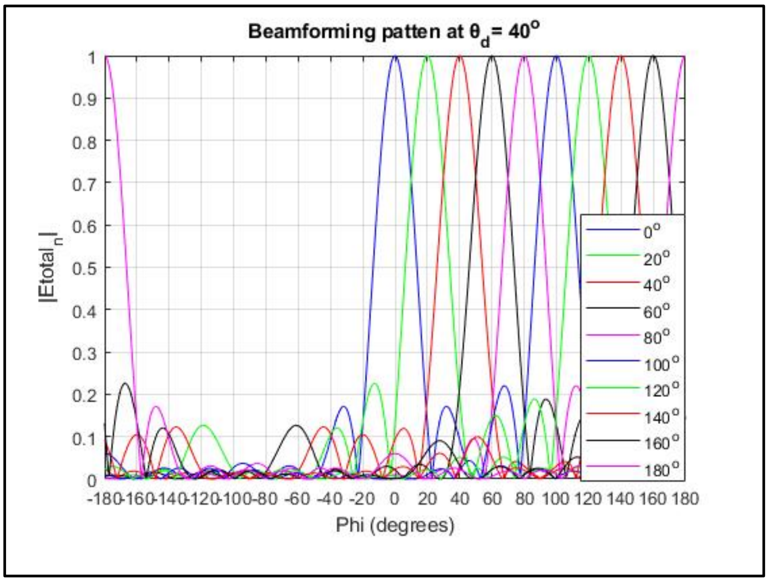

Figure 14: Radiation pattern for phi (Azimuth)-plan.

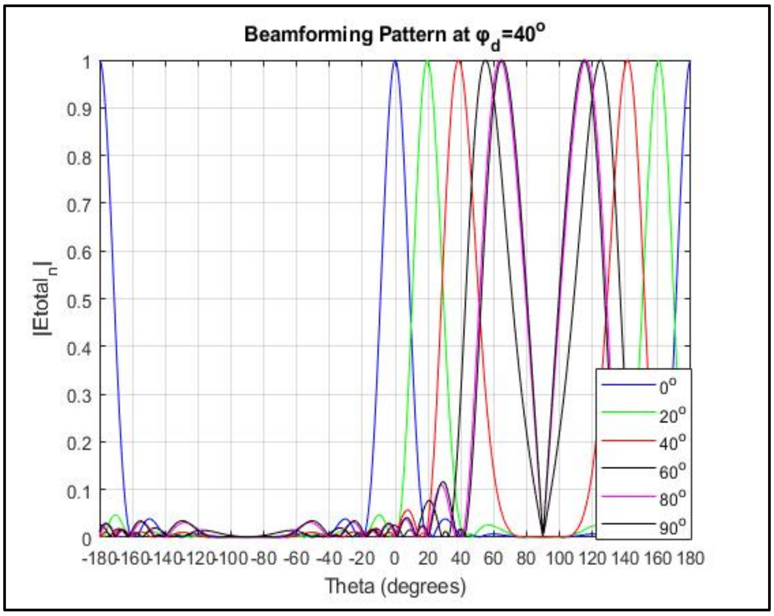

Figure 15: Radiation pattern for theta (Elevation)-plan.

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5. CONCLUSION

The present paper has discussed the possibility of designing a planar microstrip patch antenna array based on adaptive beamforming of LMS algorithm and it can be used for the smart antenna system. An array of 8×8 microstrip antenna elements has been designed to operate at 28.7GHz for the 5G networks with an inter-element spacing of 0.5λ. A considerable bandwidth of this antenna was over 1.2 GHz and a gain of about 21 dB. The main beam of the studied antenna can be steered towards the required user in the desired direction of (θ_d, φ_d) using the beamforming of LMS algorithm. The program of CST Microwave Studio has been utilized to optimizing the design of antenna while MATLAB software program has been used to obtain array patterns and weights factors of amplitude and phases for the exciting currents for each array element. The designed antenna array can scan an angle from 0^o to 180^o in phi-plane at constant theta-angle which is suitable for one sector base station; therefore, two sectors of this array at the base station could satisfy the smart mobile system.

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