Mathematical Modelling on the Effects of Conductive Material and Substrate Thickness for Air Substrate Microstrip Patch Antenna

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Abstract ─ The use of microstrip patch configuration in the 5th generation (5G) wireless network is expected to fulfill the demands of smartphone users by significantly increasing the capacity of the communication technology. The main aim of this paper is to disclose the development of a mathematical model on the effects of conductive material and substrate thicknesses on the centre frequency for the performance evaluation of a low profile, cost-effective antenna in 5G devices applications. This mathematical model is proposed for an antenna system operated with air substrate resonating at a bandwidth range of 5 GHz - 38 GHz. The effects of different thickness of conductive material and substrate on the antenna's bandwidth, gain, and efficiency for 5G applications were studied. Antennas were fabricated and tested in this study to evaluate the robustness of the proposed mathematical model at 28 GHz, 24 GHz, and 10 GHz. Gains of 9.55 dBi, 9.53 dBi and 10.1 dBi, impedance bandwidths of 2.12 GHz, 2.14 GHz and 0.41 GHz, with input reflection coefficients of 42.75 dB, 25.33dB and 21.51 dB, and performance efficiencies of 98.91, 87.4 and 83.2% were obtained for the respective resonances. For validation of results, the experimental results and the simulation results from the proposed mathematical model were made into comparison, and excellent correlation between the measured and simulated results was obtained.

Index Terms ─ 5G technology, conductive material thickness, mathematical model, microstrip patch inset-fed antenna.

I. INTRODUCTION

The fifth-generation (5G) wireless technology is expected to overcome the drawbacks of the previous generations of networks by supporting higher frequency bands as well as providing more benefits. Considering the end user's demand, it is necessary to design novel antenna systems for modern compact devices. To support the expected requirements for a higher data traffic, intensive researches were carried out on the fifth-generation (5G) cellular system [1]. Since 5G cellular systems are anticipated to work at a frequency band of 30 - 300 GHz close to millimeter-wave, it will become available in the future technologies [1-4]. The 26 GHz, 28 GHz, 38 GHz, and 50 GHz bands are the four frequency bands currently being investigated for 5G applications by academia and industry worldwide [5]. The extreme free space path loss that occurs at these frequencies is one of the drawbacks in using mm-wave frequencies for mobile communication. To solve potential path loss issues, a highly directional arrayed antenna is needed. A 5G antenna must have two distinct characteristics – high gain and wide bandwidth. Both properties depend strongly on the thickness of radiating patch and substrate used in fabricating antennas. Recent trends lead to the development of an antenna that transmits and receives the broadband characteristics and high gains that can be operated at high frequencies. In this way, size reduction and bandwidth enhancement have become major design issues for sensible applications of microstrip antennas [4-6].

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Much research has been focused on modeling, designing and optimizing 5G antennas in the last eight years. However, most of the published work focused on a) investigating different configurations of (massive) Multiple Input Multiple Output (MIMO) antennas [7-12] as well as methods for reducing antenna element isolation [13-14]; b) new 5G mm-wave antennas with a wide range of polarizations like circular polarization [15-17] dual polarization [18-19] and polarization configurability [20]; c) study of multiple dual-band antenna structures (covering the proposed 28 GHz and 38 GHz band for 5G application) like rectangular slot patch [21], integrated substrate waveguide [22], printed slot [23-25], slot waveguide [26] and PIFA [27] are proposed.

Based on available literatures in this domain, no research findings have reported on the effects of the thickness of conductive material and substrate on the production of 5G antennas for their extensive performance. Therefore, this paper demonstrates the formulation of a mathematical model based on the effects of conductive material thickness and substrate height on a single rectangular microstrip patch inset-fed antenna operates from 1 - 40 GHz resonance for 5G wireless communication applications. The influences of these parameters were quantified on the antennas' impedance bandwidth, efficiency and gain. The use of air substrate was integrated in the designs to greatly reduce the cost of antenna manufacturing. The approach used in this work involved three phases summarizing the following: data acquisition and analysis, parameter substitution and optimization, and model development and optimization. The detailed explained in section (iv). The antennas were designed and tested, and the performance results are summarized in Table 1. An excellent correlation between the measured and mathematical modelled (simulation) results was obtained.

Table 1: Performance of the proposed mathematical model antennas

Frequency (GHz)	Gain (dB)		Bandwidth (GHz)		Return Loss (dB)		Efficiency (%)
	Sim.	Mea.	Sim.	Mea.	Sim.	Mea.	
28	9.58	9.45	2.12	2.00	42.75	38.53	83.2
24	9.53	9.40	2.14	2.01	25.33	25.13	87.4
10	10.1	9.87	0.41	0.39	21.51	21.73	98.9

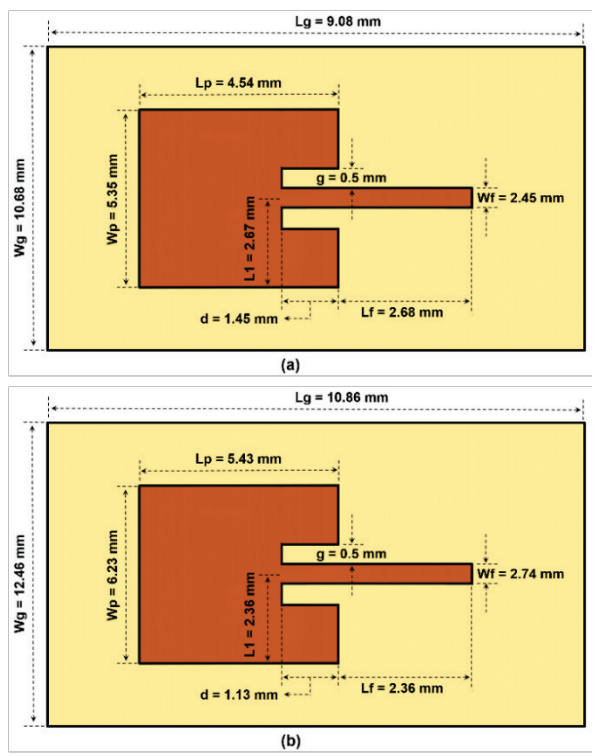
II. ANTENNA CONFIGURATION AND DESIGN

The material used for this proposed antenna's radiation patch is copper. Typically, the dimensions of an inset-fed microstrip patch antenna are determined using the equations regarded to the microstrip antenna as provided in references [28-29]. Air substrate which has a dielectric constant (ε_r) of 1 and a negligible loss tangent was used. To achieve the goals, optimization of the antenna dimensions is necessary. The optimized design parameters at 28 GHz are listed in Table 2.

Table 2: Dimensions of the proposed antenna

Parameter	Value (mm)
Length of patch (L_p)	4.54
Width of patch (W_p)	5.34
Length of ground plane (L_g)	9.08
Width of ground plane (W_g)	10.68
Thickness of substrate (h_s)	0.50
Conductive thickness (h_t)	1.00
Length of inset-fed (f_i)	1.45
Width of feedline (W_f)	2.45
Gap between patch and inserted-fed (G_{pf})	0.50
Feedline length (L_f)	2.68

The geometric configurations of the proposed antennas with the following necessary dimensions; width of the patch (W_p), length of the feeder (L_f), inset depth (d), gap width (g), and feeder length from the left edge of a patch (L_1) are illustrate in Fig. 1.



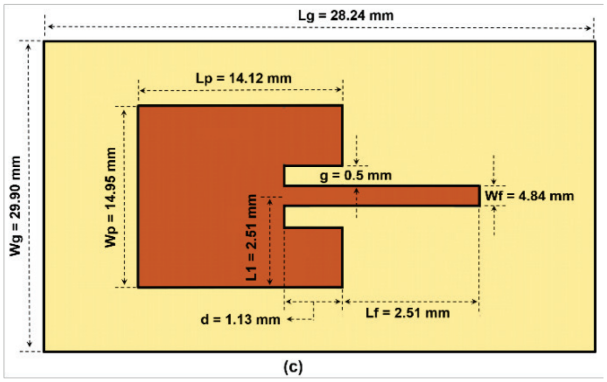


Fig. 1. Geometry of the proposed antennas with required dimensions at: (a) 28 GHz, (b) 24 GHz, and (c) 10 GHz.

III. PARAMETRIC ANALYSIS ON THE PERFORMANCE OF ANTENNA

Several design parameters affecting the bandwidth of the operating impedance were studied to comprehend the design guidelines of the proposed antenna. The radiating rectangular patch was designed using a standard formula applied in any conventional resonant frequency design. The key design parameters, which are useful in maximizing the bandwidth of an antenna, are the thickness of conductive material (h_c) and the substrate height (h_s). Parametric analysis was carried out at a thickness variation of 0.1 mm to 2 mm with varying antenna parameters. The simulated results are as shown in Table 3, and it is observed that with increasing conductor thickness (h_c) and constant width of patch and length of inserted-fed, the bandwidth increases but the length of the patch slightly decreases from the thickness of 1.1 to 2.0, as well as the centre operating frequency which shifts away from the desired resonant frequency. The resonant frequency resonated at 28 GHz at thickness of 0.1 mm to 1 mm. The most appropriate conductor thickness for this proposed antenna is 1 mm.

The selection of a proper substrate thickness is another important task in the development of microstrip patch antennas. In choosing the most appropriate substrate thickness (h_s), a developer needs to have knowledge on the effect of substrate thickness variation on the resonant frequency. In this case, h_s is varied from 0.4 mm to 1 mm with other varying antenna design parameters and the simulated results are as shown in Table 4. From the results, it is observed that when the air substrate thickness is increased while keeping the dimensions of the other parameters as in Table 2, there is a shift in the resonant frequency and the effective dielectric constant changes; which leads to a change in the effective dimensions of the patch. In this set of observation, as the height increases, a volume of fringing effect occurs, and this leads to the increase in the bandwidth. With greater height of substrate, higher amount of modes is excited, resulting in the degradation of the gain. The most appropriate height for this proposed antenna design at 28 GHz is 0.5 mm. However, surface waves are generated as the height of the substrate increases. These waves extract power in the direction of radiation from the total available power. Reduction in the parameters of the antenna design is therefore observed.

IV. DEVELOPMENT OF MATHEMATICAL MODEL

In this work, the effect of the variation of the resonance frequency (F_r); patch Length (L_p); patch width (W_p); and dielectric permittivity (ε_r) on the antenna parameters (gain, directivity, impedance bandwidth and input reflection coefficient), were studied with respect to conductor thickness (h_c) and substrate height (h_s), using computer simulation technology (CST) studio 2016 Software package However, the simulated data obtained where used to develop mathematical models which are father described in this manuscript MATLAB V19 Software package was used as the modeling environment.

In order to develop a mathematical model for the conductor thickness (h_c) and substrate height (h_s), simulated data were obtained from the CST studio suit 2016 for different center frequencies based rectangular microstrip inset patch antenna which are shows in Table 3 and Table 4 respectively. However, due to the limited amount of data, artificial neural networks (ANNs) toolbox in MATLAB was used to train a model and used to generate the desired amount of data to enable model creation. The steps involved in the proposed model development can be summarized as follows:

i. Data Acquisition and Preparation;
ii. Parameter Substitution and Optimization;
iii. Model Development and Optimization [30].

i. Data Acquisition and Preparation

This stage can be described using the following block diagram.

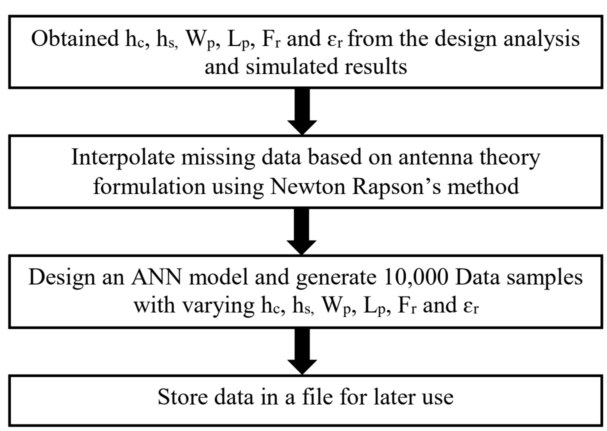


Fig. 2. Data acquisition and preparation block diagram.

ii. Parameter Substitution and Optimization

However, since the width and length (W_p and L_p) of patch are dependent on other parameters of the model, based on antenna theory formulations, these parameters can be substituted for. To achieve that, the following stages were further executed.

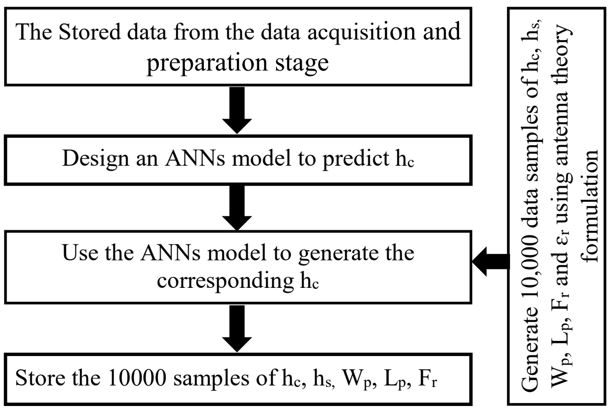


Fig. 3. Parameter substitution and optimization.

iii. Model Development and Optimization

This represents the main stage of this work, and it presents the strategy used in developing the set of mathematical function that could be used to evaluate a suitable value for h_c and h_s for a given antenna design specification. In this work, h_s is chose to be defined using the following simplified mathematical expressions in equation (1):

$$h_S = \left(\frac{\alpha F_r \sqrt{\varepsilon_r + 1} + \beta \sqrt{2} C_O}{\sqrt{2} C_O + \gamma F_r \sqrt{\varepsilon_r + 1}} \right), \tag{1}$$

where the α, β, and γ can be found using an optimization technique. However, the particle swarm optimization (PSO) techniques was chosen. The objective function of the optimization was to minimize the difference between the estimation and true value of the h_s. After the optimization, it was found that the model was inaccurate when α and β are fixed at constant values, however, γ can be fixed at 0.5053. In order to make α and β vary with change in parameter specification, let α and β be as shown in equations (2) and (3), respectively:

$$\alpha = X_1 \begin{pmatrix} X_2 (W_p)^{X_3} - X_4 (F_r)^{X_5} - X_6 (F_r)^{X_7} \\ + X_8 (E_r)^{X_9} - X_{10} (E_r)^{X_{11}} + X_{12} \end{pmatrix}, \tag{2}$$

$$\beta = Y_1 \begin{pmatrix} Y_2 (W_p)^{X_3} - Y_4 (F_r)^{X_5} - Y_6 (F_r)^{X_7} \\ + Y_8 (E_r)^{X_9} - Y_{10} (E_r)^{X_{11}} + Y_{12} \end{pmatrix}. \tag{3}$$

The set of parameters X and Y are unknown variables that can be determined using PSO. The resulting mathematic model for substrate height was determined as presented in the following equations (4) and (5) respectively:

A. Substrate height model (h_s)

The substrate height of a rectangular patched antenna can be calculated using equation (4),

$$h_S = \left(\frac{7.6904 \alpha F_r \sqrt{\varepsilon_r + 1} + 1.4142 \beta C_O}{1.4142 C_O + 0.5053 F_r \sqrt{\varepsilon_r + 1}} \right), \tag{4}$$

where, α and β are represented in equation (5) and (6) respectively:

$$\alpha = \begin{pmatrix} 0.8525 \left(\dfrac{C_O}{2 F_r \sqrt{\varepsilon_r + 1}} \right)^{1.041} \\ - 0.7464 (F_r)^{0.3993} - 0.3902 (F_r)^{0.6572} \\ + 0.0817 (E_r)^{0.3679} - 0.5217 (E_r)^{-0.5611} \\ + 4.4398 \end{pmatrix}, \tag{5}$$

$$\beta = \begin{pmatrix} 2.4846 \left(\dfrac{C_O}{2 F_r \sqrt{\varepsilon_r + 1}} \right)^{-0.1202} \\ - 0.3713 (F_r)^{0.4138} + 3.1339 (F_r)^{-0.223} \\ - 0.4411 (E_r)^{-0.3029} - 1.2403 (E_r)^{-8.1344} \\ + 0.6557 \end{pmatrix}. \tag{6}$$

Based on this model, the mathematical model for computing the conductive material thickness can be generated. Finally, the mathematical model of the conductor thickness was found to be in equation (7).

B. Conductive material thickness model (h_c)

The height of conductive mat Height of conductive material thickness of a rectangular patch antenna can be calculated using equation (7):

$$h_C = \begin{pmatrix} \left(\dfrac{F_r \varepsilon_r \sqrt{2\varepsilon_r + 2}}{C_O} \right)^{(\varepsilon_r - 1)} \times \\ \begin{pmatrix} 1.3703 h_S + 83.1872 (h_S)^{8.2891} \\ -172.286 (h_S)^{11.07824} - 0.3501 \end{pmatrix}^2 \end{pmatrix}, \tag{7}$$

where, C_o is the speed of light in air (mm/s); F_r is the desired center frequency (GHz) and h_S is the substrate height (mm) and it can be evaluated using the mathematical formulation. Table 5 shows the optimized dimensional parameters of the proposed mathematical modelled antennas.

V. RESULTS AND DISCUSSION

A. Input reflection coefficients

In reference to the optimized antennas dimensions as well as the developed mathematical model, prototypes of the proposed antennas were fabricated and tested to validate their operational performances through the mathematical model. The antennas were made excited using a long pin SMA connector by connecting its coaxial probe to the rectangular patch. Figure 4 displays a photograph of the fabricated antenna prototype. The S-parameters of the antennas were tested using the Agilent Vector Analyser (N5245A). On the other hand, Fig. 5 presents the input reflection coefficient characteristics of the simulated and measured results. The simulated input reflection coefficients are lower than -10 dB (VSWR< 2), measurably around 42.75 dB, 25.33 dB and 21.51 dB at frequencies of 28 GHz, 24 GHz and 10 GHz with bandwidths of 2.12 GHz, 2.14 GHz and 0.41 GHz, respectively. The measured return losses of 38.53 dB, 25.13 dB and 21.73 dB with bandwidths of 2.00 GHz, 2.01 GHz and 0.39 GHz respectively are found enough for proper impedance matches. However, it is pointed out that the bandwidth differences for 0.12 GHz, 0.13 GHz and 0.02 GHz constitute about 5.83%, 6.27% and 5.00% respectively between the simulated and measured bandwidth. These differences arise from the manufacturing sensitivity and the effect of the coaxial feed connector. An excellent correlation was observed between the measured and simulated results.

Table 3: Variation of antenna parameters with thickness of conductive material (simulated)

h (mm)	**d (mm)**	**W_p (mm)**	**L_p (mm)**	**F_r (mm)**	**D (dB)**	**G (dB)**	**R (dB)**	**BW (GHz)**
0.1	1.45	5.34	4.38	28.00	10.150	10.10	24.47	1.0930
0.2	1.45	5.34	4.78	28.00	10.130	10.10	25.69	1.1269
0.3	1.45	5.34	4.73	28.00	10.090	10.10	27.57	1.2092
0.4	1.45	5.34	4.70	28.00	10.040	10.00	26.70	1.2586
0.5	1.45	5.34	4.67	28.00	9.970	9.97	27.86	1.3566
0.6	1.45	5.34	4.63	28.00	9.880	9.88	35.94	1.4225
0.7	1.45	5.34	4.61	28.00	9.790	9.79	33.88	1.5158
0.8	1.45	5.34	4.57	28.00	9.694	9.69	33.54	1.6091
0.9	1.45	5.34	4.55	28.00	9.589	9.59	32.65	1.7025
1.0	1.45	5.34	4.54	28.002	9.474	9.47	31.49	1.7245
1.1	1.45	5.34	4.54	27.907	9.373	9.37	30.17	1.8852
1.2	1.45	5.34	4.51	27.809	9.211	9.22	26.78	1.9895
1.3	1.45	5.34	4.50	27.850	9.086	9.06	25.06	2.0609
1.4	1.45	5.34	4.46	27.880	8.940	8.94	20.63	2.0983
1.5	1.45	5.34	4.44	27.800	8.766	8.77	18.69	2.0928
1.6	1.45	5.34	4.42	27.744	8.620	8.62	17.47	2.1642
1.7	1.45	5.34	4.41	27.728	8.473	8.47	16.66	2.2411
1.8	1.45	5.34	4.40	27.728	8.306	8.31	16.03	2.2840
1.9	1.45	5.34	4.39	27.760	8.164	8.16	15.50	2.3830
2.0	1.45	5.34	4.36	27.760	7.992	7.99	14.36	2.3940

Table 4: Variation of antenna design parameters with substrate thickness (simulated)

h_s (mm)	**L_p (mm)**	**W_p (mm)**	**d (mm)**	**F_r (GHz)**	**D (dBi)**	**G (dB)**	**R (dB)**	**BW (GHz)**
0.4	4.54	5.34	1.45	28.576	9.585	9.58	19.323	1.5471
0.5	4.54	5.34	1.45	28.024	9.451	9.45	42.648	2.1180
0.6	4.54	5.34	1.45	27.696	9.310	9.31	28.001	2.3009
0.7	4.54	5.34	1.45	26.696	9.188	9.19	25.616	2.3512
0.8	4.54	5.34	1.45	26.467	9.064	9.06	28.118	2.3725
0.9	4.54	5.34	1.45	26.008	8.932	8.93	40.162	2.4405
1.0	4.54	5.34	1.45	25.656	8.785	8.79	32.600	2.5075

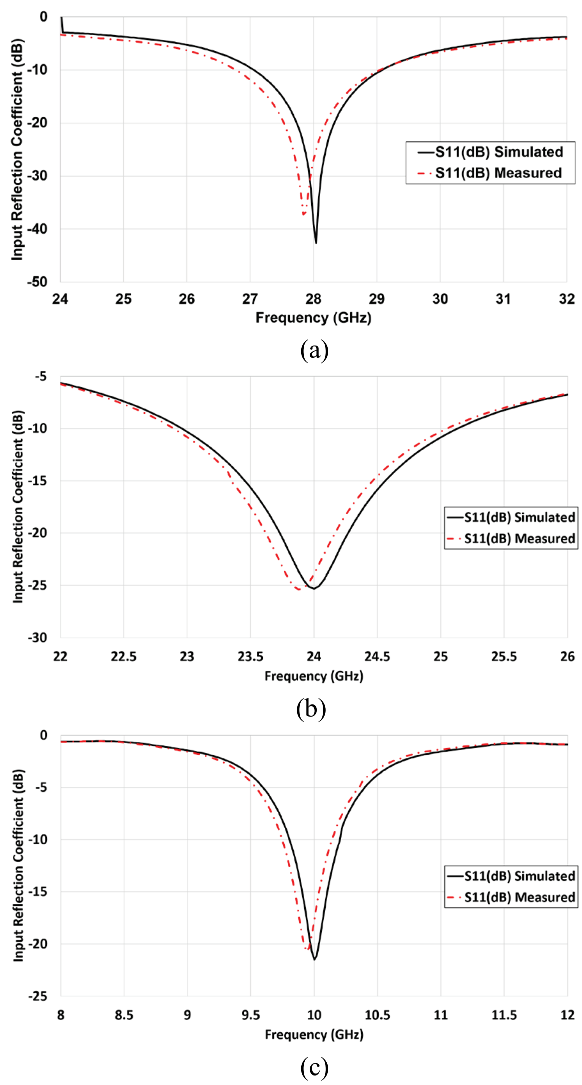


Fig. 5. Comparison of the measured and simulated results "input reflection coefficient" of a fabricated air substrate patch at: (a) 28 GHz, (b) 24 GHz, and (c) 10 GHz resonances.

B. Radiation pattern

Radiation patterns were measured using a swept frequency measurement conducted in an anechoic chamber. The measured radiating patterns of the proposed antennas were plotted at 28 GHz, 24 GHz and 10 GHz resonances and are presented in Fig. 6. The measured input impedance was 50.401–j1.02, which is approximate to 50Ω. Since both the real and imaginary parts of the measured input impedance were close to the Smith chart centre, it therefore indicates a maximum power transfer has occurred. Figures 6 (a), (b) and (c) show the normalized measured and simulated radiation patterns of the proposed linearly omnidirectional polarized antennas at 28 GHz, 24 GHz and 10 GHz resonances respectively in the E- and H-planes obtained using a swept frequency measurement in an anechoic chamber. The simulated patterns are reasonably in agreement with the measured patterns, and this shows that the antenna is rather of the directional type. Nonetheless, the contrast between the measured and simulated radiation patterns indicates some variations between these patterns. The measured E-plane radiation pattern indicates a reasonable degree of variation. This is probably due to the coaxial feed probe's effect on the height variability. It is important to note that the pattern of a radiation is mainly generated due the current of excitation from a coaxial probe to the radiating element and the current in the probe. Regarding the H-plane, both the simulated and measured patterns of radiation show a constant good agreement, but with a minor difference and a good directivity in both frequencies. The actual measured radiation patterns and gains of the proposed antennas are in close agreement with the simulated results.

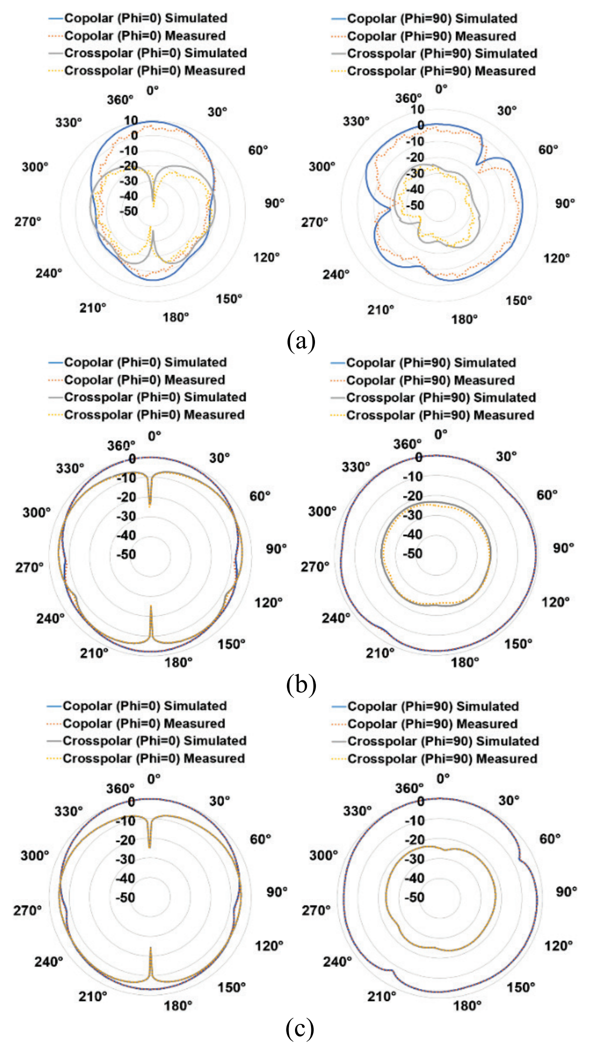


Fig. 6. Measured radiation patterns (E & H planes) of the proposed antennas at: (a) 28 GHz; (b) 24 GHz, and (c) 10 GHz.

C. Comparison of the proposed mathematical model

Table 6 provides a contrast between the published works performance profile comparisons with proposed antennas in terms of resonant frequency overall size and measured values, gain, radiation efficiency, return loss as well as bandwidth. This comparison shows that the proposed mathematical model antennas operating at 28 GHz, 24 GHz and 10 GHz has a wider bandwidth and a high gain compared to other antennas published previously.

The proposed mathematical model has the following advantages:

i. Ability to predict resonance frequency faster and more accurately compared to many advanced simulation tools that are available commercially
ii. Simplifies and save the simulation time to analyses parameters and process parametric result data compared to many advanced simulation tools that are available commercially
iii. It reduced the cost of optimum performance requirements for electromagnetic simulation (such as high clock speed and core count CPU, an efficient GPU workstation, and fast RAM.

Table 6: Publish works performance profile comparison with proposed antennas

Frequency (GHz)	Size (mm^2)	Gain (dB)	Bandwidth (GHz)	Efficiency (%)	Return loss (dB)	Ref. Antenna
28	04.42 × 3.47	8.58	0.63	N/A	44.46	[31]
28	04.40 × 4.20	4.47	1.55	94.00	N/A	[32]
28	20.00 ×16.50	9.33	0.45	N/A	23.50	[33]
28	**05.34 × 4.54**	**9.45**	**2.00**	**83.20**	**38.53**	**Proposed Antenna**
24	07.27 × 7.27	3.24	1.87	90.00	32.50	[34]
24	13.80 × 11.40	3.00	0.40	N/A	32.00	[35]
24	28.00×20.00	8.20	2.00	93.00	23.00	[36]
24	**5.20× 7.00**	**9.40**	**2.01**	**87.40**	**25.13**	**Proposed Antenna**
10	N/A	N/A	1.18	66.30	41.50	[37]
10	50× 25	8.76	1.14	82.32	27.77	[38]
10	20×18	3.14	0.80	N/A	34.50	[39]
10	**13.6× 07**	**9.87**	**0.39**	**98.90**	**21.73**	**Proposed Antenna**

VI. CONCLUSION

Evaluation of the effects of conductive material and substrate thickness, as well as the development of a mathematical model of a single element rectangular microstrip patch inset-fed antenna for 5G wireless communication application are presented in this paper. Microstrip patch antennas operated using air substrate at 28, 24 & 10 GHz resonance were designed, simulated, optimized and analysed accordingly. The conductive patch materials and substrate techniques used to produce mm-wave integrated antennas have a significant impact on the antennas' impedance and radiation characteristics. Therefore, the effects of conductive patch material and substrate technology on the performance of an antenna must be thoroughly defined and properly understood prior to the designing of a 5G antenna. The validity of the proposed model equations is verified by comparison with the measured results. The measured results obtained from the fabricated antennas prototypes are in good agreement with the simulated (model equations) results. The implementation of this proposed mathematical modelling approach will minimize the time required to obtain the best resonant frequency design compared to the parametric studies using a simulation software. The proposed antennas support a very low profile, which is an excellent in the integrated low-cost millimeter-wave applications.

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