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AN ANALYTICAL INVESTIGATION ON THE PERFORMANCE OF 1D AND 2D ANTENNA ARRAYS FOR MM-WAVE MODERN COMMUNICATION SYSTEMS

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Abstract*- Millimeter wave (mm-Wave) wireless technology has invaded every aspect of modern life because of its ability to transmit data quickly and securely. This paper presented a square patch antenna at a resonance frequency of 26.2GHz for millimeter wave wireless communication. The proposed antenna consists of single square radiating element. The suggested antenna was designed using CST Microwave Studio's version 2020 on a Rogers RO 3003 lossy substrate with a relative permittivity of 3 . The result of this paper shows a minimum S_{11} of 19.34 dB, a gain of 6.97dBi, with bandwidth of 2GHz at the resonant frequency of 26.2GHz. The gain was enhanced to 16dBi and 25.8dBi with a high radiation efficiency by converting the single element patch antenna to a uniform linear array of 8 elements and uniform planar array of 8×8 elements respectively. The simulation results show that despite the simple design of the patch (without holes and cracks), which facilitates manufacturing in a small size; However, it achieves higher gain than the more complex designs found in the previous literature to suit mm wave communication requirements. Also, we used CST Microwave Studio for simulation which provides two methods for implementing arrays: the array factor method, which builds virtual arrays (the direct method), or building arrays by repeating the elements depending on the required size of the array, A comparison has been conducted between the numerical analysis of both methods, and the results show that even though the numerical analysis of the second method gives more accurate results that can be close to a manufactured antenna array, it needs high processing ability and time. Creating arrays with array factor may save time and processing ability but the results may not be accurate. Therefore, a relation was driven to show the error that can be added to give precise results.

keywords: **Millimeter Waves, Uniform Linear Array, Planar Array, 5G Communication.**

I. Introduction

Extremely high data rates are becoming more and more necessary for transmitting and receiving of highdefinition films and massive amounts of traffic [1]. Many academics have focused their study on applying the utilization of millimeter waves in contemporary communication systems because the frequency bands at 6GHz are severely constrained to narrow bandwidth and lack efficient solutions to cover high data rates in 5G systems [2]. In order to provides a 10Gbps data speed, the 5G and beyond systems based on current technology are developed to cover the frequency band between 28 and 100GHz [3].

The definition of 5G millimeter-wave (mm-wave) technology is currently unclear; instead, it deals with the integration of many methodologies, instances, and scenarios [4]. To reach larger data speeds and bandwidths, this

technology would employ the unlicensed millimeter wave spectrum, which ranges from 30-300 GHz [5]. Additional issues for mm-wave applications include losses in free-space propagation associated with upper frequencies [6]. To reduce the problems with free-space propagation, Pico and Femto cells were employed [7]. Atmospheric attenuation, which includes

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scattering from rain, snowfall, fog and many other phenomena, is another challenge that the MM-Wave technology faces [8]. By using highly directional antennas with large gains, this issue is resolved [9]. A possible method for enhancing capacity and service quality is the use of massive MIMO base stations, which precisely focus transmitted energy to the mobile users [10]. At MM-Waves, various researchers researched on various wireless communication elements for 5G technologies [11]. Their designs' primary goal is to produce high gain antennas with improved radiation patterns [12]. Simple antenna geometries may be sufficient for these antennas' applications because they do not acquire any additional size reduction.

The primary goal of this work is to design a single square patch antenna without using a highly complex design for ease of manufacturing. The proposed antenna elements provide 2GHz bandwidth with gain of 6.97dBi and S_{11} of -20 dB at 26.2GHz. The proposed single square patch antenna was developed to an antenna array constructed from 8 elements forming a uniform linear array (ULA) that realized a gain of 16.2dBi. The proposed ULA performs well in terms of S_{11}, large bandwidth and high gain to suit 5G wireless communication systems. The design was then converted to 8×8 uniform planar array antenna (UPA), the UPA yields 25.8dBi gain with very good S_{11} and radiation performance, and smaller size compared to other published papers.

II. ANTENNA DESIGN AND CONFIGURATION

A. *Single Element Antenna*

The single element square patch antenna is designed to operate at 26.2GHz frequency resonance. Fig. 1 depicts the suggested single element square patch antenna's geometry.

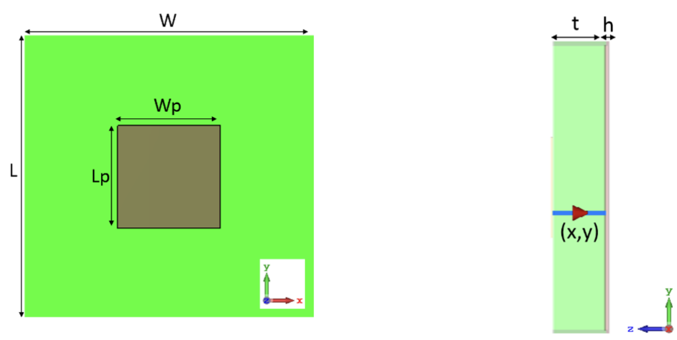

Figure 1: Geometry Of the Suggested Single Element Patch Antenna (a) Front View, and (b) Side View

The proposed patch antenna is mounted on 0.787 mm substrate thickness from the Rogers family RO 3003 (lossy) with relative permittivity of 3 . A ground plane with dimensions of $(4 \times 4\ \text{mm}^2)$, which is supposed to be made of copper material with a 0.035 mm thickness, supports the proposed antenna's back side completely.

The antenna patch occupies an area of $1.395\ \text{mm}^2$ from copper with thickness 0.035 mm. Table I lists the proposed single element patch antenna's geometrical specifications. The antenna element is exited with a co-axial prob feed. The

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TABLE I
Geometrical Parameters Of the Suggested Single Element Patch Antenna

Parameter	Description	Value (mm)
T	Substrate thickness	0.787
L	Substrate length	4
W	Substrate width	4
L_P	Patch length	1.395
W_P	Patch width	1.395
H	Patch and ground thickness	0.035
x, y	Position of feed	$(0.45, -0.533)$

feed location is fixed to the x-axis of the antenna at 0.45 mm from the patch edge. Input impedance for the co-axial probe is fixed at 50 ohms for the targeted frequency range. Analytical calculations are used to determine the single element patch antenna's dimensions [13].

$$\epsilon_{reff} = \frac{\epsilon_r + 1}{2} + \frac{\epsilon_r - 1}{2}\left[1 + \frac{12h}{w}\right]^{-1/2} \tag{1}$$

$$\Delta L = h \times 0.421 \frac{(\epsilon_{reff} + 0.3)\left(\frac{w}{h} + 0.264\right)}{(\epsilon_{reff} - 0.258)\left(\frac{w}{h} + 0.8\right)} \tag{2}$$

Where ϵ_{reff} is the effective relative permittivity, ϵ_r the relative permittivity, w is the patch width, ΔL is the extension of the length and h is the thickness of substrate. The actual length of patch is expressed as [13]:

$$L = L_{eff} - 2\Delta L \tag{3}$$

The effective length and width of the square patch are calculated as [13]:

$$L_{eff} = \frac{v0}{2f_r\sqrt{\epsilon_{reff}}} \tag{4}$$

$$W = \frac{vo}{2f_r}\sqrt{\frac{2}{\epsilon_r + 1}} \tag{5}$$

Where vo is speed of light which 3×10^8 m/s

These parameters are utilized as starting points for a parametric analysis based on the numerical analysis that will be optimized to produce the desired performance. The performance of the antenna is remarkably impacted by all these dimension values.

B. *Array Configuration*

1) ***Uniform Linear Array (ULA):*** Antenna array technology is considered to be one of the most appealing applications since modern communication systems necessitate steerable antenna systems, high gain arrays, and radiation patterns that

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are effectively increased. The suggested single element patch antenna shown in Fig. 1 of our design has a maximum gain of $6.97\mathrm{dBi}$ at $26.2\mathrm{GHz}$. Due to propagation restrictions, such gain is insufficient for mm-wave technology. As a result, a 1D array structure is suggested to get overcome the antenna gain limitation [14].

The proposed antenna element is periodically arranged in 8 elements on the x-axis to form ULA antenna. The chosen distance between the 8 elements is $(\lambda/2)$. Fig. 2 depicts the array's geometry. The results of the 8 antenna elements were combined to find the total pattern and gain.

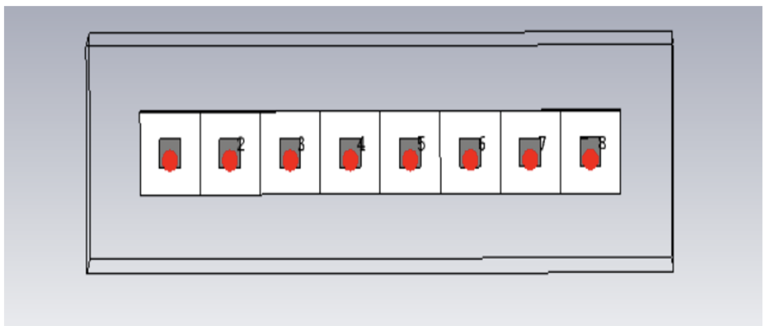

Figure 2: ULA Antenna Array Geometry

*2) **Uniform Planar Array (UPA)**:* In this part the proposed single element antenna design was converted to uniform planar array antenna (UPA) of eight elements in each axis and total of 64 elements. The chosen distance between elements was set to $(\lambda/2)\mathrm{mm}$. Fig. 3 shows the structure of 8×8 UPA.

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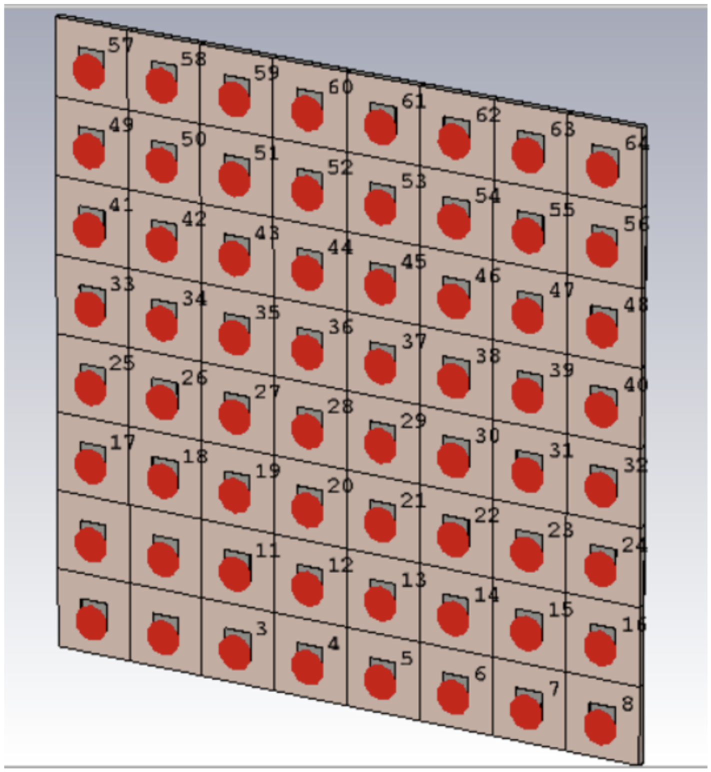

Figure 3: UPA Antenna Array Geometry

III. Results and Discussion

A. Single Elements Results

Fig.4 depicts the single element patch antenna's S_{11} curve. As can be observed, the central frequency is 26.2 GHz, and the bandwidth spans 25 to 27GHz.

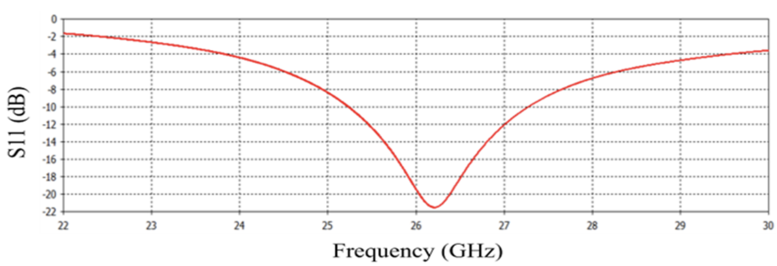

Figure 4: Curve Of the Suggested Single Element Patch Antenna.

Fig. 5 illustrates the single element's far field radiation pattern. The major lobe's orientation is at 0.0 degrees, and its magnitude is 6.9dBi, which represents the gain (IEEE). Fig. 6 depicts how the proposed patch antenna's gain varies with

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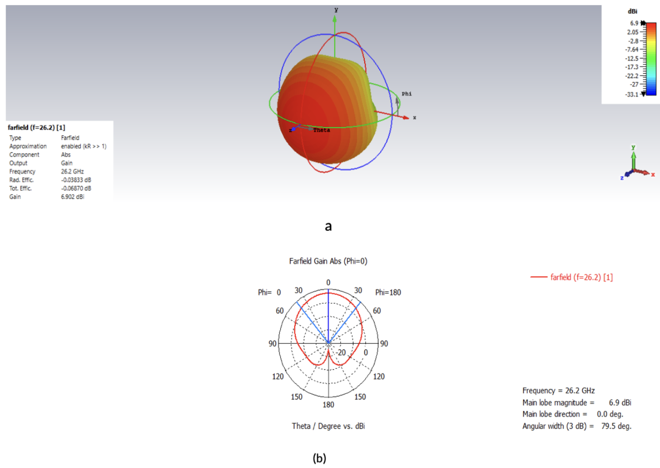

Figure 5: Far Field Radiation Pattern Of the Suggested Single Element Patch Antenna at 26.2GHz (a)2D and (b) 3D.

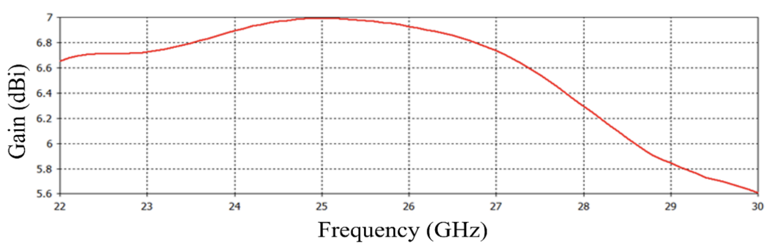

Figure 6: Gain Variation Over Frequencies Of the Suggested Single Element Patch Antenna.

*B. **Antenna Array Results***

*1) **ULA Results :*** The proposed 8 element ULA is simulated element by element and then the results were combined to show the total results. S_{11} curve of the proposed 8 element ULA antenna array is depicted in Fig. 7.

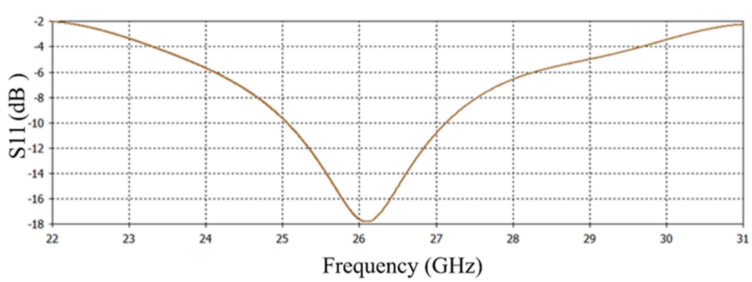

Figure 7: S11 Curve Of the Suggested 8 Element ULA Antenna Array.

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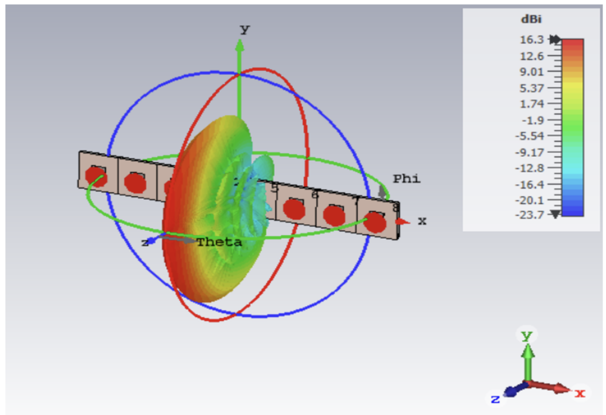
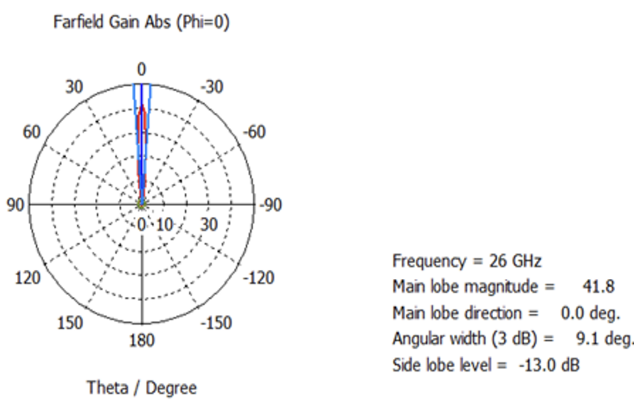
The far field pattern at 26.2GHz of the 8 element ULA is shown in Fig. 8 (a) and (b). It can be seen that the resulting pattern is very directive with gain 16.3dBi and since the phase shift was set to zero it can be observed that the major lob direction is still at zero.



(a)



(b)

Figure 8: Far Field Of the Proposed 8 Elements ULA at $f = 26.2GHz$(a)3D and (b) 2D

*2) **UPA Results**:* The 3D radiation beam pattern of the 8×8 planar array at directions $\theta = 0°$ and $\varphi = 90°$ is shown in Fig. 9 . Obviously, the designed array has good beam steering characteristics with a wide range of beam-coverage properties. The obtained gain is 25.8dBi. It can be seen that the array has very good radiation performance with minimum side and back lobes.

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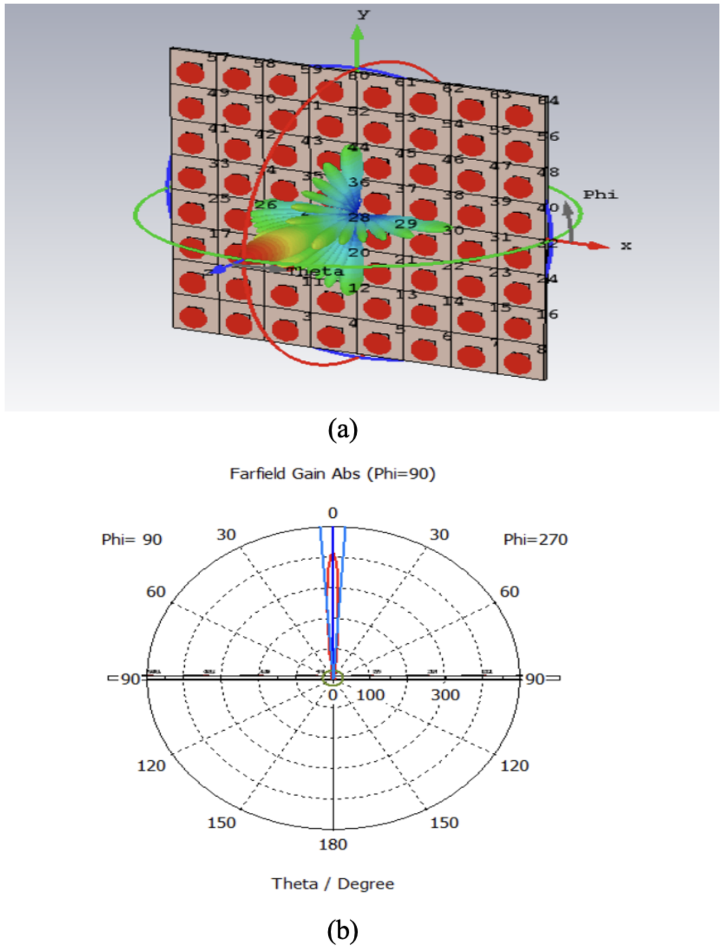

Figure 9: Far Field Of the Proposed 8×8 Elements UPA at $f = 26.2\text{G}Hz$(a)3D and (b) 2D.

The S_{11} results of planar antenna arrays are depicted in Fig. 10. As shown, the arrays provide good S_{11} at the desired frequency (26.2GHz).

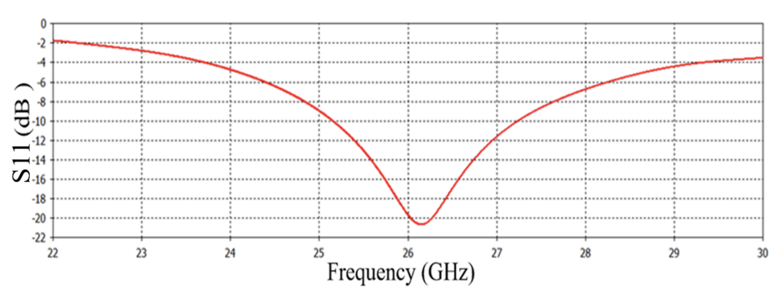

Figure 10: S11 Curve Of the Suggested 8×8 Element UPA Antenna Array

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C. *Effects Of Array Factor*

The variations in the proposed antenna array performance in terms of gain, radiation efficiency and beamwidth are discussed in this work with respect to the number of antenna elements variation repetition factor. Therefore, we change the array factor from one element to 8 elements with step of one element. The obtained results shown in Table II, from the real array construction in the CST environment are compared to their identical from the array built using direct method. This comparison is introduced to realize the influence of the virtual array approximation on the array calculations. It is found from the obtained results, a remarkable difference between the array built using direct method and real arrays. This difference is attributed to the approximation that neglects fringing effect, coupling, capacitive storing, and boundary discontinuities [13]. Therefore, it is very important to emphasize the effects of such differences on the antenna array performance could realize a magnified errors on the channel performance that must be consider in the future researches.

It's good to mention that the proposed study is considering the issue of gain difference only; this is because the efficiency factor is matter of a ratio between the directivity and gain. That is consistently involved simultaneously during the gain analysis. Therefore, we didn't apply a specific analysis for the efficiency and we stratified with the antenna gain. Also, it obvious that the antenna efficiency is in the range of 98% which is quite similar to many published results in the literature; also, it can't exceed beyond this value because the effect of dielectric and conductor losses.

TABLE II
Results Differences Between Constructed Array and Array Factor

No. of Elements	Array Factor method			Building Array using Element repetition		
	Gain	Efficiency	Beam width	Gain	Efficiency	Beam width
2	10.2	0.98	37.1	10.2	0.96	39.1
3	11.9	0.98	24.4	11.9	0.96	25.4
4	13.1	0.98	18.2	13.2	0.95	18.6
5	14.1	0.98	14.5	14.2	0.95	14.7
6	14.9	0.98	12.1	15	0.95	12.2
7	15.6	0.98	10.3	15.6	0.95	10.4
8	16.1	0.98	9	16.2	0.95	9

We estimated the regression analysis using curve fitting in excel to evaluate these changes with respect to the number of antenna elements. The obtained relationship is given in the following sets: The array factor method has the following gain polynomial where x is the number of elements

$$y = 0.0111x^3 - 0.2726x^2 + 2.7758x + 5.6714 \tag{6}$$

The array build by repeating element design has the fallowing gain polynomial

$$y = 0.0139x^3 - 0.3202x^2 + 3.0349x + 5.3 \tag{7}$$

By subtracting both equations the difference is the parameter that will be add to equalize the result. We concluded from such study, applying the real configuration of any antenna array by using element repeating method may realize

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more accurate results without many approximations. However, involving the real number of antenna elements in the array construction could consume a high computational time for the analysis. Such computational time may limit the possibility of arriving to the optimal design. In such case the channel optimization through the antenna configuration parametric study would be very complicated. Thus, using the previous set of equations save time consuming with minimum approximation errors specifically for massive MIMO systems.

Finally, the proposed antenna array performance with respect to other published results in the literatures are compared in Table III. From this comparison a remarkable enhancement is found in the antenna gain with acceptable size reduction.

TABLE III
Comparison Of Various PLANAR Antenna Arrays Proposed for Millimeter Wave Applications

Ref	Size $(\mathrm{L} \times \mathrm{W})\mathrm{mm}$	Number of ports	Operating band (GHz)	Gain (dBi)
[5]	20×24	4	$27.6 - 28.6$ $37.4 - 38.6$	7.9
[6]	80×80	4	$23 - 24$	12
[15]	30×30	4	28	6.5
[16]	30×30	4	28	6
Proposed array	32×32	8	$25.2 - 27.34$	16

IV. Conclusion

In this paper a design for a single element patch antenna for $5\mathrm{Gmm}$-wave communication system is proposed. The suggested antenna is designed as a square patch with size $(1.395\ \mathrm{mm}^2)$. The proposed antenna covers $2\mathrm{GHz}$ bandwidth with center frequency $26.2\mathrm{GHz}$ and yields gain of (6.97dBi). The single element patch antenna design is then transformed to an 8 identical elements array along the x-axis to form ULA. Then the single element is then converted to 8×8 UPA. The arrays provide high radiation performance efficiencies with gains of $16\mathrm{dBi}$ for ULA and $25.8\mathrm{dBi}$ for UPA, with directive beam which can be used for beamforming. These outcomes demonstrated that the suggested antenna arrays are strong contender for $5\mathrm{G}$ due to their straightforward design, compact size in comparison to existing designs, and high performance. Since arrays in $5\mathrm{G}$ are large in size it may require high processing time to get the accurate results of the array for that reason some authors may prefer virtual array using array factor, however this may not give the accurate results for S11 and gains. In this study a CST was used to derive a relationship between array constructed using array factor method and building array but this time by repeating the element number of times to find error factor which represent the difference that must be added to the array factor method to correct its results.

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CONFLICTS OF INTEREST

The author declares no conflict of interest.

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