Enhanced Performance of a 2.4 GHz Microstrip Patch Antenna for WLAN, 4G and 5G Networks using HFSS

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Abstract: - This paper describes the performance development of a rectangular microstrip patch antenna specifically designed for use in wireless local area networks (WLAN), 4G and 5G. the antenna operates at a resonant frequency of 2.4 GHz, this structure was chosen for its efficient ability to accommodate the target frequency band, thus making it as a very suitable option for WLAN systems, as well as operation at 2,4 GHz ensures compliance with the IEEE 802.11 standard, ensuring full compliance with established WLAN requirements. The physical prototype was designed using HFSS software on an FR-4 substrate with a relative permittivity of 4.4 and a thickness of 1.6 mm, resulting in final dimensions of 60 mm 60 mm 1,6 mm. The simulation results obtained confirmed the performance of our antenna at the resonant frequency of 2.4011 GHz, a reflection coefficient (S11) of -49.47 dB, and a bandwidth of 64.7 MHz. The design also achieved a gain of 3.14 dB, a directivity of 6,31 dB, and an electric field radiation (rE) of 20.92 dB. The proposed antenna successfully meets performance criteria for fourth generation (4G) networks, highlighting its applicability in contemporary wireless communication environments.

Key-Words: - Antenna Design, Microstrip Patch Antenna (MSPA), 2.4 GHz Patch Antenna, 2.4 GHz Frequency, Gain (dB), Voltage Standing Wave Ratio (VSWR), IEEE 802.11 Standards, WLAN Applications, Wireless Communication, HFSS 2024R2 Simulation.

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1 Introduction

In the early 1950s, the idea of creating microstrip antennas (MSAs) first emerged. But with the advancement of printed circuit board (PCB) technology in 1970s, great interest and widespread use of this class of antennas was attracted. Since then, MSAs have gained fame thanks to their outstanding features. Including being lightweight, low-level, cost-effective, and having a flat structure, [1]. This has given these features a special character by applying them across a wide range of fields such as RFID systems, broadcasting, mobile communications, GPS, satellite links, television, MIMO technology, vehicle collision avoidance, surveillance, direction finding, radar, remote sensing, and missile guidance systems, among others, [2].

Central microstrip patch antennas are expected to remain at the height of future technological progress, due to their distinct and useful characteristics. Its compact and lightweight shape, fast and simple manufacturing process, and ability to adapt to diverse mounting structures make it highly flexible and suitable for many integration scenarios, [2], [3]. These qualities ensure that microstrip antennas will remain indispensable in the development of current and next-generation wireless communication systems.

In our current digital age, technological advancements like 3G, 4G, and modern 5G networks are changing communication, with wireless communications becoming more important and promising, [4]. The rapid adoption of these technologies has increased the demand for devices that can support them, [5], [6], but legacy systems have proven insufficient despite evolving technical standards and user requirements, which has led to the development of more advanced and efficient solutions. Wireless local area network (WLAN) systems are among the most widely used applications, and they have grown significantly, [7], [8]. Because antennas are central to these systems and play a crucial role in data transmission, a lot of research has been done on designing antennas that meet performance requirements and with the demand for WLAN systems increasing dramatically, great importance is given to the development and improvement of wireless and mobile communications networks. Many legacy systems have had difficulty keeping up with this development, leading to thinking about creating more compact and efficient solutions, [9], [10]. Thanks to the proposal of many different WLAN antenna designs, these requirements have been met, with an emphasis on features such as low profile, low weight and individual feed configurations that are compatible with modern technological trends, [11]. As a result, relying on miniaturizing WLAN devices has become effective and necessary. To overcome these challenges, ongoing efforts by researchers aim to improve antenna performance, improve development processes, and enhance overall efficiency, [12]. This has resulted in the active design of high-performance antennas capable of meeting the needs of modern wireless communications technologies, [13].

Although cost-effective and easy to manufacture, an efficient antenna must also meet practical performance requirements. In this regard, new technologies and solutions have emerged related to changing the design as well as reducing the size of the microstrip antenna as a leading solution to meet modern needs within specific frequency bands, which in this study comply with IEEE 802.11 standards, [14]. These standards establish the protocols governing wireless local area networks (WLANs). Over the past decades, microstrip antennas have become widely used due to their practical advantages, ease of manufacture, light weight, and adaptability to various mounting surfaces, which serve as the backbone of contemporary wireless systems. Despite their many advantages, microchip antennas still face limitations, most notably narrow bandwidth. However, extensive research has been conducted to mitigate these disadvantages, [15].

One of the main limitations of microstrip antennas is limited bandwidth. To solve this problem, the researchers focused on modifying some techniques such as feeding and improving the antenna geometry and design, as well as modifying and adjusting the antenna dimensions while incorporating holes in the surface of the microstrip, with the aim of improving the performance and efficiency of this type of antenna, [16]. These changes are primarily aimed at improving important criteria such as loss of return and gains. The better the antenna design and geometry, the better the overall understanding of its critical parameters, and the final geometry often results from modifications across multiple design variables. Therefore, a large part of the work in wireless communications research is devoted to small-scale studies that enhance performance and efficiency, [17]. This research often uses iterative, trial-and-error approaches to optimize designs until desired performance is achieved.

This research is organized in four parts as follows: First, we present a general applied introduction. Subsequently, we discuss in section 2 the process related to the design of this proposed antenna and in section 3, we simulate it in HFSS simulation tools. A thorough and detailed analysis will be carried out of all the simulation results obtained and the correlation between the different results that this proposed antenna gives compared to those available now. Finally, the last section concludes this research.

2 Design & Methodology

Based on calculating the length and width of the microstrip antenna, its patch is designed in this study. These dimensions are determined by established methodologies for microchip line feeding, [18], [19], axial feeding [20], and standard configurations targeting a resonant frequency of 2.4 GHz [21]. The first crucial step depends mainly on choosing the right substrate of the right height (h). To achieve this goal, an FR-4 substrate is used, with an insulation constant of 4.4, a loss shadow of 0.02, and a thickness of 1.6 mm. Next, the correction and feed line dimensions are carefully determined, with the feed line precisely positioned for optimal performance at the operating frequency of 2.4 GHz.

Several structural changes were made to the design to improve the antenna's performance. The basic parameters - such as substrate dimensions (L_{sub}, W_{sub}), part dimensions (L_A, W_A), feed line dimensions (L_{fed}, W_{fed}) and feed position (y0 = 9 mm) - were carefully determined and kept constant as in [18]. In addition, we will vary the parameter (g), ranging from 0.4 mm to 1.7 mm with a pitch of 0.1 mm, was introduced to adjust the design. These modifications aim to improve the radiation performance of the antenna and ensure that it meets the required practical and scientific specifications. Calculations of the antenna parameter values are based on the formulas provided in [19].

The width of the patch antenna is calculated using the following formula:

$$W_A = \frac{C}{2f_0\sqrt{(\epsilon_r + \frac{1}{2})}} \tag{1}$$

where: $C = 3 \times 10^8 m/s$ and $f_0 = 2.4GHz$

The effective length of the patch antenna is determined by the resonant frequency (f_0).

$$L_{eff} = \frac{C}{2f_0\sqrt{\varepsilon_{reff}}} \tag{2}$$

where:

$$\epsilon_{reff} = \frac{\epsilon_r + 1}{2} + \frac{\epsilon_r - 1}{2}[1 + 12\frac{h}{W_A}]^{-\frac{1}{2}} \tag{3}$$

$$L_A = L_{eff} - 2\Delta L \tag{4}$$

where ΔL depends on the effective dielectric constant ϵ_{reff} and the width to height ratio ($\frac{W_A}{h}$).

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

The input impedance is highest at the edge of the patch antenna. It decreases rapidly if the inset feed is positioned too far from the edge towards the center. To ensure impedance matching with a 50Ω connector, a curve-fit expression for the inset feed depth y_0 is provided as follows:

$$y_0 = 10^{-4}\{0.016922\epsilon_r^7 + 0.13762\epsilon_r^6 - 6.1783\epsilon_r^5 + 93.187 - 682.69\epsilon_r^3 + 2561.9\epsilon_r^2 - 4043 + 6697\}\frac{L_A}{2} \tag{6}$$

To achieve a 50Ω characteristic impedance, the required feed width-to-height ratio ($\frac{W_f}{h}$) is calculated as follows:

$$\frac{W_f}{h} = \begin{cases} \frac{8e^A}{e^{2A} - 2h}\frac{W_0}{h} \\ \frac{2}{\pi}\{B - 1 - \ln(2B - 1) + \\ \frac{\epsilon_r - 1}{2\epsilon_r}\left[\ln(B - 1) + 0.39 - \frac{0.61}{\epsilon_r}\right]\}\frac{W_0}{h} \geq 2 \end{cases} \tag{7}$$

where:

$$A = \frac{Z_0}{60}\sqrt{\frac{\epsilon_r + 1}{2}\frac{\epsilon_r + 1}{\epsilon_r - 1}(0.23 + \frac{0.11}{\epsilon_r})} \tag{8}$$

$$B = \frac{277\pi}{2Z_0\sqrt{\epsilon_4}} \tag{9}$$

The resonant frequency of a patch antenna is influenced by the notch gap (g). The relationship between the notch gap and the resonant frequency is given by the following expression:

$$g = \frac{v_0}{\sqrt{2 \times \epsilon_{reff}}}\frac{4.65 \times 10^{-12}}{f_0(in\ GHz)} \tag{10}$$

At this stage, a numerical model of the desired antenna has been optimized. The calculations above provided the antenna dimensions outlined in Table 1, which were validated against the results in [19].

Table 1. The antenna dimensions

Parameters	This Work Values (mm)	[18] Values (mm)	[19] Values (mm)	[20] Values (mm)
Frequency	2.4GHz	2.4GHz	2.4GHz	2.4GHz
dielectric substrate ϵ_r	4.4 (FR-4)	4.4 (FR-4)	4.4 (FR-4)	4.5 (Rogers TMM4)
$W_g = L_{sub}$	60	60	31.14	37.89
$W_g = W_{sub}$	60	60	37.26	47.22
h	1.6	1.6	1.6	1.59
L_A	29.4	29.4	28	28.35
W_A	35	35	37.26	37.68
L_{fed}	26	26	15	-
W_{fed}	3	3	2.98	-
$y0$	9	9	-	-
g	1.2	1	-	-

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Figure 1 shows the computed antenna design that was developed. It utilizes this data to optimize antenna realizing both bandwidth and dimension reduction, [22].

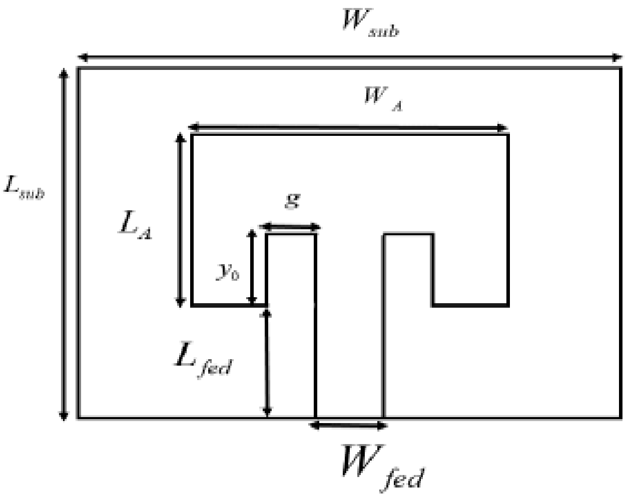
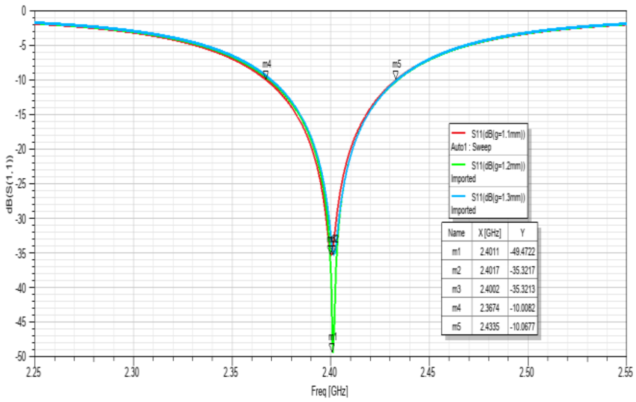
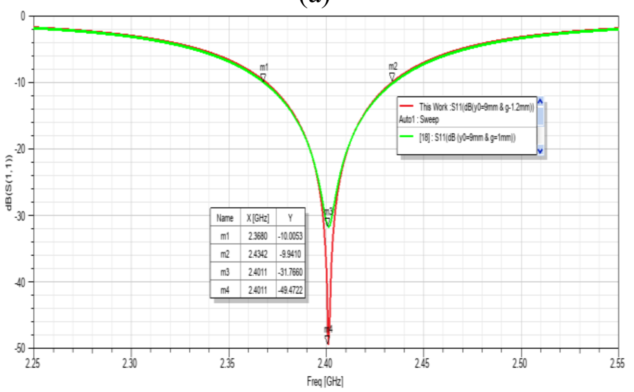


Fig. 1: Shape of the antenna considered in this study
Source : [22]



(a)



(b)

Fig. 2: (a) The 3 best S11 return loss curve of the proposed antenna. (b) comparison with [18]
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3 Results and Discussion

In Figure 2, the return loss of the proposed antenna configuration is simulated and displayed. This return loss quantifies the power reflected back to the antenna port because of the impedance mismatch with the feed line. S(1,1), measured in decibels (dB), is said to be lower than -10dB, which indicates a value for PRE/PIN where PRE is the power at the port input and PIN is power incident upon the port, also termed input port [21]. In addition, it indicates that if the S(1,1) parameter is below -10dB, it implies that 90% of the excitation power is passed through.

$$S_{1,1} = 20\log\left(\frac{PRE}{PIN}\right)(dB) \qquad (11)$$

Simulations of the antenna were carried out using HFSS. A key parameter of the proposed antenna is the reflection coefficient S(1,1), which is shown in Figure 2. This parameter is essential for calculating the bandwidth and the level of impedance matching.

We remind you that we varied the ***g*** parameters from [0.4mm; 1.7mm] with a 0.5mm step until we found a better result with ***g***=1.2mm.

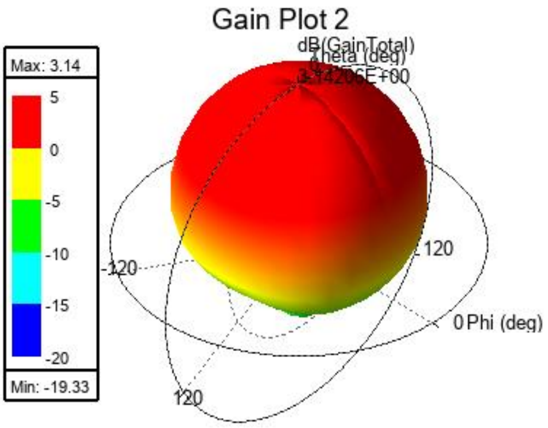
Figure 2-(a), compares three optimized simulations corresponding to different values of the parameter g (1.1 mm, 1.2mm and 1.3 mm). The three curves show a similar behavior around 2.4 GHz. The best performance is obtained for g=1.2mm with a minimum S(1,1) of -49.4722 dB at 2.4011 GHz, closely followed by the other variants with minimums of -35.3217 dB and -35.3213 dB with a bandwidth of 66.1MHz (2.4335GHz - 2.3674GHz) respectively. This indicates that the optimization of the g parameter has a noticeable effect on antenna fit and depth of S(1,1). All models cover a satisfactory bandwidth for WLAN as well as 4G and 5G applications. The slight offset and variation of the depth of the S11 cavity demonstrate the sensitivity of the design to minimal physical variations, justifying the importance of fine optimization.

Figure 2-(b) shows a comparison of the simulated S(1,1) parameter of the proposed antenna with reference results [18]. The latter [18] operates at a frequency of approximately 2.4 GHz with a minimum S11 of -31.766 dB to 2.4011 GHz when y0 = 9 mm and g = 1 mm. While the proposed antenna operates with a minimal S11 of -49.4722 dB, the 2.4011 GHz has a bandwidth of 66.1 MHz (2.4342GHz – 2.3680GHz) when y0 = 9 mm and g = 1.2 mm, as indicated by the m1 and m2 panels. The simulation shows a good correspondence with

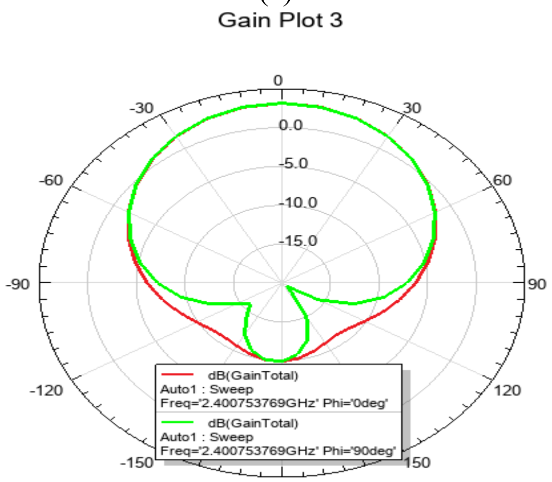
reference [18], with a significant improvement in the depth of reflection coefficient S(1,1), indicating better impedance matching and increased efficiency. This performance effectively covers WLAN wireless communication bands, as well as some 4G and 5G frequencies, proving the importance of optimization.

Another essential property for evaluating antenna performance is the radiation pattern. Through it, we can describe how the radiated energy changes spatially, highlighting the values of the specific angles (θ0, φ0) where the emission reaches its peak. It is important to note that the radiation pattern is only meaningful when the emitted wavefront is spherical. The three-dimensional and two-dimensional representations of the proposed antenna's radiation behavior are illustrated in Figure 3.

Figure 3, Figure 4 and Figure 5 present the curves of gain, directivity, and electric field radiation (rE) obtained for the proposed antenna designs using the HFSS simulation tool. At the resonant frequency of 2.4 GHz, the antenna exhibits a gain of 3.14 dB, a directivity of 6.31 dB, and an electric field radiation level of 20.92 dB.



(a)



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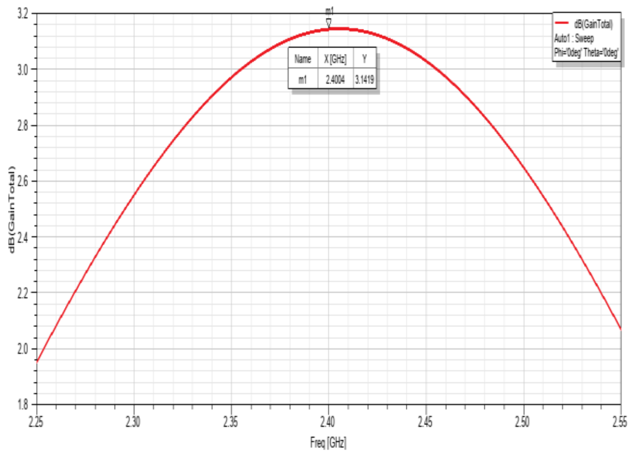

(c)

Fig. 3: (a) 3D Total Gain (dB), (b) 2D Radiation Parttner (dB), (c) Gain vs Freq (dB).
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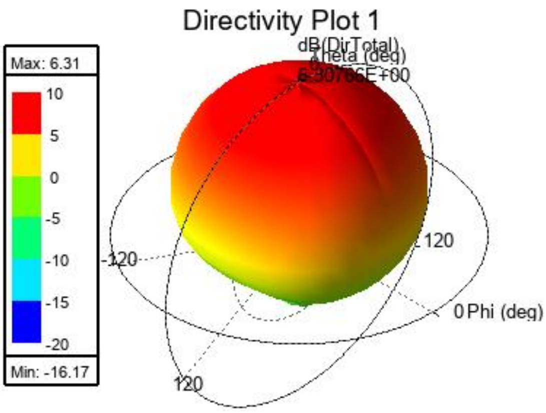
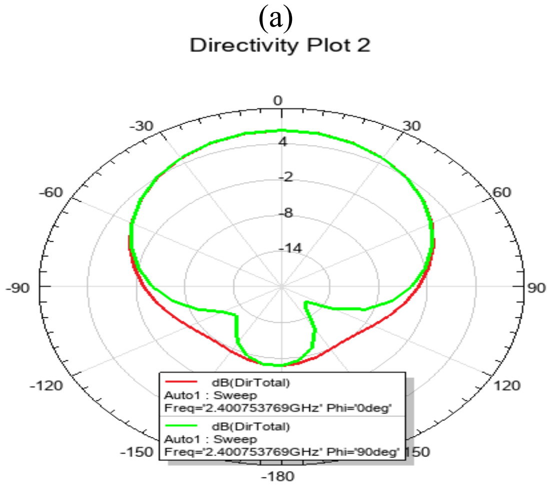


(a)



(b)

Fig. 4: (a) 3D Directivity Total(dB) , (b) 2D Radiation Parttner(dB).
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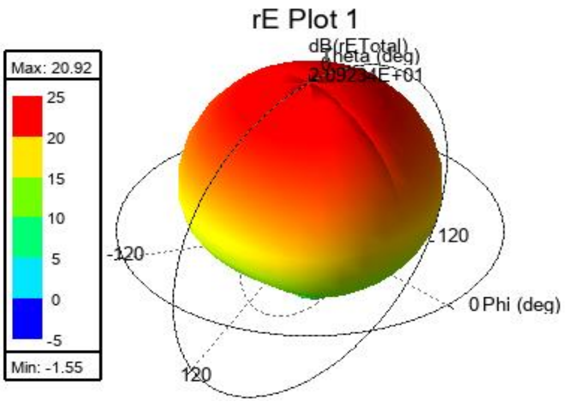
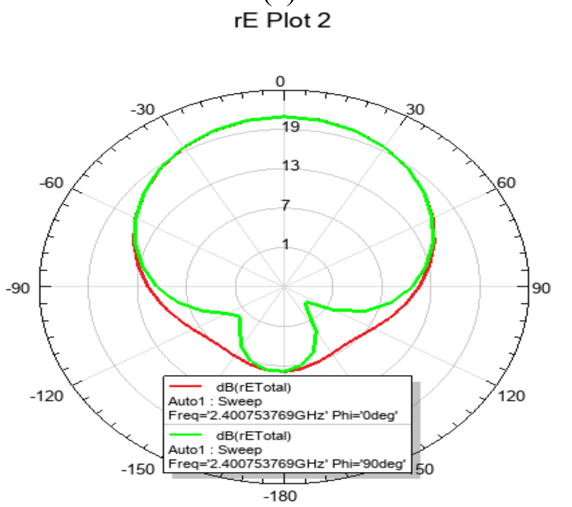


(a)



(b)

Fig. 5: (a) 3D Electric Field Radiation (rE), (b) 2D Radiation Parttner (dB).

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Table 2 provides a summary of all simulation results for this antenna, with a comparison to the same type of antenna [18], including gain, directivity, bandwidth, parameter S(1,1), and electric field radiation.

Table 2. Simulation Results & Comparison of the Proposed Antenna

Parameters	Antenna Design Results	[18]
Return Loss (dB)	-31.766	-49.4722
Gain (dB)	3.13	3.14
Directivity (dB)	6.29	6.31
VSWR (dB)	0.5341	-
Bandwidth (MHz)	67	66.1
Electric Field Radiation	20.21	20.92

Source : Created by the authors

Table 3 provides a summary comparison with [18] [19] and [20] of the critical characteristics of the above research studies. The performance of the proposed antenna, such as the reflection coefficient, gain, directivity and bandwidth, S(1,1) and Electric Field Radiation.

Table 3. Comparison Results Between the Proposed Antenna and Existing Design

References	$S_{1,1}(dB)$	Gain (dB)	VSWR	Directivity (dB)	Bandwidth (MHz)	Electric Field Radiation (dB)
[18]	-31.766	3.13	0.5341	6.29	67	20.21
[19]	-29.6925	2.14	1.2	-	-	-
[20]	-27.5	4.96	0.7421	-	-	-
This Work	**-49.4722**	**3.14**	**-**	**6.31**	**66.1**	**20.92**

Source : Created by the authors

4 Conclusion

The proposed antenna achieves a return loss of -49.4722 dB at the target frequency of 2.4 GHz. Its design and simulation were carried out using the HFSS software package. Through the application of the microstrip line feeding technique, the antenna obtained a bandwidth of 66.1 MHz, a gain of 3.14 dB, a directivity of 6.31 dB, and an electric field radiation intensity of 20.92. The configuration has been specifically optimized for wireless local area network (WLAN) applications and for 4G and 5G communication. Thanks to its compact shape, ease of manufacturing and the incorporation of a 50-ohm microstrip power line, the proposed design represents an efficient and practical solution for current and future WLAN systems.

In the perspectives, future work will focus on using metaheuristic algorithms and artificial intelligence, which are more efficient for antenna optimization.

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