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Design and simulation of high efficiency rectangular microstrip patch antenna using artificial intelligence for 6G era

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ABSTRACT

Sixth-generation (6G) applications require ultra-speed and large-capacity wireless communication services. Millimeter wave technology can be used to satisfy these requirements, especially at 28 GHz. This paper study used the Ansys® high-frequency structure simulator (HFSS) to design and simulate rectangular and slotted rectangular microstrip patch antennas (MSPAs) at 28 GHz. The proposed designs contained a Rogers RT/Duroid® 5,880 substrate with a dielectric constant (ε_r) of 2.2 and a loss tangent of 0.0009. The performance of both the proposed antennas was compared to determine which was more efficient. This present study also used an adaptive network-based fuzzy inference system (ANFIS) to determine the optimal frequency and gain. The main objective of the manuscript is to use artificial intelligence (AI) to obtain the best design results for MSPA. The results indicated, with the use of AI, the gain of the rectangular and slotted antennas, was 6.3943 and 6.3094 dB at an efficiency of 98.338% and 98.651%, respectively.

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1. INTRODUCTION

Multiple new methods of enhancing the performance of fourth-generation (4G) and fifth-generation (5G) cellular networks [1], [2] to satisfy evolving requirements and applications [3], [4] have emerged in recent decades. These requirements include high data rate, low latency, and connection reliability. However, designing antennas that function in millimeter wave sixth-generation (6G) networks is very challenging as millimeter wave technologies require a wide bandwidth (BW) and an antenna that is no more than a few millimeters in size [5]. Therefore, the challenge is to design an antenna that can consistently provide high performance while maintaining a small size, especially for portable devices [6]. Microstrip antennas have a low efficiency and narrow BW as well as substrate characteristics; such as dielectric constant (ε_r) and tangent loss; that negatively affect their performance [7]. With the evolution of wireless technology comes the need for antennas that are lightweight, low and compact, cheap to mass-produce, easy to install, conform with and without planar surfaces, and mechanically strong when placed on rigid surfaces [8], [9].

Modern technologies such as millimeter wave technology [10], reconfigurable surface technology (RIS) [11], and massive multi-input multi-output (mMIMO) technology need efficient microstrip patch antenna (MSPA) design [12]–[14]. Several shapes of MSPA have been designed, including rectangular, circular, and different figures with or without a slot [15], [16]. Wideband MSPAs with a center frequency of 28 GHz have been designed for 5G wireless applications. The rectangular MSPA that an extant study developed had a frequency of 27.992 GHz with a return loss ($S_{1,1}$) of -54.49 dB. The problem of mutual coupling with the

MSPA array was also decreased by 67.2% [17]. Another study used a new configuration of the MSPA array at a center frequency of 2.4 GHz [18]. Three distinct versions of microstrip antennas have been proposed for 5G applications operating at 28 GHz. An operating frequency of 28 GHz is considered acceptable for 5G antenna designs [19]. Novel design methods for square and rectangular patch antennas include neural networks and neuro-fuzzy (NF) systems. Multiple studies have used artificial neural networks (ANN) to estimate the resonant frequency of microstrip patch antennas at various lengths [20], [21]. An adaptive network-based fuzzy inference system (ANFIS) was used to add two slots of equal dimensions to a single-layer MSPA to correct the frequency. Another study proposed a new model of multiple ANFIS operating at frequencies of 2.68, 3.33, and 4.10 GHz. It also included a U-shaped MSPA with a slot to increase the BW range from 2 to 10.75 GHz [22]. An NF analytical approach has also been used to determine the operating frequency of a triangle ring MSPA used in ultra-wideband (UWB) applications [23].

This present study is structured as follows: section 1 provides an introduction while the section 2 provides an overview of an ANFIS. The section 3 discusses the mathematical equations that were used to design the MSPA while the section 4 describes how an ANFIS was used in the proposed antennas. The section 5 presents the final designs of the antennas and the results of each antenna while the section 6 presents the conclusions of this present study.

2. ANFIS

The fuzzy inference system (FIS) is comprised of multiple components (Figure 1). Its primary function is to compute imprecise and granular data and use membership functions to calculate numerical values for large and small datasets. The FIS originates from the concepts of fuzzy sets, fuzzy reasoning, and fuzzy if-then rules. When required, an FIS can significantly aid in data classification. The procedures to be sequentially followed once the inputs and outputs of an FIS has been defined is described in the subsequent paragraphs [24].

The first fuzzification phase involves expressing the variables as fuzzy expressions and determining how dependent each variable is on the fuzzy set. As the membership functions have many different forms, those with a smooth shape may be effective. In the second stage, the statement level is evaluated and a few algebraic operators are used to perform the categorization task. The next stage calculates the activations of the applied rules. Lastly, the accumulation process connects all the outputs of the activations [25], [26].

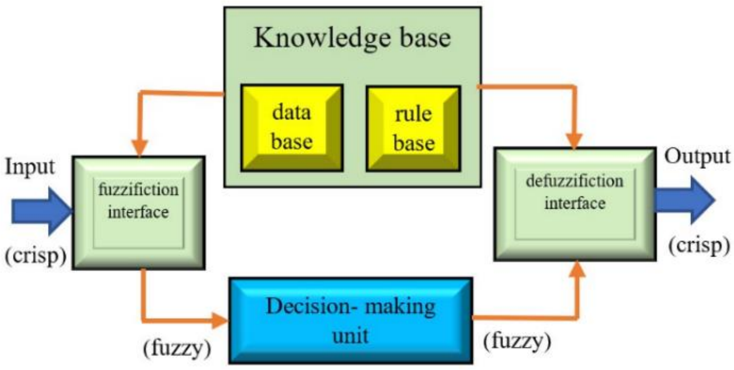

Figure 1. A fuzzy inference system [20]

3. MATHEMATICAL EQUATIONS FOR DESIGNING MSPA

The parameters to be used for the rectangular microstrip antennas were calculated using equations obtained from [27]–[30]. These parameters are intrinsic to the initial design and include the following: the first parameter is antenna width (Wt).

$$W_t = \frac{C}{2f_o\sqrt{\frac{(\varepsilon_r+1)}{2}}} \tag{1}$$

Where C: the velocity of light. The second one is the effective dielectric constant (ε_{reff}).

$$\varepsilon_{reff} = \frac{\varepsilon_r+1}{2} + \frac{\varepsilon_r-1}{2}\left(1+12\frac{h}{W_t}\right)^{-\frac{1}{2}} \tag{2}$$

The other parameter is the effective length.

$$L_{eff} = \frac{c}{2f_o\sqrt{\varepsilon_{reff}}} \tag{3}$$

The fourth parameter is fringe length (ΔL) as (4):

$$\Delta L = 0.412h \times \left\{\frac{(\varepsilon_{reff}+0.3)\left(\frac{W_t}{h}+0.264\right)}{(\varepsilon_{reff}-0.258)\left(\frac{W_t}{h}+0.8\right)}\right\} \tag{4}$$

The actual length L, as well as the width and length of the ground.

$$L = L_{eff} - 2 * \Delta L\,, L_g = 6h + L\,, W_g = 6h + W \tag{5}$$

The feedline width represents the fifth parameter.

$$W_f = \frac{7.84h}{\exp\left(z_o\frac{\sqrt{\varepsilon_r}+1.41}{87}\right)} - 1.25t \tag{6}$$

Where t is the thickness of the ground (mm) and z_o is the input impedance (50 ohms). The important parameter is the feedline Insertion.

$$F_i = 10^{-4}\{0.001699\varepsilon_r^7 + 0.13761\varepsilon_r^7 - 6.1783\varepsilon_r^5 + 93.187\varepsilon_r^4 - 682.69\varepsilon_r^3 + 2561.9\varepsilon_r^2 - 4043\varepsilon_r + 6697\}\frac{L}{2} \tag{7}$$

The following equations were used to analyse the slot on the patch:

$$Z_{in} = \frac{1}{\frac{1}{R_1}+j\omega C_1+\frac{1}{j\omega L_1}} \tag{8}$$

$$C_1 = \frac{\varepsilon_{reff}\varepsilon_o LW\, cos^{-2}}{2h}\left(\frac{\pi z_o}{L}\right) \tag{9}$$

$$L_1 = \frac{1}{C_1\omega_r^2} \tag{10}$$

$$R_1 = \frac{Q}{\omega_r C_1} \tag{11}$$

Where ε_o is the permittivity of free space. Figure 2 shows the equivalent slot that was placed on the patch circuit.

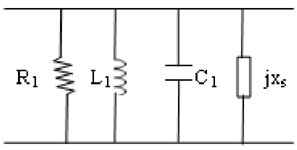

Figure 2. The equivalent slot circuit

The equation that was used to calculate the reflection coefficient is as (12) and (13):

$$\Gamma = \frac{Z_{in}-Z_o}{Z_{in}+Z_o} \tag{12}$$

$$\text{Return Loss} = 20\log|\Gamma| \tag{13}$$

The last parameter is the voltage standing wave ratio (VSWR).

$$\text{VSWR} = \frac{1+|\Gamma|}{1-|\Gamma|} \tag{14}$$

4. ANTENNAS IMPLEMENTED USING ANFIS

4.1. Rectangular antenna MSPA

Figures 3 and 4 depict the fuzzy rules that were used to produce rectangular MSPAs with the best gain, directivity, and efficiency. Only phase was used as the inputs for each rule. The maximum directivity and gain occurred at phase 180°. Figure 5 shows the fuzzy rules that were used to obtain the best efficiency for the rectangular MSPA (28 GHz), for which the inputs were phase, gain, and efficiency. The output was at the maximum (1 for normalized value) when the gain and efficiency were equal. The structure of the ANFIS model was designed to maximize the directivity of the rectangular antenna at 28 GHz, with a Gaussian membership of 15 for 20 epochs as shown in Figure 6. The input was the angle, and the error was 0.009525.

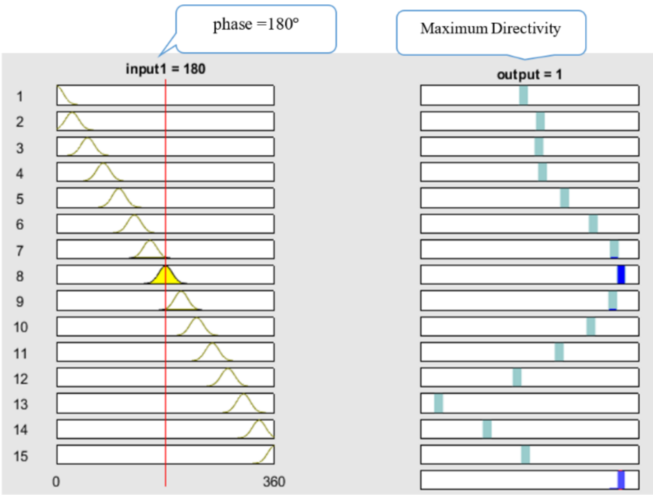

Figure 3. Fuzzy rules for a rectangular MSPA with the best directivity

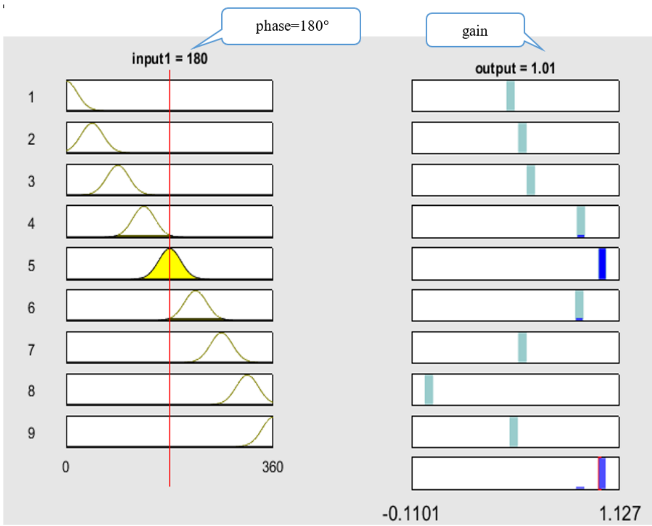

Figure 4. Fuzzy rules for a rectangular MSPA with the best gain

Figure 7 illustrates the structure of the ANFIS model for the best gain in the rectangular MSPA at 28 GHz, with a Gaussian membership of nine for 20 epochs. The input was the angle while the error was 0.021193. The structure of the ANFIS model was designed to maximize the efficiency of the rectangular antenna at 28 GHz, with a Gaussian membership of three for seven epochs. The inputs were the angle, gain, and directivity while the error was 0.0021488. Table 1 lists the optimization objectives for the rectangular MSPA at 28 GHz in the ANFIS model. Figure 8 presents a 3D view of the rectangular antenna with the best efficiency at 28 GHz. As seen, the system performed most efficiently when the efficiency was 1.

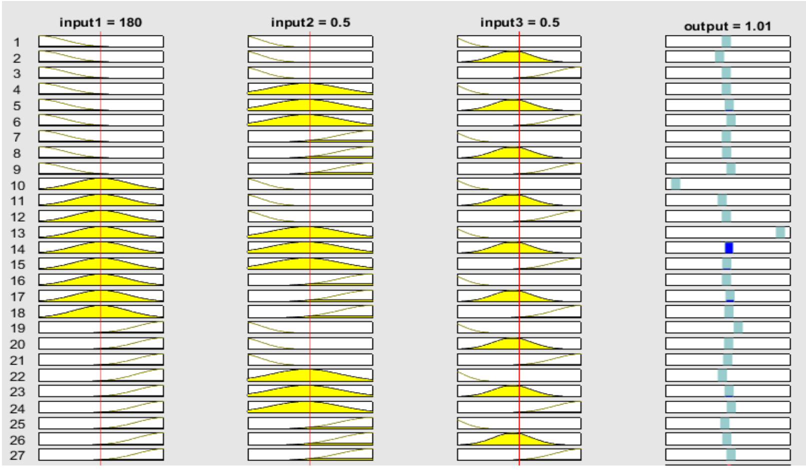

Figure 5. Fuzzy rules for a rectangular MSPA with the best efficiency

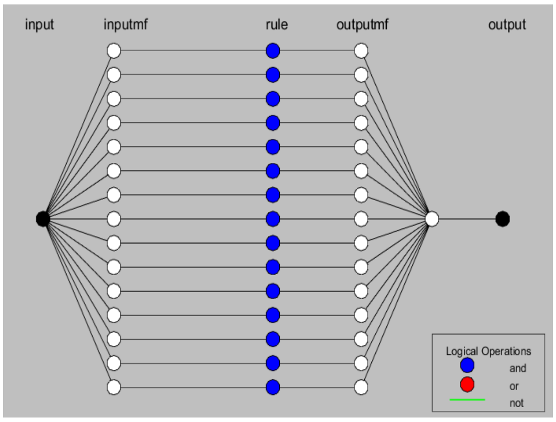

Figure 6. Structure of the ANFIS model for a rectangular MSPA with the best directivity

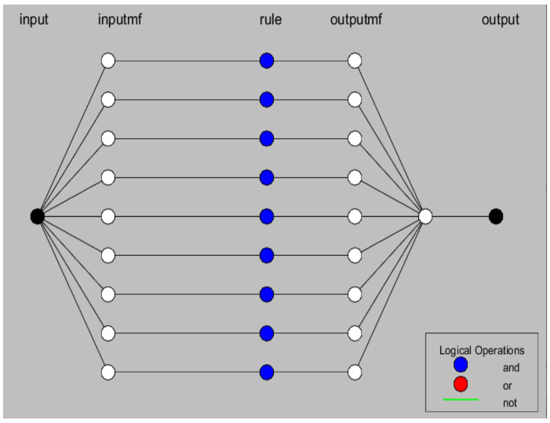

Figure 7. Structure of the ANFIS model for a rectangular MSPA with the best gain

Table 1. Optimization of the rectangular MSPA at 28 GHz

Parameter	Gain	Directivity	Efficiency
Input	1	1	3
MF type	gaussmf	gaussmf	gaussmf
MFs	9	15	3 3 3
Epoch	20	20	7
Error	0.021193	0.009525	0.0021488

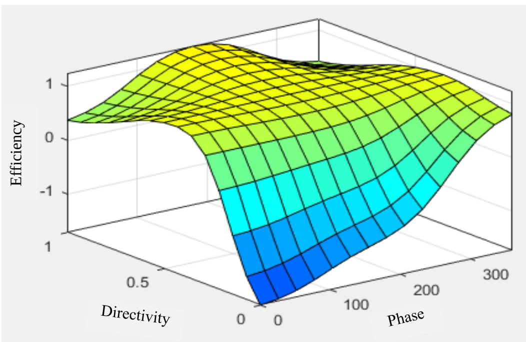

Figure 8. 3D surface of fuzzy system of the rectangular MSPA with the best efficiency

4.2. Slotted rectangular MSPA

Figures 9-11 show the fuzzy rules that were used to produce slotted rectangular MSPAs with the best gain, directivity, and efficiency, respectively. The structure of the ANFIS that was designed to produce slotted rectangular MSPAs with the best gain, directivity, and efficiency was identical to that of the rectangular MSPA (28 GHz), only with different membership and number of epochs (Table 2). Figure 12 shows the 3D surface of the fuzzy system of the slotted rectangular MSPA with the best efficiency.

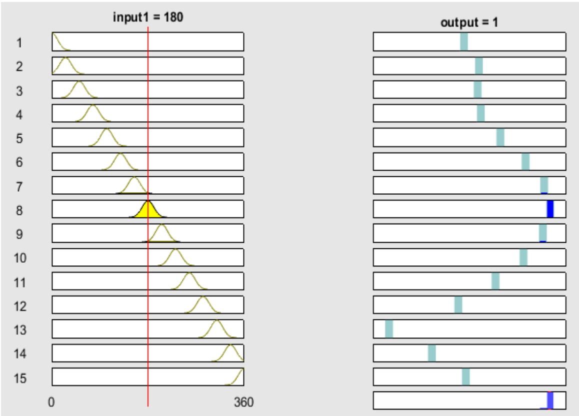

Figure 9. Fuzzy rules for a slotted rectangular MSPA with the best directivity

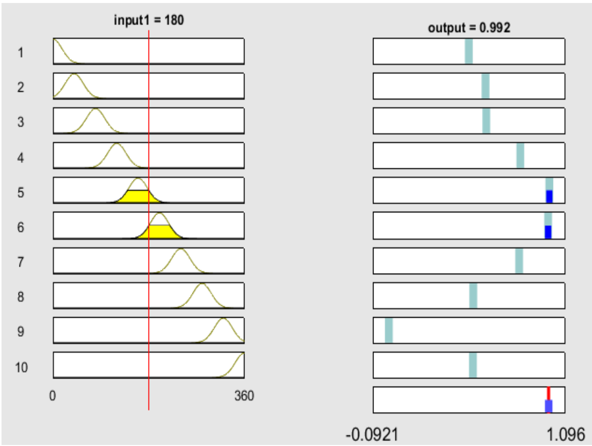

Figure 10. Fuzzy rules for a slotted rectangular MSPA with the best gain

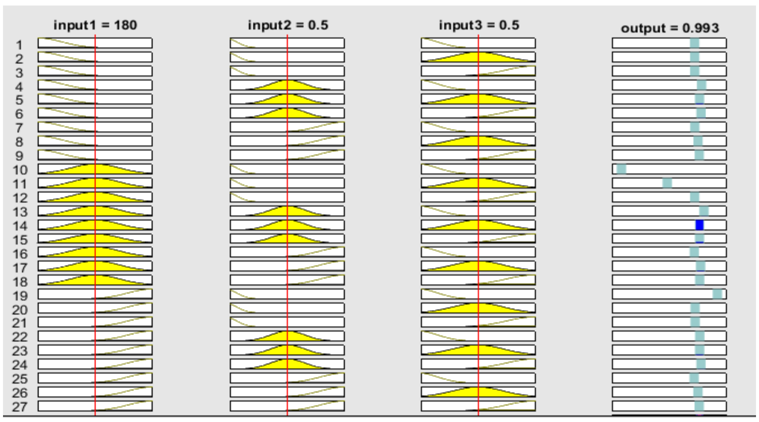

Figure 11. Fuzzy rules for a slotted rectangular MSPA with the best efficiency

Table 2. Optimization of the slotted rectangular MSPA at 28 GHz

Parameter	Gain	Directivity	Efficiency
Input	1	1	3
MF type	gaussmf	gaussmf	gaussmf
MFs	10	15	3 3 3
Epoch	25	20	7
Error	0.01739	0.009525	0.00065512

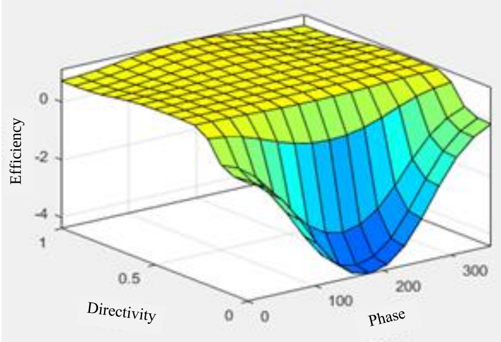

Figure 12. 3D surface view of a fuzzy system of the efficiency slotted rectangular MSPA

The position of the patch affected the $S_{1,1}$ and the VSWR plot which, in turn, affected the BW. Therefore, the slot on the patch also affected the BW. Table 3 shows the dimensions of the two proposed antennas.

Table 3. Dimensions of the proposed antennas

Symbol	Dimension value (mm)
Wt	4.2
L	3.4
W_g	7.235
L_g	6.285
h	0.5
W_f	1.75
F_i	1.25
t	0.035
L_s (slot)	1.9
W_s (slot)	0.1

5. FINALIZED ANTENNAS DESIGNS AND RESULTS

The Ansys® HFSS was used to design the final antennas. Figure 13 shows a typical rectangular MSPA while Figure 14 shows the slotted rectangular MSPA that this present study proposes. Figures 15 and 16 show the $S_{1,1}$ of every rectangular MSPA and slotted rectangular MSPA, respectively.

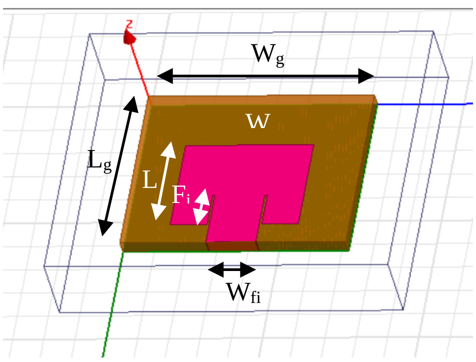

Figure 13. The proposed rectangular MSPA

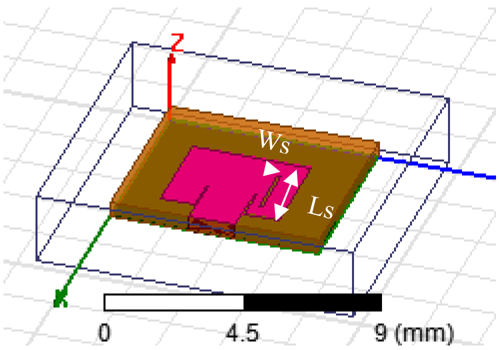

Figure 14. The proposed slotted rectangular MSPA

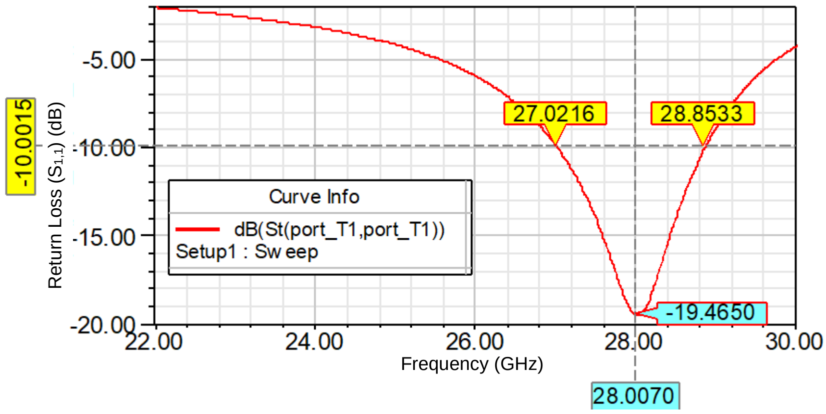

Figure 15. $S_{1,1}$ of the rectangular MSPA

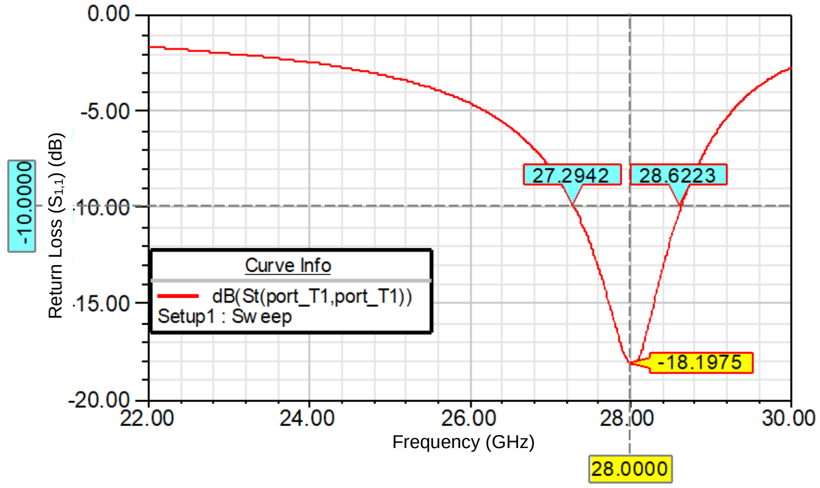

Figure 16. $S_{1,1}$ of the slotted rectangular MSPA

It was noted that the BW and $S_{1,1}$ of the rectangular MSPA at the required frequency was 1.8 GHz and -19.47 dB, respectively. The rectangular slotted MSPA had a BW of 1.3 GHz and $S_{1,1}$ of -18.214 dB at the desired frequency of 28 GHz. Figures 17 and 18 display the $S_{1,1}$ of the rectangular MSPA and the slotted MSPA, respectively, where the VSWR was 1.8557 for the first antenna and 2.1487 for the second one.

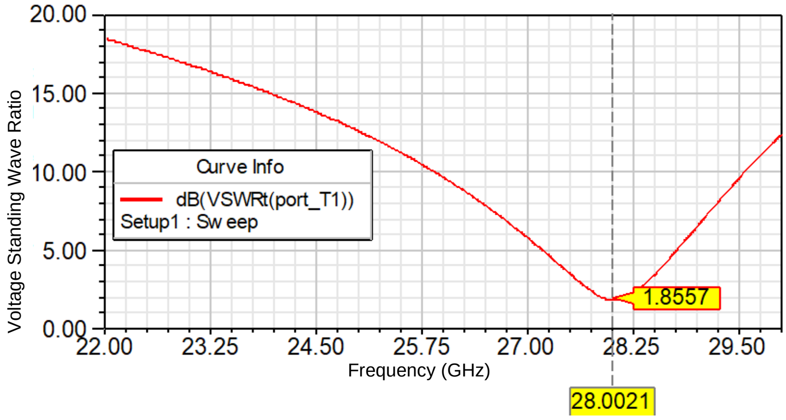

Figure 17. VSWR of the rectangular MSPA

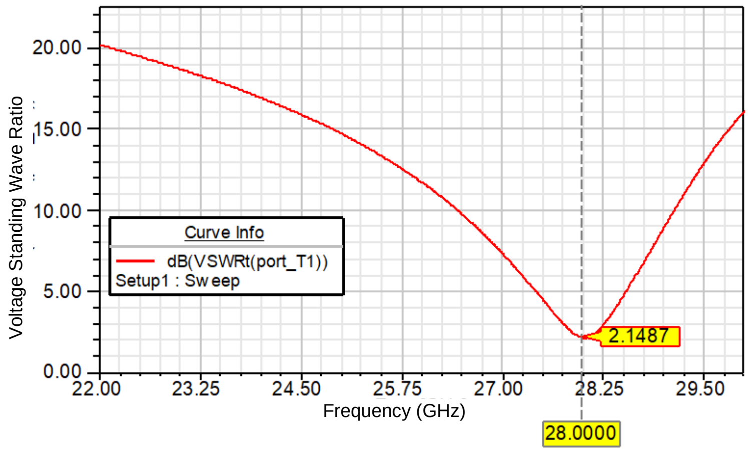

Figure 18. VSWR of the slotted rectangular MSPA

The directivity of first and second antennas are shown in Figures 19 and 20, respectively, while Figures 21 and 22 illustrate the gain for each rectangular MSPA and slotted rectangular MSPA, respectively. Meanwhile, Figures 23 and 24 display the radiation pattern of the two antennas in addition to their half power beamwidth (HPBW). Table 4 presents the detailed results of the proposed rectangular MSPA and the slotted rectangular MSPA.

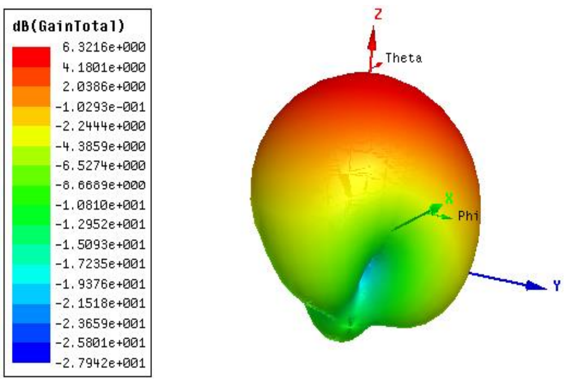

Figure 19. Directivity of the rectangular MSPA

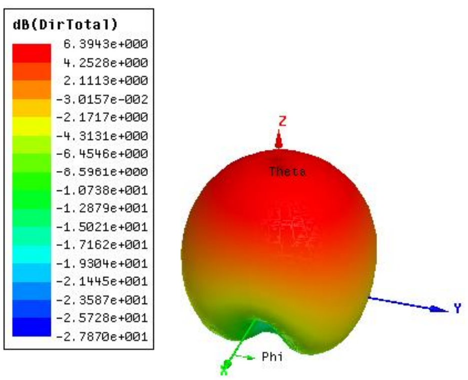

Figure 20. Directivity of the slotted rectangular MSPA

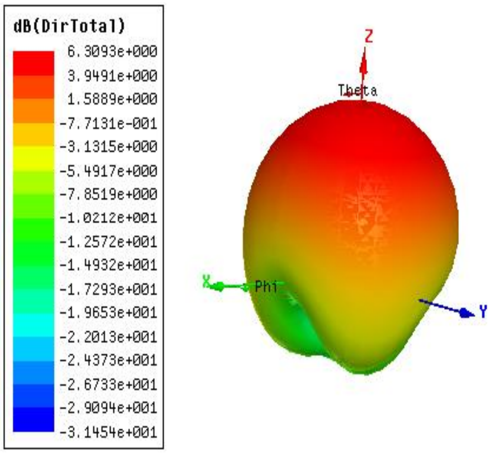

Figure 21. Gain of the rectangular MSPA

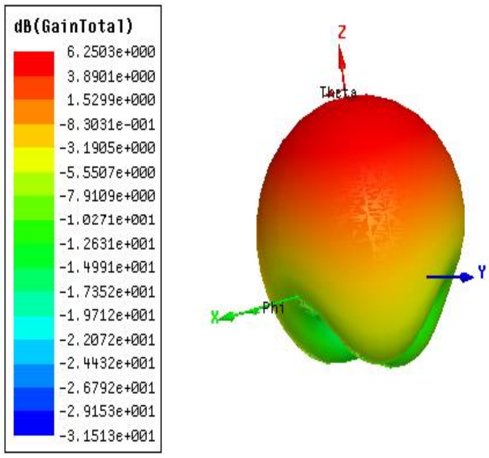

Figure 22. Gain of the slotted rectangular MSPA

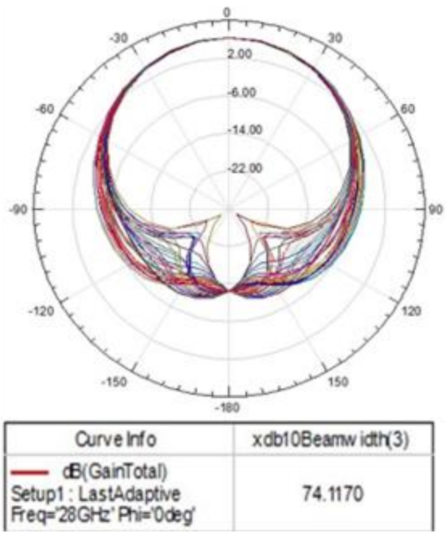

Figure 23. HPBW of rectangular MSPA

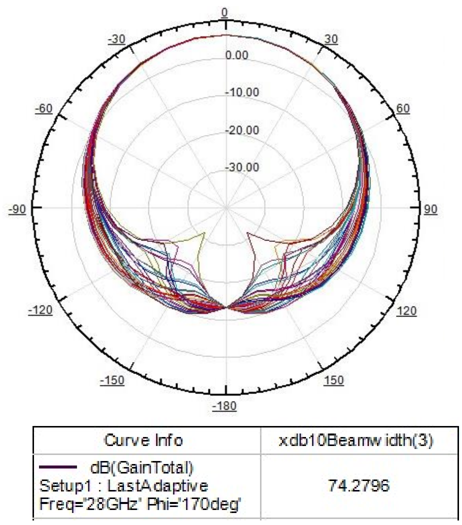

Figure 24. HPBW of the slotted the rectangular MSPA

Table 4. Results of the proposed antennas

Result	Rectangular MSPA	Slotted rectangular MSPA	[31]	[32]	[33]
Return loss (dB)	-19.4701	-18.2144	-26.056	-17.83	-16.8
VSWR	1.8557	2.1487	1.1048	1.2944	1.45
Directivity (dB)	6.3943	6.3094	6.327	-------	7.38
Gain (dB)	6.3216	6.2503	5.7	12.013	7.01
HPBW	74.1170	74.2796	81.49	-------	------
Efficiency	98.338	98.651	86.64	-------	92
BW (GHz)	1.8	1.3	2.3865	0.44	0.68

As seen in Table 4, the proposed rectangular and slotted MSPAs outperformed the [31] antenna in terms of gain, efficiency, and HPBW. It is clear from this comparison to obtain the excellent radiation efficiency. It is worth noting that the radiation efficiency of the proposed design is 98.338%, better than 92% for [33].

6. CONCLUSION

Two types of MSPA antennas were designed within the millimeter wave range at the desired frequency of 28 GHz. The first as a rectangular MSPA, which achieved a 1.8 GHz bandwidth with an HPBW of 74.117°, while the second was a slotted rectangular MSPA, which achieved a BW of 1.3 GHz and a HPBW of 74.279°. It is noteworthy that the lower the HPBW, the lower the interference between the beams when the beamforming technique was used. An ANFIS was used to determine the best dimensions for the both the proposed antennas to improve their gain, directivity, and efficiency at the required frequency. Therefore, ANFIS is a new method of designing antennas for 6G applications. This technology can be successfully applied to the remaining 6G frequencies in the future.

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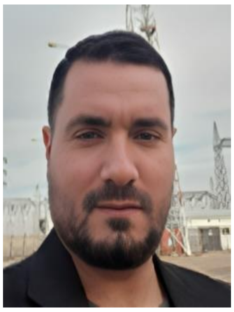

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