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Performance Comparison of 28 GHz Rectangular Patch Antenna Based on Three Different Dielectric Constant Substrates for 5G Communications

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***Abstract*— This article introduces a design and analysis of three inset-fed rectangular patch antennas based on three different dielectric constant substrate materials. These substrate materials include Rogers RT-5880, Preperm 260 LDS, and Polycarbonate. The introduced structures are resonant at a frequency of 28 GHz and employ copper material for a radiating patch on the top of the dielectric substrate and a ground plane on the bottom of the substrate. The design dimensions of the three structures have been calculated, while the three materials employed as the substrate in the three antenna structures are different. Furthermore, Computer Simulation Technology (CST) software was employed to simulate and compare the performance of the three introduced designs. The performance indexes used to evaluate and compare the performance of the three proposed designs include realized gain, return loss, radiation efficiency, bandwidth, radiation pattern, and voltage standing wave ratio.**

***Index Terms*— dielectric constant, fifth-generation (5G) system, rectangular patch antenna, antenna performance parameters, Rogers RT-5880, Polycarbonate, Preperm 260 LDS.**

I. INTRODUCTION

In general, the antenna is considered an essential element in any communication system because its function is to exchange informational messages in the form of electromagnetic waves. The fifth generation (5G) system is a modern cellular mobile communication system that requires a compact, low-profile, and portable antenna [1]-[3]. Furthermore, the used antenna needs to be suitable for a planar and non-planar surface, easy to install, cover a wide range of frequencies, and be able to perform its function with electromagnetic waves in the mm-wave frequency range [1]-[3]. For this purpose, a rectangular microstrip patch antenna can be an appropriate option for wireless 5G communication devices due to its advantages, which meet 5G system antenna requirements. The patch antenna is made up of a dielectric substrate material that is separated between the top radiating patch layer and the bottom ground plane layer, resulting in both layers being made up of the same perfect metallic conductor [1, 3]. The microstrip patch antenna is also called a "printed antenna" because it uses printed circuit board (PCB) technology to etch the radiating patch element on a dielectric substrate [3]–[5]. Despite the variety of[1] radiating patch geometric configurations, the rectangular geometric configuration is the most common [3, 6, 7]. In terms of microstrip antenna feeding methods, there are three: aperture coupling, coaxial probe, and microstrip line, which are the most frequent methods [6, 7]. In a 5G system, the microstrip patch antenna needs to transmit and receive electromagnetic waves in the mm-wave frequency band assigned by the International Telecommunication Union (ITU), which extends from 24 GHz to 80 GHz [3, 6, 8].

In the literature, many research studies have proposed and presented a microstrip patch antenna for 5G wireless technology. In [9], authors proposed a design of a compact inset-fed rectangular patch antenna employing a Roger RT Duroid 5880-based substrate for 5G applications. The proposed antenna has a resonant frequency of 27.954 GHz and shows a return loss (s_{11}) value of -13.48 dB, bandwidth (BW) of 847 MHz, a gain (G) value of 6.63, and an efficiency of 70.18%.

El-Mashade and Hegazy designed in [4] an inset-fed FR-4 single-element rectangular patch antenna; the introduced antenna structure shows a directivity (D) value of 6.921 dBi, (s_{11}) value of -15.352 dB at 27.901 GHz and voltage standing wave ratio (VSWR) value of 1.787 at 28 GHz.

Gemeda et al. [2] presented a design of a 28 GHz FR-4 substrate microstrip patch antenna for 5G communication systems, The results indicate that the proposed structure has a bandwidth (BW) value of 1.046 GHz, a directivity (D) value of 7.509 dBi, a radiation efficiency (ηrad %) of 98.214 % and beam-gain value of 7.587 dBi.

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The author of [3] proposed a compact inset-fed design of a 28 GHz rectangular patch antenna based on polyimide substrate for a 5G system, with a BW of 1.427 GHz, gain (G) of 5.406 dBi, VSWR of 1.3, ηrad % of 86%, and (s_{11}) value of -17.68 dB.

It can be seen from the introduced literature that researchers concentrated on designing 5G patch antennas based on substrate materials such as FR-4, Roger RT Duroid 5880, and polyimide, which are common in this research field. However, this study introduces a design of three inset-fed rectangular patch antenna structures that operate in the 28 GHz mm-wave frequency band. These proposed structures employ three different dielectric constant substrate materials, including Rogers RT-5880, Preperm 260, and Polycarbonate. This article's main contribution is to propose and compare the performance of three different dielectric constant substrate materials that can be used as a substrate for microstrip patch antenna design. The Computer Simulations Technology (CST) program is used to simulate proposed structures and evaluate their performance [10]. The remainder of the article is organized as follows. In section II, materials and methods are introduced. Section III analyzes, discusses, and compares the simulation results. The simulation results comparison of three proposed structures with similar designs from scientific literature is introduced in Section IV. The conclusion and future work are in Section V.

II. MATERIALS AND METHODS

This study evaluates and compares the performance of three rectangular patch antennas employing different substrate materials for a 5G system. The antennas design are presented in the following flowchart:

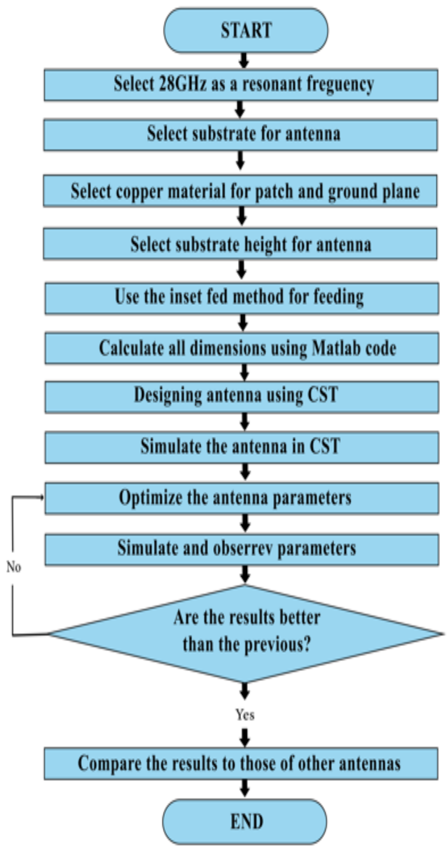

Figure 1. Flowchart for antenna design.

The design process is divided into several parts. Firstly, designing the radiating patch, which mainly involves calculating the length and width of the patch which requires the resonance frequency(f_r), the height of the substrate (h), and the dielectric constant of the substrate (ϵ_r). Second, determining the substrate and ground dimensions; and third, calculating the inset feeding method parameters.

A. *Radiating Patch*

The width of the patch W_p is determined as follows [9]:

$$Wp = \frac{c_0}{2fr\sqrt{\frac{(\epsilon_r+1)}{2}}} \tag{1}$$

Where ($c_0 = 3 \times 10^8$ m/s) is the speed of electromagnetic waves in free space, ($f_r = 28$ GHz) refers to the resonant frequency, and (ε_r) relative permittivity.

The actual patch length L_P is determined based on the following formula [9]:

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

Where L_{eff} is the effective length, and ΔL is the extension length, L_{eff} is calculated as follows [9]:

$$L_{eff} = \frac{c_0}{2fr\sqrt{\epsilon_{reff}}} \tag{3}$$

Here ϵ_{reff} is the effective dielectric constant and it can be determined using the following formula [9]:

$$\epsilon_{reff} = \frac{\varepsilon_r+1}{2} + \frac{\varepsilon_r-1}{2}\left(1 + 12\frac{h}{Wp}\right)^{-0.5} \tag{4}$$

In terms of ΔL, it is calculated based on the following equation [12]:

$$\Delta L = 0.412h\frac{(\epsilon_{reff}+0.3)\left(\frac{Wp}{h}+0.264\right)}{(\epsilon_{reff}-0.258)\left(\frac{Wp}{h}+0.8\right)} \tag{5}$$

B. *Substrate and Ground Dimensions*

The substrate length Ls and ground length Lg in the designed structures have the same length (Ls =Lg), and the following equation was used for calculation [9]:

$$L_s = 6h + Lp \tag{6}$$

The same principle is applied for substrate width Ws and ground width Wg. The next equation is applied to calculate the substrate width [9]:

$$W_s = 6h + W_P \tag{7}$$

C. *Feed-line*

Microstrip inset feed line is a vital feeding method of the patch to give suitable impedance matching. The microstrip transmission line length (TL) is calculated as follows [11]:

$$TL = 3 \times h \tag{8}$$

The next relation is used to determine the inset feed Depth (F_i) [9]:

$$F_i = 10^{-4}[0.001699\varepsilon_r{}^7 + 0.13761\varepsilon_r{}^6 - 6.1783\varepsilon_r{}^5 + 93.187\varepsilon_r{}^4 - 682.69\varepsilon_r{}^3 + 2561.9\varepsilon_r{}^2 - 4043\varepsilon_r + 6697](Lp/2) \quad (9)$$

In terms of feed line width (Wf), to obtain 50Ω characteristic impedance (Zo), the required feed line width to height ratio can be calculated using the following formula [11, 12].

$$\frac{Wf}{h} = \begin{Bmatrix} \frac{8e^A}{e^{2A}-2} \; when\ A \geq 1.52 \\ \frac{2}{\pi}\begin{Bmatrix} B - 1 - \ln(2B-1) + \frac{\varepsilon_{r-1}}{2\varepsilon_r} \\ \left[\ln(B-1) + 0.39 - \frac{0.61}{\varepsilon_r}\right] \end{Bmatrix} when\ A < 1.52 \end{Bmatrix} \quad (10)$$

Where

$$A = \frac{Z_o}{60}\sqrt{\frac{\varepsilon_r+1}{2}} + \frac{\varepsilon_r-1}{\varepsilon_r+1}\left(0.23 + \frac{0.11}{\varepsilon_r}\right) \quad (11)$$

$$B = \frac{60\pi^2}{Z_o\sqrt{\varepsilon_r}} \quad (12)$$

The following equation is used to determine the notch gap (g) [13]:

$$g = \frac{c}{\sqrt{2*\varepsilon_{reff}}} \frac{4.65*10^{-12}}{f_r(in\ GHz)} \quad (13)$$

The Matlab code was used to calculate the design parameters of the three structures at 28 GHz using three different substrate materials. These three substrate materials are Rogers RT-5880, Preperm 260 LDS, and Polycarbonate, which have dielectric constant values of 2.2, 2.6, and 2.9, respectively. The calculated dimensions were optimized using the trial and error method to obtain better performance results.

The considered design parameters in the design process of the three rectangular patch antennas are shown in Fig. 2

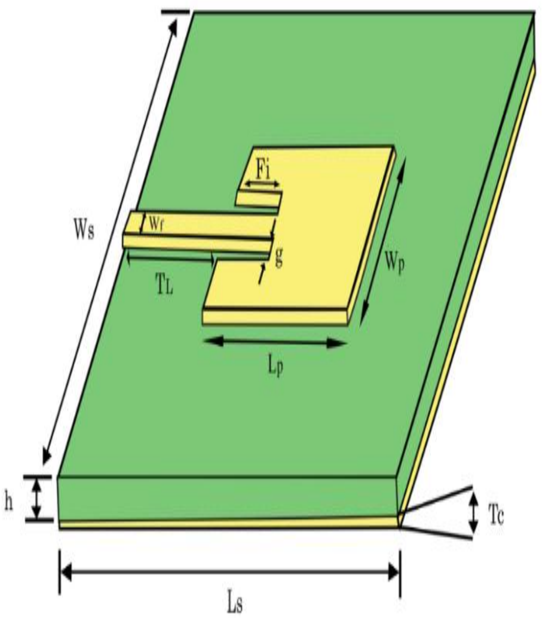

Figure 2. Proposed rectangular patch antenna structure

The design parameters of the proposed structures are tabulated in Table I

TABLE I. DESIGN PARAMETERS

Parameters	**Symbol**	**Calculated values (mm)**	**Optimized Values (mm)**
Rogers RT-5880 substrate material (ε_r=2.2)			
Patch width	W_p	4.23519	4.412
Patch Length	L_p	3.50504	3.449
Feedline Width	W_f	0.616213	0.6
Transmission line length	T_L	0.6	0.73
Feedline inset distance	F_i	0.84354	1.1
Substrate Length	L_s	4.70504	4.906
Substrate Width	W_s	5.43519	5.221
Notch Gap	g	0.0244307	0.071
Substrate height	h	0.2	0.2
Copper Thickness	T_c	0.035	0.035
Preperm 260 LDS substrate material (ε_r=2.6)			
Patch width	W_p	3.99298	3.993
Patch Length	L_p	3.23327	3.183
Feedline Width	W_f	0.553184	0.6
Transmission line length	T_L	0.6	0.63
Feedline inset distance	F_i	0.820106	1.12
Substrate Length	L_s	4.43327	4.4333
Substrate Width	W_s	5.19298	5.193
Notch Gap	g	0.022589	0.068
Substrate height	h	0.2	0.2
Copper Thickness	T_c	0.035	0.035
Polycarbonate substrate material (ε_r=2.9)			
Patch width	W_p	3.83633	3.755
Patch Length	L_p	3.06611	3.122
Feedline Width	W_f	0.514404	0.6
Transmission line length	T_L	0.6	0.57
Feedline inset distance	F_i	0.808877	1.1
Substrate Length	L_s	4.26611	4.266
Substrate Width	W_s	5.03633	5.036
Notch Gap	g	0.0214592	0.07
Substrate height	h	0.2	0.2
Copper Thickness	T_c	0.035	0.035

III . SIMULATION RESULTS ANALYSIS AND DISCUSSION

In this section, the simulation results of the three designs are presented, analyzed, and compared. The performance parameters used to evaluate and compare the performance of the three proposed designs include S_{11}, BW, VSWR, radiation pattern, and G, and ηrad %.

A. Performance Evaluation Parameters

Return Loss (S_{11}): This parameter, which is also known as the reflection coefficient, is obtained in dB and indicates the ratio of the incident power to the reflected power [3]. In this parameter, the -10 dB value is considered a reference value, which indicates that 10% of the incident power will be reflected and the remaining 90% will be received, which is considered acceptable in mobile communication [2,3]. A -10 dB reflection coefficient value or lower indicates better performance [3, 14].

Bandwidth (BW): This parameter represents a region of the frequency range in which the return loss is less than -10 dB [3, 15].

Voltage Standing Wave Ratio (VSWR): It shows how much power is reflected from the antenna toward the transmitter [3,15]. Both S_{11} and VSWR indicates an impedance mismatch between the antenna and transmission line [7], however, S_{11} based on the ratio between the incident power and reflected power [3], whereas VSWR is the ratio between the highest voltage value and the lowest voltage value on standing waveform through transmission line length [16]. The acceptable value of VSWR in a patch antenna is between 1 and 2 through the bandwidth, and 1 is the optimal value [3, 15].

Radiation Pattern and Gain (G): The radiation pattern is one of the important antenna performance parameters that shows the amount of radiated energy by the antenna [3, 17]. In terms of antenna gain, it represents the ratio of the antenna power density at a certain point to the isotropic antenna power density at the same point when both antenna structures are fed by the same amount of power [3]. While gain excludes some efficiency loss and mismatching loss, the realized gain has included these losses; therefore, realized gain is lower than gain [18]

Radiation Efficiency (ηrad %): it represents the ratio between the total power radiated by the antenna and the total input power injected into the same antenna [3, 17]. This parameter indicated how the antenna is effective in the radiating and receiving process of electromagnetic waves; therefore, in this case, for better performance, this parameter should be higher [3].

B. *Comparison of Simulation Results Of Three Proposed Patch Antenna Structures*

The previous performance parameters of the three proposed antenna designs have been compared with each other as indicated in figures 3 to 7. In addition, Table II provides a summary of the comparison of the simulation results between the three structures.

TABLE II . COMPARISON OF SIMULATION RESULTS OF THREE PROPOSED PATCH ANTENNA STRUCTURES

Parameter	Rogers RT-5880	Preperm 260 LDS	Polycarbonate
S_{11} (dB)	-43.09	-37.22	-31.21
BW(GHz)	1.037	0.978	1.091
VSWR	1.014	1.028	1.056
ηrad %	90.77%	90.89%	76.58 %
HPBW (deg)	88.9	93.1	93.8
Realized Gain (dBi)	6.379	6.145	5.307

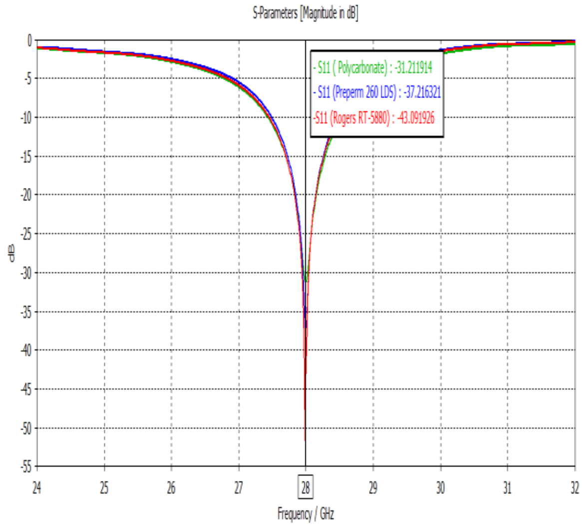

Figure 3. S_{11} plot of the three proposed designs.

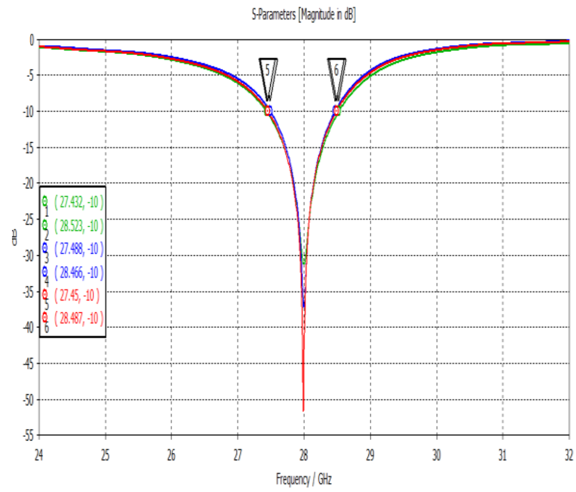

Figure 4. BW plot of the three proposed designs.

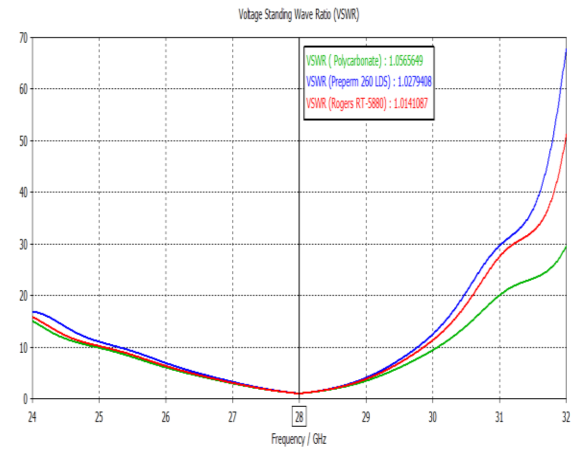

Figure 5. VSWR plot of the three proposed designs.

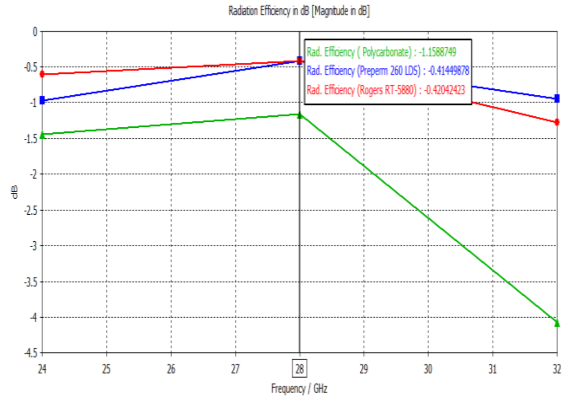

Figure 6. ηrad % plot of the three proposed designs.

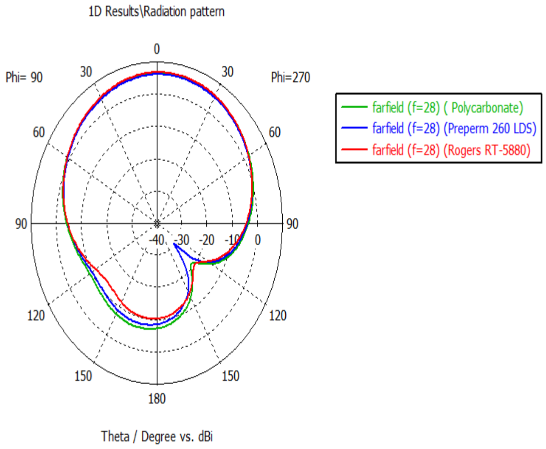

Figure 7. 2-D radiation pattern of the three proposed designs.

It can be observed from Table II, Figure 3, and Figure 5 that the Rogers RT-5880 substrate antenna achieved the best performance in terms of realized gain and VSWR. It provides a realized gain value of 6.379 dBi, a value of -43.09 for S_{11}, and a VSWR value of 1.014; This is because the Rogers RT-5880 substrate has a lower dielectric constant value, which is recommended for high-frequency applications to reduce power loss [19]. furthermore, figure 4 indicates that Rogers RT-5880 has a BW of 1.037 GHz (28.487-27.45 = 1.037 GHz), whereas the ηrad % value of 90.77 % which is equivalent to -0.42 dB as shown in figure 6, in terms of HPBW, it provides 88.9 deg. Regarding the Preperm 260 LDS substrate antenna design, it provides the best ηrad % with a value of 90.89 % (-0.41 dB) as shown in Figure 6 In terms of realized gain, it provides a realized gain of 6.145 dBi, but the bandwidth is 0.978 GHz as shown in figure 4. The same structure has a value of-37.22 dB for S_{11} as observed in Figure 3, whereas it shows values of 1.028 and 93.1 deg. for VSWR and HPBW respectively. On the other hand, the Polycarbonate substrate antenna structure shows the highest HPBW and BW. It has a realized gain value of 5.307 dBi and a bandwidth of 1.091 GHz; it also provides values of -31.21 dB, 1.056, and 76.58 % for S_{11}, VSWR and ηrad % respectively.

IV . COMPARISON OF THREE PROPOSED ANTENNA STRUCTURES WITH SIMILAR DESIGNS

In Table III, similar structures from the literature have been compared to the performance of the three proposed antenna structures.

TABLE III. COMPARISON OF THREE PROPOSED ANTENNA STRUCTURES WITH SIMILAR DESIGNS

Work Ref. No.	S_{11}(dB)	BW	VSWR	ηrad %
[3]	-17.68	1.427GHz	1.3	86%
[4]	-15.35	-	1.78	87.78 %
[9]	-13.48	847MHz	1.53	70.18%
[20]	-12.59	-	1.77	-
Rogers RT-5880	-43.09	1.037 GHz	1.01	90.77%
Preperm 260 LDS	-37.22	0.978 GHz	1.02	90.89%
Polycarbonate	-31.21	1.091 GHz	1.05	76.58%

In terms of S_{11}, the proposed designs offer a competitive and lower return loss compared to designs in [3, 4, 9, 20]. The minimum S_{11} values indicate that more power is received, which shows that the proposed designs outperform other designs in terms of S_{11}. Similarly, regarding VSWR, the introduced designs provide better performance compared to the designs reported in [3, 4, 9, 20]. This is because the VSWR value of the proposed structures is closer to the optimal value 1. In terms of BW, the proposed structures show a competitive result. It can be noticed that the Polycarbonate substrate antenna provides a wider BW than the BW of the antenna structure introduced in [9]. Finally, regarding ηrad (%). The introduced Rogers RT-5880 and Preperm 260 LDS substrate antennas outperform the ηrad (%) of the designs in [3, 4, 9] while polycarbonate substrate antenna provides ηrad (%) better than the design reported in [9].

Generally, the proposed structures provide a reasonable and competitive performance compared to similar structures existing in the literature.

V. CONCLUSION AND FUTURE WORK

This research has proposed three different dielectric constant substrate materials Rogers RT-5880, Preperm260 LDS, and Polycarbonate to be utilized as substrates in the designing process of the rectangular patch antenna for the 5G system. The three antenna structures have been designed and simulated using CST software to observe the impact of employing three different dielectric constant material substrates on the performance parameters of three antenna structures. It can be concluded that the proposed three designs provide reasonable and competitive results so that one of these proposed substrates can be used for a 5G system patch antenna based on the nature of the application. In future work, the number of patch elements can be increased to create an array patch antenna to observe the improvement in the antenna performance parameters. Furthermore, a microstrip patch antenna can be proposed for the 6G system, as it is still in the research phase.

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