New microstrip patch antenna array design at 28 GHz millimeter-wave for fifth-generation application

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ABSTRACT

This paper presents a study and an array design consisting of two microstrip patch antennas connected in series in a 2×1 form. This antenna provides better performance for the fifth-generation (5G) wireless communication system. The microstrip line feeding technique realizes the design of this antenna. This feed offers the best bandwidth, is easy to model, and has low spurious radiation. The distance between the feed line and the patch can adapt to the antenna's impedance. In addition, the antenna array proposed in this paper is designed and simulated using the high frequency structure simulator (HFSS) simulation software at the operating frequency of 28 GHz for the 5G band. The support material used is Rogers RT/duroid® 5880, with relative permittivity of 2.2, a thickness of h=0.5 mm, and a loss tangent of 0.0009. The simulation results obtained in this research paper are as: reflection coefficient: -35.91 dB, standing wave ratio (SWR): 1.032, bandwidth: 1.43 GHz, gain: 9.42 dB, directivity: 9.47 dB, radiated power: 29.94 dBm, accepted the power: 29.99 dBm, radiation efficiency: 29.95, efficiency: 99.83%. This proposed antenna array has achieved better performance than other antenna arrays recently published in scientific journals regarding bandwidth, beam gain, reflection coefficient, SWR, radiated power, accepted power, and efficiency. Therefore, this antenna array will likely become an important competitor for many uses within the 5G wireless applications.

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1. INTRODUCTION

Today, the growing demands and uses of wireless communication devices in various fields, such as medicine, defense, or aeronautics, drive manufacturers to continuously develop new wireless communication systems. In this perspective and during the last years, the technologies have evolved significantly in microwave circuits [1], [2]. The antenna occupies a larger space in the communication chain, which implies a more significant footprint that complicates its installation in small spaces. Microstrip antennas and patch antennas are essential elements for modern fifth-generation (5G) wireless communications due to several characteristics such as small size, low cost, and easy mounting on integrated electronic circuits, satellites, vehicles, and airplanes, inside and outside the human body. On the other hand, they have performance drawbacks such as an extended bandwidth, the collection power as well as the gain are relatively small, which limits their use in certain situations [3]. The 5G wireless communication technology has high frequencies that are strongly influenced by the antenna performance, particularly concerning return loss, gain, and bandwidth. To solve these problems and to meet user demand, it is essential to produce and design antennas with highly satisfactory characteristics concerning the gain, return loss, and bandwidth [4], [5].

The 5G wireless communication technology only allows a maximum data transfer rate of 100 Mbps, but the current requirements are estimated to be more than 10 Gbps. Therefore, it is necessary to have a wireless communication technology capable of meeting these requirements, and this is called the 5G wireless network. The latter provides data transmission capabilities of 10 Gbps, as well as extensive coverage of 1 million components on a single square kilometer with network access of 10 Tbps on a single square kilometer, a very low response time of no more than a millisecond, and many other things [6]. To meet all the requirements presented above and achieve good results with 5G, it is necessary to use the highest frequencies. In this sense as special frequency bands for 5G were defined as the frequency bands in the intervals of 3.4 to 3.6 GHz, 5 to 6 GHz, 24.25 to 27.5 GHz, 37 to 40.5 GHz, and 66 to 76 GHz that were determined by the International Telecommunication Union (ITU), as well as the 27.5 to 28.35 GHz band, which was determined by the Federal Communications Commission (FCC) [7]. Of all these frequency bands, we carefully selected the 28 GHz Band for our research due to its high attractiveness for 5G and its experimental use in several countries.

Antennas for 5G must have good performance, including high bandwidth and directivity, to meet user requirements and needs, including the high data rates of current technology (5G). These antennas also need to have high gain to avoid problems caused by microwaves. Thus living organisms may block the transmission of electromagnetic signals on millimeter waves and the undesirable effects caused by very high operating frequencies [8]. Typically, the 5G wireless technology needs to accommodate antennas that are high performance, low weight, small profile (compact size), low cost, easy to implement on all electronic systems and devices, adaptable to planar and non-planar surfaces, and mechanically sound when mounted on the rigid surfaces. A microstrip patch antenna has become an indispensable component in all 5G wireless communication system devices, which has driven researchers to work on this scientific topic. This research paper is, therefore, highly dependent on this type of antenna. Along with this development, the requirements and needs of the wireless communication network have increased tremendously. Wireless standards have emerged recently to meet these challenges almost every decade after creating the next generation of standards [9], [10].

Much research is associated with the studies and design of millimeter band antennas for 5G, specifically in the 28 GHz frequency band, which offers the best possible performance for the 5G. For this purpose, it is necessary to design new antenna kinds suitable for fifth-generation technologies, which is a challenging task and a significant challenge for antenna design specialists. Therefore they proposed different types of antennas, which are described as: the antenna [11] has a gain of 12 dB in the 28 GHz frequency band, but it does not guarantee perfect impedance matching (-15 dB). Its size is 53×20 mm^2, large enough to be incorporated into the cell phone. Hwang [12] proposed a design of the 4-element Quasi-Yagi array that achieved a maximum gain of 9.98 dBi with a full size of 20×8.4 mm^2. Prabu *et al.* [13] also proposes designing and constructing antenna arrays with eight elements that achieve a gain of 9.89 dB but are unsuitable for 5G technology. In [14], the printed antenna design in the metal housing has a gain of 11.21 dBi for the operating frequency 28 GHz, but this is not sufficient for 5G operation, and the design method is very complicated. Ali and Sebak [15] presented the design of a printed antenna array consisting of four elements with the highest gain of 13.5 dBi. In [16], there is also an antenna array design consisting of 8 elements, which achieved a gain of 9.57 dBi for 28 GHz. This design is very costly. Because of these studies regarding the design of antennas for 5G, it is found that there is still a need to design antennas that offer good performance with sizes that allow them to be integrated into 5G devices such as the cell phone. In this study, we tried to address this problem [17]. Design and optimization of a rectangular dual-band microstrip slot-pi antenna using surface response methodology for 5G applications. This antenna achieves an extended bandwidth in the frequency range between 27.214 and 34.445 GHz and between 34.816 to 38.99 GHz. Awan *et al.* [18] proposed a miniaturized, high gain, frequency-switched linear multiple input, multiple output (MIMO) antenna array with vertical stubs. These sections allow for frequency changes from 28 to 24.8 GHz with gains of 16.02 and 15.07 dB, as well as a bandwidth of 2.1 and 1.9 GHz, respectively. Zahra *et al.* [19] presented the design of a free planar single-hole helical antenna for broadband applications at 28 GHz. This antenna provides a wide impedance bandwidth from 26.25 to 30.14 GHz, gain measured up to 5.83 dB, and radiation efficiency measured up to 85%.

Awan *et al.* [20] proposed an antenna design that relied on a pair of parasitic patches arranged linearly near this classical antenna. It offers a bandwidth of 7.1 GHz, a large radiation pattern, and a gain of more than 10 dB. Hussain *et al.* [21] proposed a compact wideband patch antenna and its MIMO configuration for 28 GHz applications. They added defected ground structure (DGS) to the ground plane for one of the elements of this array to significantly improve the bandwidth. Zahra *et al.* [22] presented a 28 GHz broadband helical inspired end-fire antenna and its MIMO configuration for 5G pattern diversity applications. This antenna initially presents a simple geometry inspired by a conventional planar helix antenna without the use of vias. It offers a bandwidth of 3.89 GHz, a gain of 5.83 dB, as well as a radiation efficiency of 88%. Ashraf *et al*. [23] proposed a flat rectangular microstrip antenna with slots in the radiating elements and the ground plane. It achieves a gain of 8.74 dB and a bandwidth of 2.817 GHz. Indeed, the 5G wireless communication system requires high-performance antennas in terms of gain, directivity, return loss, bandwidth, and efficiency. To meet this need, we propose a patch antenna array design that consists of two patch antennas, one of which has a slot. The role of this slot is to improve performance. This antenna array operates at a resonant frequency of 28 GHz in the fifth-generation millimeter band.

This article divides into several steps: we start with an introduction that focuses on microstrip antennas and the 5G technology. Then we present the design procedure in more detail in section 2. After that, we present the simulation software in section 3, and then we analyze the simulation results in section 4. Finally, we compare these results with previous studies and conclude our research.

2. THE PROPOSED ANTENNA DESIGN

Based on the simplified formulation of the transmission line model described, one can follow the straightforward and practical design procedure for rectangular microstrip antennas. By applying this procedure, we specify the resonant frequency values, the substrate's permittivity to be used, and its thickness. We, therefore, specify εr=2.2, fr=28 GHz, and h=0.5 mm. As a first approach, the patch dimensions are calculated according to the characteristics of the substrate (relative permittivity εr, thickness h) and the resonance frequency. The power supply is made through a microstrip line. We chose Rogers RT/duroid® 5870 (tm) for the type of material because it has a good price/quality ratio, and its permittivity is 2.2, which is perfect. The chosen characteristics are thus: resonance frequency: f=28 GHz, substrate type: epoxy-“Rogers RT/duroid® 5870” of relative permittivity εr=2.2. To adapt to 50 Ω, we used the food source provided by the micro ribbon cable. This microstrip line is widely used for microwave circuit fabrication, mainly because it is well suited for photolithographic fabrication and also because it allows simple integration of passive and active components by surface mounting. The reference equations of [24]–[26] for 28 GHz allowed calculating the maximum substrate thickness, as well as the different antenna elements such as the size of the radiated piece (patch): its width and length, as well as the dimensions of the ground plane, generally, should be 1/4 wavelength from the foot of the antenna. This is true as long as the antenna and the ground plane are orthogonal (perpendicular). The ground plane can be limited to 4 copper strands of the desired length, perpendicular to each other and to the antenna; it is not necessary to have a continuous surface.

$$E_s \leq \frac{0.3c}{2\pi f_{res}\sqrt{\varepsilon_r}} \tag{1}$$

$$W_p = \frac{c}{2f_{res}}\sqrt{\frac{2}{\varepsilon_r+1}} \tag{2}$$

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

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

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

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

$$Wg = Wp + 6Es \text{ and } Lg = Lp + 6ES \tag{7}$$

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

$$B = \frac{Zc}{60}(\frac{\varepsilon_r+1}{2})^{0.5} + \frac{\varepsilon_r-1}{\varepsilon_r+1}(0.23 + \frac{0.11}{\varepsilon_r}) \tag{9}$$

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

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

E_s represents the diameter of the substrate on which an antenna is etched, in other words, the substrate, *C* is also the speed of light in a vacuum, whose value is equal to *c*=3×108 m/s, f_{res} is the operating frequency, whose value is f_{res}=28 GHz, ε_r actually indicates a dielectric coefficient, W_P corresponds to the width of the plate as well as L_p represents the length of the plate, ε_{eff} signifies the effective dielectric coefficient, ΔL_p allows you to know the extension of the length of the plate, L_g actually signifies that the length of the ground plane, W_g presents the width of the ground plane, W_{fed} generally gives the width of the feeder conductor, L_{fed} corresponds to the length of the feeder conductor, as well as S_{11} is denoting the coefficient of reflection.

We apply (1)-(11) to determine the different possible indicators of the metric, which are shown in Table 1, namely the complete format of the studied structure. Figure 1 illustrates the result of the calculations performed to determine the parameters of this antenna. These results make it possible to improve and optimize the performance of this antenna in particular concerning its reflection coefficient, bandwidth, gain, efficiency, and the reduction of its dimensions. We use the results from the transmission line model to design a rectangular-shaped patch antenna with a frequency that resonates for 28 GHz. This step guarantees the resonant frequency at 28 GHz with the best possible match. The process of creating and designing a patch antenna consists of three different parts: the radiated element (the patch) and the transmission line on top, the substrate in the middle, and the ground plane on the bottom. A microstrip line feeds this antenna. The latter is matched to an impedance of 50 ohms. Figure 1 shows the geometry of a single proposed patch antenna, and then Figure 2 shows the structure of the proposed patch antenna array.

Table 1. The parameters of the proposed antenna

Parameters	Values (mm)
(L_g-Wg)	(9-10.3)
h	0.5
(W_A-L_A)	(4.2-3.3)
(W_{fed}-L_{fed})	(1.54-4.26)
(y_0-y_1)	(3.26-3.08)
(W_f-L_f)	(1.517-0.66)

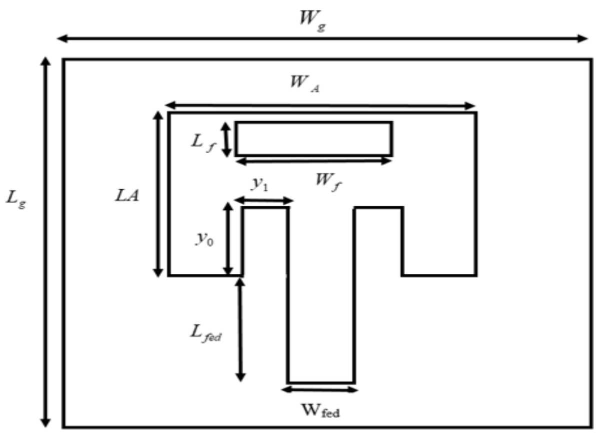

Figure 1. Geometry of the proposed single antenna

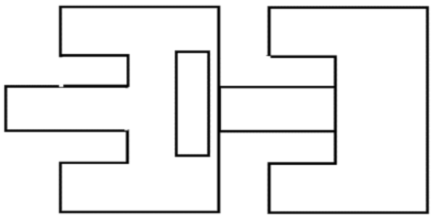

Figure 2. Geometry of the proposed antenna array

3. SIMULATION SOFTWARE

In this paragraph, we will explain and present the tool that performs the calculations necessary for the simulation of this study. High frequency structure simulator (HFSS) is an electromagnetic simulation software that studies complex structures in three dimensions by simulating these structures and providing clear visualizations of the results in 2D and 3D. HFSS is mainly used for experiments and studies of systems operating at high frequencies. It is used to calculate S-parameters, resonance frequencies, and electromagnetic fields.

Using Maxwell's equations, the HFSS divides complex geometric structures into simpler geometric forms, precisely tetrahedrons, on which the mathematical calculation will be more feasible. Hence, we begin to speak of convergence which is the persistence of the results obtained. The software presented here uses the finite element method.

In addition, we have advantages and disadvantages arising from this software, and that lies in the following points: The complexity of work and the creation of structures with significant design details. The need to have mastered the use of the program before starting the project, because sometimes we have to use Boolean operations to draw surfaces or shapes that do not have a well-defined geometric form. Also, we need to be careful about boundaries so that there are no conflicts between a radiating surface and a conducting surface, for example. The simulation can take several hours to several days, especially if the project is relatively large and has many details.

Models based on finite element principles have become standard tools in the design and analysis of industrial products. As modeling tools are becoming increasingly sophisticated, the finite element method has developed widely and may seem less and less a matter for specialists. Suppose the use of the method is democratized by the increasing simplicity of implementation, the algorithms' reliability, and the method's robustness. In that case, it remains that essential questions arise for the engineer if he wants to perform a finite element analysis in good conditions: formalize the unspoken and the thoughts that justify the explicit or implicit choices of his analysis of the problem; evaluate his confidence in the results produced; analyze the consequences of these results to the objectives.

4. SIMULATION RESULTS AND DISCUSSION

An antenna is connected to the source by a transmission line of characteristic impedance *Zc*. To ensure maximum power transfer between the feed and the antenna, it is necessary to provide an impedance matching. The matching cancels the reflection coefficient S_{11} at the antenna input. The antenna matching is characterized by the voltage standing wave ratio (VSWR). The higher the VSWR, the worse the matching. The minimum SWR=1 corresponds to perfect matching; for $1 \leq SWR < 2$, there is matching. Maximum power transfer can only be achieved if the input impedance of the antenna is matched to that of the generator.

Having designed the antenna based on the results obtained from the transmission line model, we now turn to the antenna simulation results on HFSS. Figure 3 shows the curve of the reflection coefficient S_{11} with its value -14.5 dB, for a resonance frequency of 29.45 GHz. This frequency shift is due to the tolerance of the transmission line model, which becomes more important for higher frequencies such as those of the millimeter-wave spectrum. In addition, the bandwidth is 0.84 GHz (29.01-29.85 GHz). Figure 4 shows a 3D gain diagram and its value of 7.5 dB. To improve these results, we added a rectangular slot (*Wf*=1.517 mm, *Lf*=0.66 mm). This slot is implemented on a radiated element to design an antenna array of two series antennas.

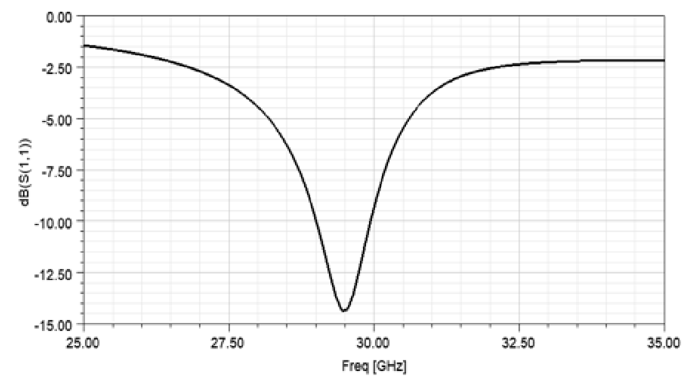

Figure 3. S_{11} curve of the proposed single antenna

Using a one-piece printed antenna is often insufficient to meet the imposed radiation constraints. Specific features such as high gain or a shaped main lobe high gain or a shaped main lobe can usually only be achieved by grouping several radiating sources to form a grouping of several radiating sources to form a system called an antenna array [27], [28]. The advantage of the assembly of several primary antennas thus allows obtaining highly directed radiation, depending on the number and nature of the elements, the form of their power supply, and their technical arrangement of the array.

The best configuration choice (feed) depends on several characteristics, such as bandwidth, required antenna gain, insertion loss, beam angle, array, sidelobe level, feed management capability, and polarization. We chose the serial transmission line feed type because of its lower insertion loss but reduced polarization and wider bandwidth [29]. Generally, the performance of microstrip patch antennas is improved depending on the number of antenna components that make up the array. To design the antenna with high-level performance, we proposed a 2×1 array of two antenna elements to achieve our research's desired results Figure 2.

The plane between the transmission source and the antenna has a discontinuity characterized by the reflection coefficient S_{11}. The ratio between the reflected wave and the incident wave at the antenna defines this coefficient (usually expressed in dB). The standing wave ratio (SWR), quantifies the matching level (or, more precisely, mismatching). This ratio tends towards 1 when the chain is perfectly matched, to infinity, when the chain is mismatched. Several matching techniques are available to ensure better energy transmission, such as single stub, double stub, and quarter-wave matching. Figures 5 and 6 show simulation results obtained for S_{11}=-35.91 dB and VSWR=1.032, respectively, with a bandwidth of 1.43 GHz. Any graph showing the radiation properties at each antenna according to their variations (θ, φ), in other words, according to the polar plane, is called a radiation pattern. The radiation characteristic curve can also be represented using a 2-D or 3-D diagram, most often circumscribed to the far field. The parameters which compose it are very close to each other, in particular the gain $G(\theta, \varphi)$, and the directivity, which gives the possibility to calculate the total efficiency of the antenna: $G(\theta, \varphi)=\eta D(\theta, \varphi)$ where η represents the total efficiency of the antenna. In this case, Figure 7 shows the 3D gain diagram, and Figure 8 the 2D gain diagram; similarly, Figure 9 shows the 3D directivity diagram, and Figure 10 the 2D directivity diagram, with a radiation efficiency of 29.95%. These results are validated by simulation with the HFSS tool.

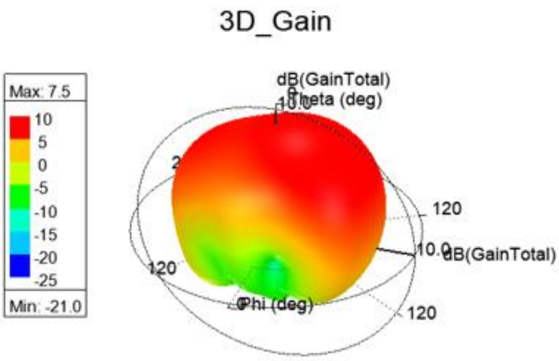

Figure 4. The 3D gain pattern of the proposed single antenna

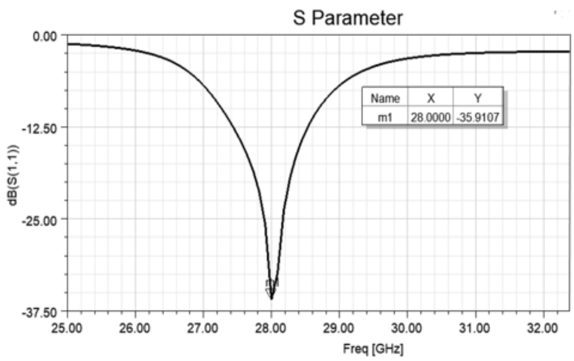

Figure 5. S_{11} curve of the proposed antenna array

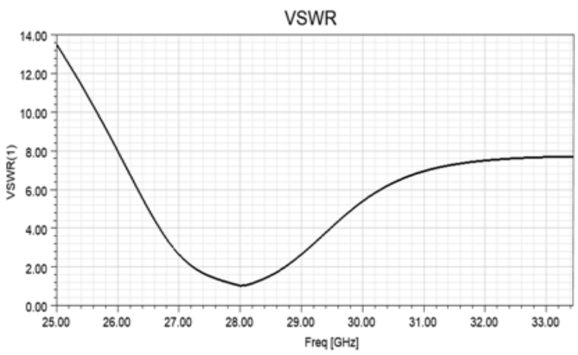

Figure 6. VSWR curve of the proposed antenna array

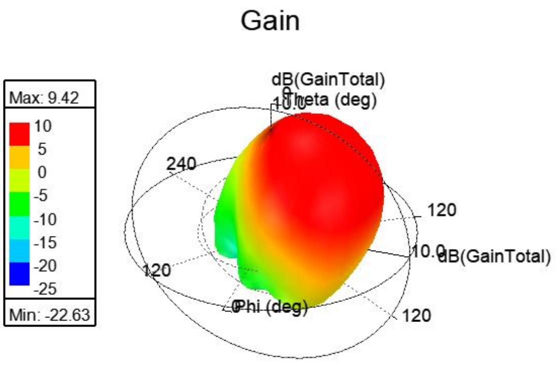

Figure 7. 3D gain pattern of the proposed antenna array

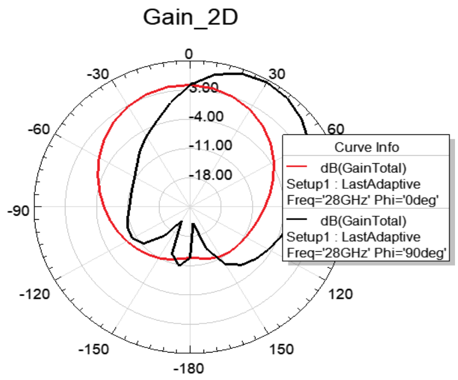

Figure 8. 2D gain pattern of the proposed antenna array

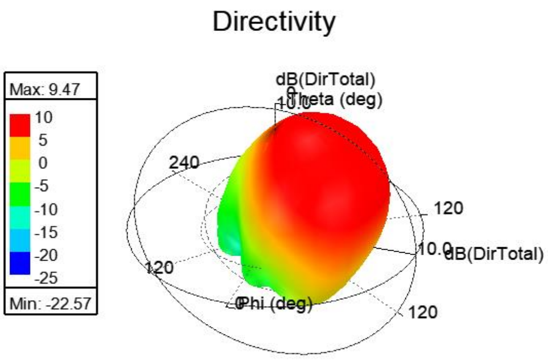

Figure 9. 3D directivity pattern of the proposed antenna array

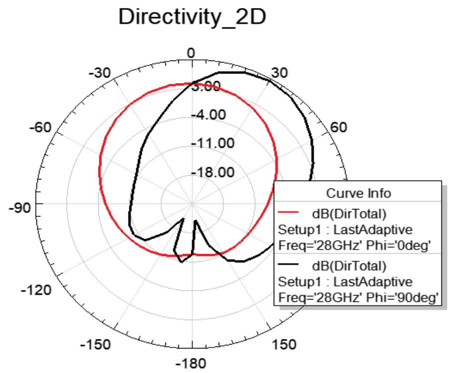

Figure 10. 2D directivity pattern of the proposed antenna array

Finally, Table 2 contains the metrics values that compare the performance of the proposed new antenna and different products currently available in the market in the 28 GHz frequency band. These include directivity, gain, S_{11} return loss, VSWR, bandwidth, and efficiency. The work by Rahayu and Hidayat [30] has a higher bandwidth than those obtained by the other works, as shown in Table 2. In addition, the work in [30] also has another advantage, namely S_{11}, which is better than the ones in [31]–[36]; on the other hand, it also has a disadvantage: the number of antenna components is greater than that of the works presented in Table 2. The performance achieved by Nabil and Faisal [33] is more satisfactory than that of other antennas [30]–[36], and the proposed antenna; the characteristics concerned here are reflection coefficient, VSWR, gain and directivity. On the other hand, the bandwidth and efficiency are lower than those of the proposed antenna, and the number of antennas is greater than that of the proposed antenna, as illustrated by Table 2. Huang *et al*. [35] obtained a better gain than those done in the other research, as shown in Table 2. The balance achieved by our proposed antenna is more efficient than that achieved by [31]–[36], where existing characteristics are reflection coefficient, VSWR, bandwidth; furthermore, the number of antennas composing the proposed array is small.

Table 2. Review of the work done by this branch and those that currently exist

References	Number of antennas	S_{11} (dB)	Gain (dB)	Directivity (dB)	Bandwidth (GHz)	VSWR	Efficiency (%)
[30]	-	-31.61	6.01	-	4.127	-	-
[31]	-	-22	10	-	1.3	-	85
[32]	-	-20.31	10.2	10.79	0,526	-	97.94
[33]	2*2	-87	14	14.3	1.14	1	93.5
[34]	1*2	-24	9.66	-	-	1.13	-
[35]	5	-30	11.2	-	1.06	-	-
[36]	13	-22	8.42	-	0.9	-	93
Proposed antenna	1*2	-35.91	9.42	9.5	1.43	1.032	99.8

5. CONCLUSION

In this study, we propose, first, a design that consists of designing a single antenna of the microstrip patch type, including its geometric structure of the rectangular format. Then, we use this component to realize the design that consists of a microstrip patch antenna array that consists of two rectangular patch antennas, and each has a rectangular millimeter band slot for 5G with an operating frequency of 28 GHz. The simulation software used in this work is HFSS. This research resulted in excellent work, light, and a small antenna. The results of this study also show that the metrics of this proposed antenna are significant as: return loss S_{11}=-35.91 dB, the bandwidth of 1.43 GHz, VSWR=1.03, a gain of 9.42 dB, and efficiency of 99.83%. The products achieved by this suggested device are excellent compared to those found elsewhere, particularly concerning the return loss, bandwidth, VSWR, gain, directivity, and radiation efficiency. The suggested antenna array is appropriate for 5G modern and mobile devices and can be designated as a candidate for being used in a network-based application of the 5G communication systems.

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