Study and Design of a 5G Millimeter Band Patch Antenna with a Resonant Frequency of 60 GHz

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This research proposes a study and design of a millimeter band patch antenna for 5G with a resonant frequency of 60 GHz. For this, we proposed a technique to improve the performance of this antenna. This technique consists of cutting a piece of the proposed antenna medium, as shown in the diagram in the design section below. We employ the Roger RT duroid 5880 type substrate in the design, which has a relative permittivity equal to 2.2, a height of $h = 0.16$ mm, and a loss tangent of 0.0009. The format of the radiated element (the patch) is as follows: length: 2 mm, width: 1.6 mm. We use high-frequency structure simulation software (HFSS) to obtain this antenna's results. These simulations yield good results: an operating frequency of 59.95 GHz, a reflection coefficient (S_{11}) of – 36.41 dB, a bandwidth of 2.15 GHz, a gain of 9.2 dB, a radiated power of 10.01 dBm and an efficiency of 99.67 %. The results obtained are very competitive and meet the requirements of the 5th generation. Thus, it is likely that the proposed antenna will be able to meet the requirements related to 5G needs.

Keywords: 5G, 60 GHz, HFSS, Microstrip antenna, Millimetre wave.

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1. INTRODUCTION

Fifth-generation (5G) wireless technology is the latest iteration of cellular technology, designed to increase the speed and responsiveness of wireless networks dramatically. With 5G, data transmitted over wireless broadband connections can reach multi-gigabit speeds, with potential peaks of 20 gigabits per second (Gbps) by some estimates. These speeds exceed those of wireline networks and offer latency of fewer than five milliseconds (ms) or less, which is helpful for applications that require real-time feedback. 5G will increase the amount of data transmitted over wireless systems due to greater bandwidth and advanced antenna technology [1-2].

The field of telecommunications in the mimes has experienced unprecedented growth for several decades. Numerous systems offer more varied services (mobile telephony, interactive multimedia services, etc.). Within the framework of a communication system, the antenna is an essential element to ensure the transmission and reception of information materialized by the waves propagating in the atmosphere. Therefore, the antennas must have wide bandwidths to ensure high speed and gain to allow short and long-range communications because of these applications related to new technologies. In addition, the millimeter band offers a very large frequency bandwidth [3-4].

During the last decade, the 60 GHz frequency band has found great interest in supporting very high-speed transmissions, depending mainly on the unparalleled bandwidth available as the ISM band, the low power radiation which allows the use of the frequency in a short or concise range propagation which makes the communication system more secure [5]. Indeed, the 60 GHz frequency band has a distance path attenuation between the transmitter and receiver a thousand times (30 dB) more significantly than the same attenuation undergone by a 2 GHz signal in free space. It is intended to support wireless network applications requiring very high data transfer rates. For example, this band supports exchanging large files, streaming High Definition videos, etc. In wireless local area networks (WLAN), wireless personal area networks (WP AN), and also point-to-point links [6-7].

The bandwidth of the patch antennas is very narrow and does not exceed 10 %, which is why coverage of unlicensed 60 GHz areas is difficult. In this case, some researchers have proposed a technique to improve this bandwidth, such as a patch with a *U*-shaped slot [8-9], an E-shaped patch antenna [10-11], a patch antenna with an L-shaped probe [12], adding parasitic patches [13] and a horn antenna structure [14]. The bandwidth improvement of the U-shaped patch antenna reaches 15 % due to the added slot. An improvement in impedance bandwidth is achieved with the *E*-shaped patch, 21.7 %. This increase is due to the presence of the *E*-shaped notch. In the case of the horn antenna, it can improve the bandwidth, but it requires additional costs due to its complex structure.

Indeed, within the communication industry, the

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largest compartment is the antennas, which creates a constraint related to their dimensions that prevents their integration into 5G electronic devices. We propose a method to reduce the antenna dimensions using slots, which solves this problem. This study presents a microstrip patch antenna design with a *T*-shaped slot connected to the stub. These slots are arranged in the middle of the patch. The dimensions occupied by this antenna are 2 mm × 1.6 mm × 0.16 mm. It also performs well for a resonant frequency of 60 GHz for 5G wireless communication technology.

This paper is structured as follows: we start with an introduction, in a second step we present the design process of a patch antenna as well as the proposed structure, then we do the electromagnetic simulation, then the simulation results and discussions, and finally we end with the conclusion.

2. PROCEDURE FOR THE DESIGN OF A PATCH ANTENNA AND THE PROPOSED STRUCTURE

2.1 Parameters Characterizing the Printed Antenna

Deschamps [15] proposed the concept of printed antennas as early as 1953 but it was not possible to realize them efficiently until 1970 (Howel and Muson) thanks to the availability of low-loss dielectrics. Since then, research in this field has been intensified to exploit the many advantages of printed antennas: low weight, low volume, and thickness, low manufacturing cost, compatibility with integrated circuits (active antennas), and antenna array. Unfortunately, these antennas also have disadvantages: narrow bandwidth, and low gain.

A rectangular patch antenna is characterized by: its electromagnetic characteristics: gain, radiation pattern, beam width, and polarization. its operating parameters: resonant frequency f_r, input resistance R_{in} and bandwidth B. Its internal parameters: quality factor Q, radiation resistance R_r, efficiency η as well as metal and dielectric losses measured by Q_c, Q_d.

For the design of a patch antenna, we start by choosing its substrate and conductor whose characteristics are to be known: for the substrate: ε_r its relative permittivity, tan ∂ its loss tangent and its height h, and for the conductor: its conductivity σ and its thickness t. Then, for the design, it is necessary to determine: the length and width of the patch (L and W), the position as well as the type of power supply (coaxial, microstrip, slot).

In this paper, we use the microstrip line feed. Indeed, in this study, we will provide the following specifications: the substrate type Roger RT duroid 5880 which has a relative permittivity equal to 2.2, a height of $h = 0.16$ mm, and a loss tangent of 0.0009. The microstrip line feed. The polarization is horizontal and the resonant frequency is 60 GHz. To determine the dimensions of the antenna, the following formulas are used [16]:

$$Es \le \frac{0.3c}{2\pi f_{res}\sqrt{\varepsilon_r}} \quad (1)$$

$$W_p = \frac{c}{2f_{res}}\sqrt{\frac{2}{\varepsilon_r+1}} = \frac{\lambda}{2}\sqrt{\frac{2}{\varepsilon_r+1}} \quad (2)$$

$$\varepsilon_{eff} = \frac{\varepsilon_r+1}{2} + \frac{\varepsilon_r+1}{2}\left(1+12\frac{E_s}{W_p}\right)^{\frac{-1}{2}} \quad (3)$$

$$L_{eff} = \frac{c}{2f_{res}}\varepsilon_{eff}^{-\frac{1}{2}} \quad (4)$$

$$\Delta L = 0.412\frac{\left(\varepsilon_{eff}+0.3\right)\left(\frac{W_p}{E_s}+0.264\right)}{\left(\varepsilon_{eff}-0.258\right)\left(\frac{W_p}{E_s}+0.8\right)} \quad (5)$$

$$L_p = L_{eff} - 2\Delta L_p = \frac{c}{2f\sqrt{\varepsilon_{eff}}} - 2\Delta L_p \quad (6)$$

$$W_g = W_p + 6E_s \text{ and } L_g = L_p + 6E_S \quad (7)$$

$$W_{fed} = \frac{2h}{\pi}\Big[B-1-\ln(2B-1)+ + \frac{\varepsilon_r-1}{2\varepsilon_r}\left(\ln(B-1)+0.39-\frac{0.61}{\varepsilon_r}\right)\Big] \quad (8)$$

$$B = \frac{Z_C}{60}\left(\frac{\varepsilon_r+1}{2}\right)^{0.5} + \frac{\varepsilon_r-1}{\varepsilon_r+1}\left(0.23+\frac{0.11}{\varepsilon_r}\right) \quad (9)$$

$$L_{fed} = 3E_s \text{ And } Z_C = 50\Omega \quad (10)$$

$$\left|S_{11}\right|^2 = \frac{\left|Z_e-Z_c\right|^2}{\left|Z_e+Z_c\right|^2} \quad (11)$$

$$Q = \frac{SE}{PR} \quad (12)$$

E_s is the diameter of the substrate on which an antenna is etched, C represents the speed of light in vacuum, its value is $C = 3 \times 10^8$ m/s, f_{res} denotes the operating frequency, its value is $f_{res} = 28$ GHz, ε_r indicates a dielectric coefficient, W_P corresponds to the width of the patch as well as L_p represents the length of the patch, εeff signifies the effective dielectric coefficient, ΔL_p allows the extension of the patch length, L_g signifies the length of the ground plane, W_g presents the width of the ground plane, W_{fed} generally gives the width of the supply conductor, L_{fed} corresponds to the length of the supply conductor, as well as S_{11} signifies the reverberation coefficient. SE: stored energy, PR: radiated power. We therefore summarize the design approach of a rectangular shaped patch antenna, as shown in Fig. 1. During this work, the substrate used for our study is Rogers RT duroid 5870 with a relative permittivity $\varepsilon_r = 2.2$, a height $h = 0.16$ mm, and a resonant frequency $f_{res} = 60$ GHz. Finally, Table 1 shows the values of the different parameters of this proposed antenna.

The parameter S_{11} of a rectangular antenna is shown in Fig. 4. It is then possible to deduce: The resonant frequency f_r: frequency for which the input impedance is purely real. The input resistance R_{in}: input resistance of the antenna for $f_r = f$. Two other parameters can be deduced from the observation of S_{11}. These are the quality coefficient Q and the bandwidth of antenna B.

The determination of the quality coefficient provides information on the ability of the antenna to radiate the power supplied by the source without the need to measure the antenna patterns in an anechoic chamber. The antenna's efficiency is determined by comparing the ideal value of the quality coefficient Qr calculated without losses and the measured value. The quality coefficient of a real antenna is given by the formula (12).

The reflection coefficient S_{11} highlights the energy absorption by the antenna. This parameter is used as the basis for the optimization.

The SWR is the mathematical expression of the non-uniformity of an electromagnetic field in a transmission line. The SWR is the ratio between a transmission line's maximum and minimum electric fields. From the SWR, we can define the VSWR and ISWR, which refer respectively to the voltage and current. Ideally, we look for an SWR of 1. Therefore, this ratio is another way of characterizing the amount of signal reflected at the terminals of a microwave component.

The antenna's input impedance is seen from the feed line at the antenna. The formula gives this impedance:

$$Z_{in} = Z_0 \frac{1+S_{11}}{1-S_{11}} \tag{13}$$

With Z_0 characteristic impedance of the supply line. Since S_{11} is a function of frequency, then Z_{in} also varies with frequency.

The radiation pattern of an antenna shows the variations of the radiated power per unit solid angle in different directions in space. Apart from the case of omnidirectional antennas in certain planes, antennas do not radiate their power uniformly in all directions in space. There is usually a maximum radiation direction around which much of the radiated power is concentrated and secondary directions around which the remaining fraction of the power is distributed.

The directivity of an antenna in a direction (θ, φ) is the ratio of the power radiated in a given direction (θ, φ) to the power that would be radiated by an isotropic antenna.

$$D(\theta,\varphi) = 4\pi \frac{P(\theta,\varphi)}{P_r} \tag{14}$$

The efficiency of the antenna is the ratio of the radiated power to the power supplied to the antenna. This ratiocharacterizes the losses inside the antenna $\eta = P_r/P_f$.

The gain is the result of two effects: directivity and losses. If G is the gain, then: $G = \eta D(\theta,\varphi)$

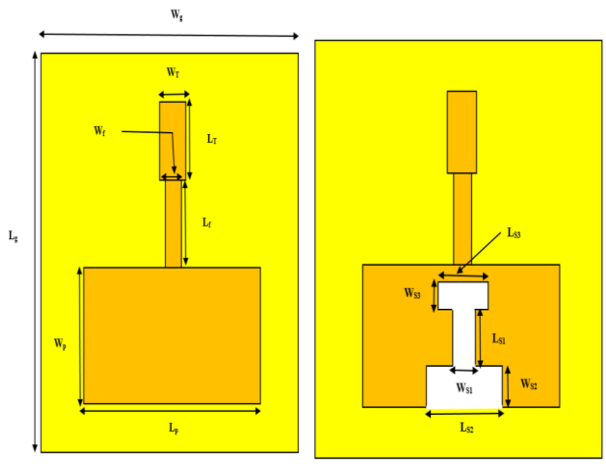
2.2 Electromagnetic Simulation

HFSS software is the standard for the full-wave 3D simulation of electromagnetic fields. Its unmatched accuracy, advanced solvers, and high-performance computing technologies make it an indispensable tool for high-frequency, high-throughput component design. The software offers several solving techniques (based on finite element method, integral equations, or advanced hybrid methods) to solve a wide range of microwave, radio frequency, or broadband applications. In addition, ANSYS HFSS solvers use an automated meshing process where you enter the geometry, material properties, and desired result. From there, ANSYS HFSS automatically generates an accurate mesh suitable for solving the problem with the chosen technology. With ANSYS HFSS, the physics defines the mesh, not the other way around [17].

The bloc diagram of the antenna is summarized in the following diagram (Fig. 1):

Fig. 1 – Operating characteristics of the printed antenna

The input parameters are the printed antenna's geometrical dimensions and the feed's position. The observed data are the resonant frequency, the input resistance, and the quality coefficient. Assuming that the system is linear (slight variation around the rest point), the superposition theorem allows us to study the impact of the different parameters. Fig. 2(a) shows a non-optimized antenna structure; on the other hand, in Fig. 2(b), the same structure is optimized.



(a) (b)

Fig. 2 – (a) proposed antenna without optimization, (b) optimized antenna geometry

Table 1 – The parameters of the proposed antenna

Parameters	Values (mm)
(L_g-W_g)	(5.8-4)
h	0.16
(W_p-L_p)	(1.6-2)
(W_T-L_T)	(0.62-1.52)
(W_f-L_f)	(0.1-1.74)
(W_{s1}-L_{s1})	(0.4-0.9)
(W_{s2}-L_{s2})	(0.2-0.9)
(W_{s3}-L_{s3})	(0.15-0.4)

3. SIMULATION RESULTS AND DISCUSSION

Simulations performed on an unoptimized antenna provide the following results: The reflection coefficient $S_{11} = -30.71$ dB at the resonant frequency of 57.19 GHz, thus VSWR = 1.06, as shown in Figs. 3 and 4. The diagram in Fig. 5 shows the 3D and 2D gain graph, which has a value of 8.6 dB.

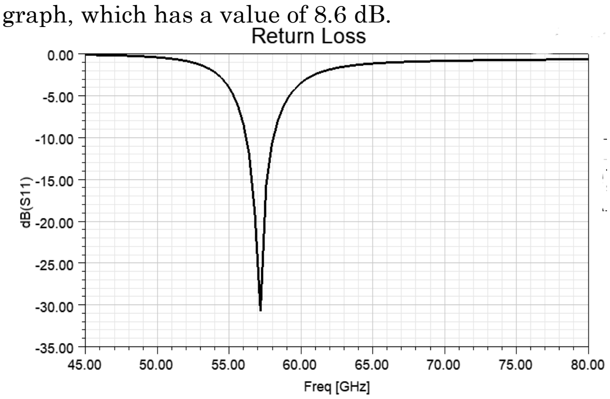


Fig. 3 – The S_{11} curve of the proposed new non-optimized antenna

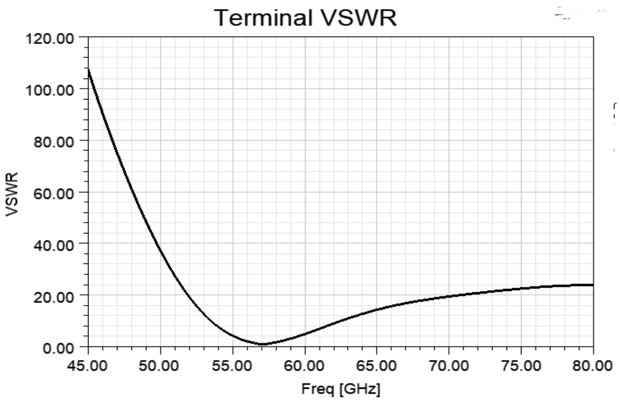


Fig. 4 – The VSWR curve of the proposed new non-optimized antenna

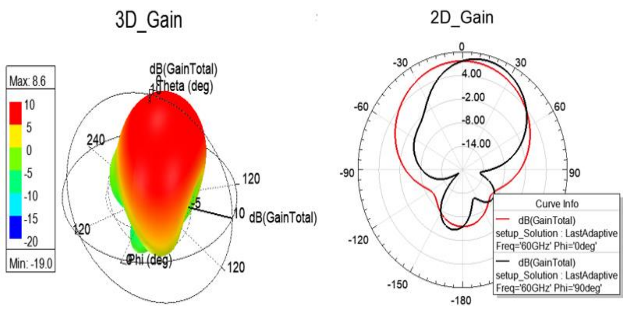


Fig. 5 – (a) The 3D and (b) 2D gain pattern of the unoptimized antenna proposal

The simulation results obtained from the suggested antenna after optimization offer good results, including $S_{11} = -36.41$ dB reflection coefficient and VSWR = 1.03 with BP = 2.15 GHz bandwidth, as shown in Figs. 6 and 7. The diagram in Fig. 8 shows the 3D and 2D gain graph, which has a value of 9.2 dB. And The diagram in Fig. 8 shows the 3D and 2D directivity graph, which has a value of 9.23 dB.

Table 2 clearly and straightforwardly details the result of simulations carried out by existential research work in specialized journals and our work, whose operating frequency is 60 GHz in applications related to 5G technology. These works have met the requirements of 5G telecommunications technologies. The reference paper [23] provides a very wide bandwidth compared to the other works. Thus, it provides a better gain than all the research except [24] and our proposed one. Moreover, the efficiency of [23] is higher than that of [24], but our proposed one is higher, as shown in Table 2.

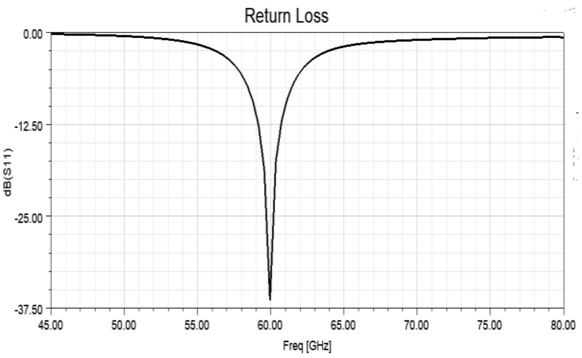


Fig. 6 – The S_{11} curve of the proposed new optimized antenna

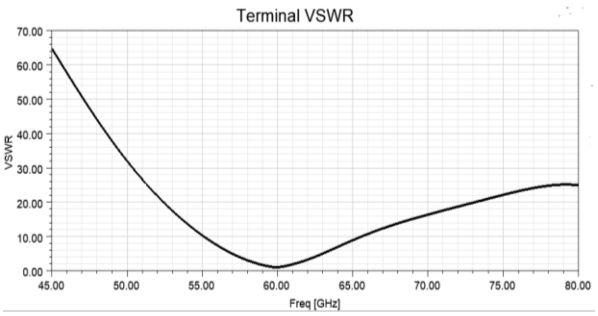
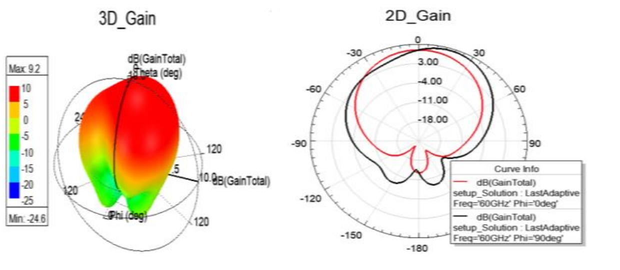
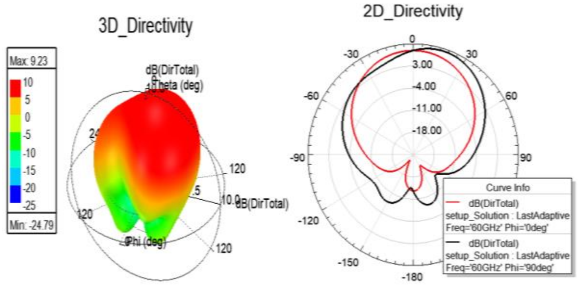


Fig. 7 – The VSWR curve of the proposed new optimized antenna



(a) (b)

Fig. 8 – (a) The 3D and (b) 2D gain pattern of the optimized antenna proposal



(a) (b)

Fig. 9 – (a) The optimized antenna proposal's 3D and (b) 2D directivity pattern

The cited paper [19] represents an antenna with a wider bandwidth than all other publications, as well as another advantage: it is a tiny size, as illustrated in Table 2. On the other hand, the antenna [24] has a very high gain compared to others and a wider bandwidth than the others, except for [19], [23], but it has a disadvantage due to its larger size. The proposed antenna gives better results in terms of gain, efficiency, bandwidth, S11, and size, as shown in Table 2.

Table 2 – Comparative analysis of the results of this antenna to the existing results

Antennas	Area (mm2)	S11 (dB)	center frequency (GHz)	Bandwidth (GHz)	VSWR	Gain (dB)	Radiation efficiency (%)
[18]	1.97×1.63	-12	59.85	1.05	1.67	7.15	-
[19]	1.117×0.68	-20	-	5	1.22	6.01	-
[20]	3.51×2.9	−28.36	-	-	1.07	6.61	-
[21]	3:43×3:83	-25	-	0.643	1.11	6.75	-
[22]	2×1.66	-29.6	59.74	2.62	1.07	5.17	-
[23]	2×1.66	-24	60.06	12.11	1.5	8.61	82.15
[24]	5×9	-32.66	59.5	4.26	1.05	9.73	77.01
Proposed antenna	2×1.6	-36.41	59.95	2.15	1.03	9.2	99.67

4. CONCLUSION

In this paper, we studied the design of a compact 5G millimeter band microstrip patch antenna for the 60 GHz frequency band. Before optimizing this proposed antenna, the results are: Resonant frequency $f_r = 57.19$ GHz, $S_{11} = -30.71$ dB, VSWR = 1.06, and gain $G = 8.6$ dB. We have optimized this antenna to improve these results by cutting an *H*-shaped part of the patch (radiating element). These results also indicate a good performance of the proposed antenna, as the values of S_{11}, gain, directivity, and bandwidth are in a reasonable range. Therefore, this antenna would be a good candidate for 5G wireless applications. We are also interested in the operation of this device in future work on antenna arrays.

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Дослідження та проектування патч-антени 5G міліметрового діапазону з резонансною частотою 60 ГГц

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У даній роботі пропонується дослідження та дизайн патч-антени міліметрового діапазону для 5G з резонансною частотою 60 ГГц. Була запропонувана методика покращення продуктивності цієї антени. У конструкції була використана підкладка типу Roger RT duroid 5880 з відносною діелектричною проникністю, що дорівнює 2,2, висотою 0,16 мм і тангенсом втрат 0,0009. Формат випромінюваного елемента (патча) наступний: довжина - 2 мм, ширина - 1,6 мм. Використовувалось програмне забезпечення моделювання високочастотної структури (HFSS), щоб отримати параметри антени. Моделювання дало хороші результати: робоча частота 59,95 ГГц, коефіцієнт відбиття (S11) – 36,41 дБ, смуга пропускання 2,15 ГГц, підсилення 9,2 дБ, потужність випромінювання 10,01 дБм і ефективність 99,67 % . Отримані результати є конкурентоспроможними та відповідають вимогам пристроїв 5-го покоління. Таким чином, цілком імовірно, що запропонована антена зможе задовольнити вимоги, пов'язані з потребами 5G.

Ключові слова: 5G, 60 GHz, HFSS, Мікросмугова антена, Міліметрові хвилі.