

Design and Simulations of 2x1 Rectangular Microstrip Array Antenna Using Inset and U-Slot Method at 3.5 GHz for 5G Communication System

Lita Farahdiba¹, Indra Surjati², Syah Alam³, Raden Deiny Mardian⁴, Lydia Sari⁵, Teguh Firmansyah⁶, Zahriladha Zakaria⁷

^{1,2,3,4,5}Department of Electrical Engineering, Universitas Trisakti, West Jakarta, Indonesia, 11440

⁶Department of Electrical Engineering, Universitas Sultan Ageng Tirtayasa, Banten, Indonesia, 42117

⁷Faculty of Electronic and Computer Engineering and Technology, Universiti Teknikal Malaysia Melaka, Malaysia, 76100

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ABSTRACT

This paper presents the design and realization of a 2×1 rectangular microstrip array antenna operating at 3.5 GHz for 5G communication systems. The design incorporates inset feed and U-slot techniques to improve antenna performance in terms of return loss, gain, and bandwidth. AWR Microwave Office 2009 was used for simulation, and iterative optimization was conducted on parameters such as feed position and slot dimensions. The final prototype achieves a return loss of -36.75 dB, a gain of 9.246 dB, a VSWR of 1.115, and a bandwidth of 169 MHz. These results demonstrate the effectiveness of combining array configuration, inset feed, and U-slot techniques for enhanced antenna characteristics.



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Corresponding Author:

Syah Alam

Department of Electrical Engineering, Universitas Trisakti, West Jakarta, Indonesia, 11440

Email: syah.alam@trisakti.ac.id

1. INTRODUCTION

The Fifth Generation (5G) of communication systems has marked a significant technological evolution since its introduction in 2017, offering extremely high data transfer speeds and much broader bandwidth compared to previous generations [1]. 5G technology enables the development of more advanced applications and enhances user experience across various sectors, including telecommunications, transportation, healthcare, and others. This generation of communication utilizes a wide range of frequency bands, such as the high band (28 GHz), mid band (15 GHz), and low band (3.5 GHz), as regulated by international standards [2].

In wireless communication systems, antennas play a vital role in transmitting and receiving signals, which are converted into electrical waves for voice and data communication [3]. One widely used antenna type in wireless systems is the microstrip antenna [4], known for its compact design, low fabrication cost, and capability to operate at high frequencies [5]. However, microstrip antennas also have limitations, such as low gain and directivity [6]. Despite these drawbacks, their compact form makes them suitable as receiving antennas in wireless communication systems. For reliable connectivity between transmitter and receiver, an antenna with optimal directionality and gain is required.

To address the gain limitation, this study focuses on enhancing microstrip antenna performance at 3.5 GHz using an array method, along with the application of inset and U-slot techniques. The array configuration increases the number of radiating elements, thereby enhancing gain and narrowing the

beamwidth for better signal direction. In addition, the inset feed and U-slot methods are employed to improve impedance matching, expand bandwidth, and reduce return loss and radiation pattern distortion. The combination of these techniques is expected to optimize antenna performance at 3.5 GHz in terms of gain and directional accuracy.

Previous studies [7] have attempted to design a 2x1 rectangular patch array antenna at 3.5 GHz but did not achieve satisfactory results in return loss, gain, or bandwidth. Another research [8] successfully designed a 1x2 rectangular patch array antenna for 5G communication at 3.5 GHz, but its parameters were still suboptimal. A different approach was presented in [9] using a 2x1 MIMO patch array with slit and inset-feed at 10 GHz, yet challenges remained in achieving the desired return loss, bandwidth, and gain. Therefore, the combination of U-slot and inset-feed techniques with a 2x1 array configuration is proposed to overcome these limitations and improve overall antenna performance [10].

This research aims to design a microstrip antenna operating at 3.5 GHz, optimized using a 2x1 array to achieve high gain. Furthermore, the inset feed and U-slot methods are applied to reduce return loss to ≤ -10 dB. As highlighted, 5G communication systems require microstrip antennas with optimal gain and directionality to ensure stable and effective connectivity. Therefore, improving microstrip antenna performance through these methods is the primary focus of this work, with the goal of meeting performance standards for 5G applications and enhancing efficiency and effectiveness at 3.5 GHz.

2. RESEARCH METHOD

This section describes the techniques and stages involved in designing the proposed microstrip antenna, including inset feed, U-slot, and 2x1 array methods. The entire research was conducted using full-wave electromagnetic simulation in AWR Microwave Office 2009 without physical fabrication. All performance parameters, including return loss, VSWR, gain, and bandwidth, were derived solely from simulation results.

2.1. Inset Feed Technique

Inset feeding is a method used to connect the RF source to a microstrip patch antenna by introducing a notch into the patch, positioned away from the outer edge. [11] This approach is primarily employed to adjust the input impedance of the antenna so it aligns with the characteristic impedance of the feed line—typically 50Ω —thereby minimizing return loss and enhancing feeding efficiency.

Determining the appropriate inset dimensions involves analyzing the variation of input impedance along the patch width, which tends to be highest at the edges and lowest at the center. The optimal inset position is selected at the point where the antenna's input impedance matches the feed line impedance. This location is identified through a combination of theoretical calculations, simulation results, and empirical models presented in relevant literature. Typically, the inset width equals the feed line width, while the inset length (L_i) is fine-tuned through simulation.

2.2. U-Slot Method

The U-slot technique modifies the patch by introducing a U-shaped slot into its surface. This approach is employed to enhance bandwidth and, in some cases, to adjust the radiation pattern or impedance matching. The slot dimensions and placement are optimized via simulation to avoid interference with the patch's fundamental resonant mode. The slot's width (W_{slot}) and length (L_{slot}) directly affect the resonance frequency and bandwidth, requiring precise tuning through iterative simulation.

2.3. Antenna Design Stages

Figure 1 presents the design evolution of the proposed microstrip antenna, comprising the following stages: (a) a basic rectangular patch, (b) a patch with inset feed, and (c) a patch incorporating both inset feed and a U-slot modification.

1. Patch Dimension Calculation: The patch width (W) and length (L) were calculated using standard equations for a 3.5 GHz resonance frequency.
2. Antenna Modeling and Simulation: AWR Microwave Office 2009 was used to model and simulate the antenna, aiming for return loss values below -10 dB.

3. Inset Feed Implementation: This technique was applied to improve impedance matching and polarization, targeting an axial ratio below 3 dB.
4. 2×1 Array Configuration: The antenna was extended to a 2×1 array to enhance gain, with careful spacing between elements and preserved feeding structure.
5. Performance Evaluation: Key performance metrics—return loss, bandwidth, VSWR, and gain - were evaluated for each configuration: rectangular, inset-fed, U-slot, and array.

To ensure simulation efficiency while maintaining result accuracy, the number of optimization iterations for key parameters (such as inset length and slot dimensions) was limited to three per configuration. This limitation was based on observed convergence trends, where performance metrics began stabilizing after the third iteration. Additional iterations were deemed unnecessary due to marginal expected improvements.

Through the systematic application of inset feeding and U-slot techniques, and careful simulation-based optimization, this study demonstrates the potential of the proposed 2×1 array antenna to fulfill the performance requirements of 5G communication systems.

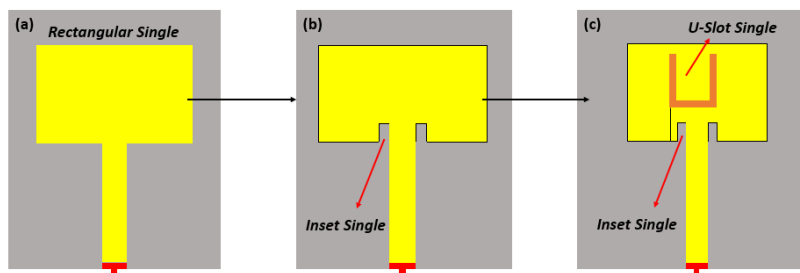


Figure 1. Microstrip antenna design development: (a) Rectangular Single, (b) Inset Single, (c) Inset Single with U-Slot

The simulated antenna was analyzed to evaluate its return loss, VSWR, gain, and bandwidth. The antenna uses an FR-4 substrate with a dielectric constant of 4.3, a thickness of 1.6 mm, and a loss tangent of 0.0265. The design is optimized to operate at a center frequency of 3.5 GHz.

3. RESULTS AND DISCUSSION

3.1 Antenna Design Parameters

In this study, the proposed microstrip antenna was designed to operate at a center frequency of 3.5 GHz, using the following substrate characteristics [12]:

- Substrate type : FR4 Epoxy
- Substrate thickness : 1.6 mm
- Dielectric constant (ϵ_r) : 4.3
- Loss tangent : 0.0265
- Operating frequency : 3.5 GHz

Based on the substrate parameters and the target resonant frequency, the dimensions of the initial rectangular single patch antenna were calculated using standard microstrip antenna design equations. The resulting patch width (W) and length (L) were 26.3 mm and 20.2 mm, respectively. These values served as the baseline for further design development.

The design process continued through a series of structural modifications—namely the implementation of inset feed, U-slot, and a 2×1 array configuration. These were introduced to overcome typical performance limitations found in single-element microstrip antennas, such as low gain, narrow bandwidth, and suboptimal return loss. While performance improvements were clearly observed in simulation results after each modification, this study does not delve into the detailed electromagnetic mechanisms that cause such improvements. The focus remains on the practical optimization of antenna design for 5G operation, rather than advancing new theoretical foundations.

Additionally, although inset feeding techniques can influence polarization characteristics, this study does not provide polarimetric results—such as axial ratio plots or polarization purity analysis—to

substantiate any claims related to polarization behavior. Therefore, statements regarding polarization improvement are qualitative in nature.

This research is centered on design optimization and simulated performance enhancement tailored for a specific application—namely 5G operation at 3.5 GHz—rather than on foundational scientific discovery or the introduction of novel concepts in electrical engineering.

1. Patch Antenna Dimensions

The proposed microstrip antenna consists of a rectangular patch whose dimensions are calculated using the following standard formulas [13]:

$$W = \frac{C}{2f\sqrt{\frac{\epsilon_r + 1}{2}}} \quad (1)$$

$$L = L_{eff} - 2\Delta L \quad (2)$$

$$L_{eff} = \frac{C}{2f\sqrt{\epsilon_{eff}}} \quad (3)$$

$$\epsilon_{eff} = \frac{\epsilon_r + 1}{2} + \frac{\epsilon_r - 1}{2} \left[1 + 12 \frac{h}{W} \right]^{-\frac{1}{2}} \quad (4)$$

$$\Delta L = 0,412h \frac{(\epsilon_{eff} + 0,3) \left(\frac{W}{h} + 0,264 \right)}{(\epsilon_{eff} - 0,258) \left(\frac{W}{h} + 0,8 \right)} \quad (5)$$

Where:

C = Speed of light in vacuum (3×10^8 m/s)

h = Thickness of dielectric substrate (1.6 mm)

W = Patch width (mm)

L = Patch length (mm)

ϵ_r = Relative permittivity of the substrat

f = Resonant frequency (3.5 GHz)

2. Inset Single Antenna Design

After calculating the patch dimensions, the feed line width was determined using transmission line theory to achieve impedance matching with a 50 Ω input. The equations used are [14]:

$$W = \frac{2h}{\pi} \left\{ B - 1 - \ln(2B - 1) + \frac{\epsilon_r - 1}{2\epsilon_r} \left[\ln(B - 1) + 0,39 - \frac{0,61}{\epsilon_r} \right] \right\} \quad (6)$$

$$B = \frac{60\pi^2}{Z_0\sqrt{\epsilon_{eff}}} \quad (7)$$

Where:

B = Impedance constant

Z₀ = Desired impedance (typically 50 Ω)

h = Substrate thickness (1.6 mm)

3. Spacing Between Antenna Elements

To implement the 2×1 array configuration and enhance the gain, the spacing between the two antenna elements (d) was calculated based on the following [10]:

$$\lambda = \frac{C}{f} \quad (8)$$

$$d = \frac{\lambda}{2} \tag{9}$$

Where:

λ = Wavelength at 3.5 GHz

C = Speed of light (3×10^8 m/s)

d = Spacing between patch elements (mm)

3.2 Antenna Simulation and Optimization Process

The antenna design process was carried out through several systematic stages using electromagnetic simulation software AWR Microwave Office 2009. Each stage involved parameter optimization to enhance performance at the operating frequency of 3.5 GHz. All results presented are based exclusively on simulation data; no physical fabrication or measurement was conducted.

1. Process Rectangular Single Microstrip Antenna Design

The initial design began with a conventional rectangular microstrip patch antenna as a baseline. The physical structure is illustrated in Figure 2(a), with key dimensions listed in Table 1. The antenna was designed using standard formulas for width (W) and length (L) of the patch, based on the chosen substrate (FR-4, $\epsilon_r = 4.3$, $h = 1.6$ mm).

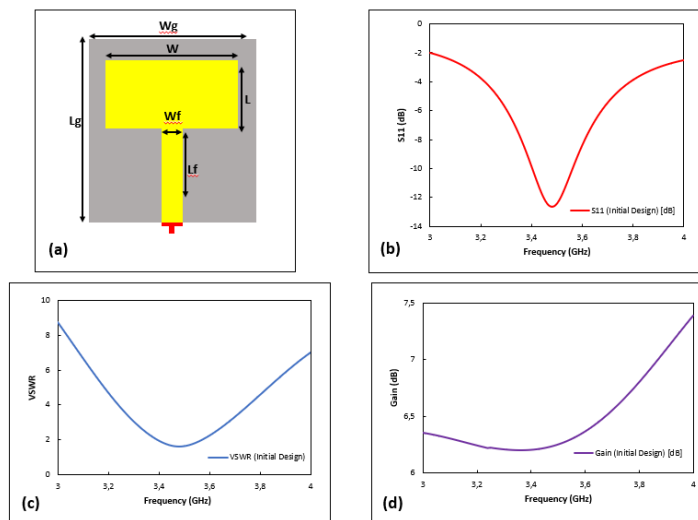


Figure 2. (a) Structure of the Rectangular Single Microstrip Antenna, (b) Return Loss Simulation Result, (c) VSWR Simulation Result, (d) Gain Simulation Result.

Table 1. Dimensions of the Rectangular Single Microstrip Antenna

Parameter	Description	Dimension (mm)
Wg	Enclosure width	50
Lg	Enclosure length	50
W	Patch width	26,3
L	Patch length	20,2
Wf	Feed line width	3,1
Lf	Feed line length	20

Simulation results in Figures 2(b)-(d) show that the antenna operates at 3.5 GHz with a return loss of -12.67 dB, a bandwidth of 160 MHz, a VSWR of 1.626, and a gain of 5.702 dB.

2. Inset-Fed Single Microstrip Antenna Design

To improve impedance matching and reduce return loss, an inset notch was introduced to the rectangular patch. The key variable optimized in this stage was the inset length (ΔY). Three simulations were conducted with ΔY values of 4 mm, 5 mm, and 6 mm. Table 2 and Figures 3(b)-(d) present the results:

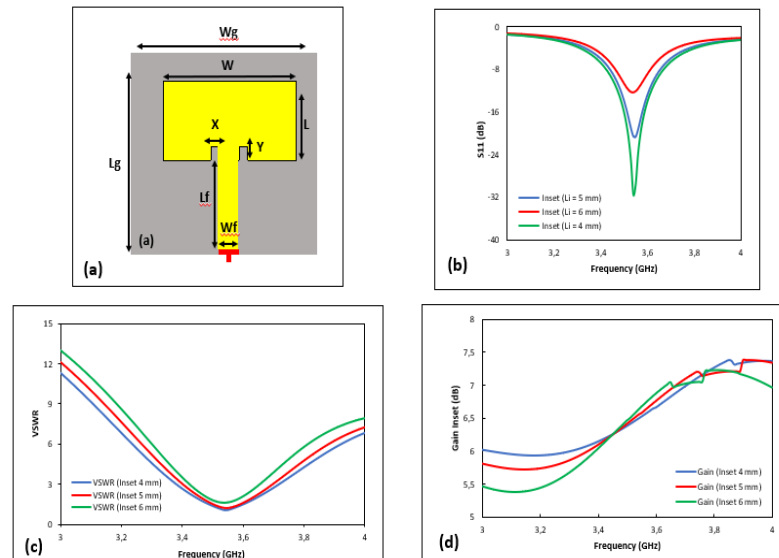


Figure 3. (a) Structure of the Inset-Fed Single Microstrip Antenna, (b) Return Loss Simulation Result, (c) VSWR Simulation Result, (d) Gain Simulation Result

Table 2. Simulation Results for Inset-Fed Single Microstrip Antenna

Iteration ΔY	Parameter			
	Return Loss (dB)	Bandwidth (MHz)	Gain (dB)	VSWR
Y_1 Iteration 4	-31,61	190	6,383	1,367
Y_2 Iteration 5	-20,65	161	6,422	1,485
Y_3 Iteration 6	-12,35	95	6,48	1,87

- The best performance was achieved at $\Delta Y = 4$ mm, with return loss = -31.61 dB, bandwidth = 190 MHz, gain = 6.383 dB, and VSWR = 1.367.

This demonstrates that adding an inset feed can significantly enhance the impedance match and widen the bandwidth.

3. Inset-Fed Single Microstrip Antenna with U-Slot

To further improve gain and bandwidth, a U-slot was introduced at the center of the patch. The slot dimensions were optimized through three iterations ($\Delta C = 4$ mm, 5 mm, 6 mm). This slot serves to perturb the surface current, enhancing radiation efficiency.

The optimal result was found at $\Delta C = 6$ mm with:

- Return loss = -14.01 dB
- Bandwidth = 132 MHz
- VSWR = 1.494
- Gain = 6.123 dB

Figures 4(b)-(d) and Table 4 show how the U-slot improves performance compared to the plain inset-fed design.

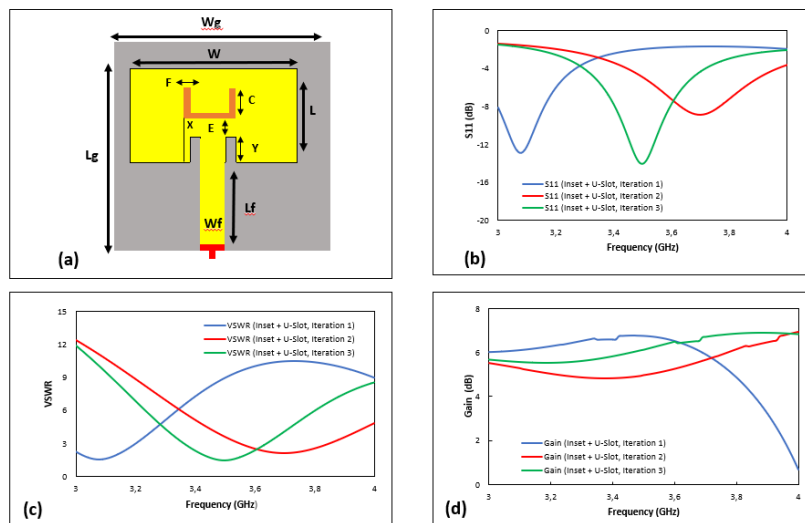


Figure 4. (a) Structure and Dimensions of the Inset-Fed and U-Slot Single Microstrip Antenna, (b) Return Loss Simulation Result, (c) VSWR Simulation Result, (d) Gain Simulation Result

Table 4. Simulation Results of the Inset-Fed and U-Slot Single Microstrip Antenna

Iteration ΔC	Parameter			
	Return Loss (dB)	Bandwidth (MHz)	VSWR	Gain (dB)
Iteration 8	-12,76	104	9	6,673
Iteration 5	-5,78	-	3,544	4,961
Iteration 6	-14,01	132	1,494	6,123

As presented in Table 4, the integration of inset feed and U-slot techniques in the microstrip antenna design resulted in notable enhancements in return loss, VSWR, and gain. The optimal performance was recorded at $\Delta C = 6$ mm, where the antenna operating at 3.5 GHz achieved a return loss of -14.01 dB, a bandwidth of 132 MHz, a VSWR of 1.494, and a gain of 6.123 dB.

4. 2×1 Inset-Fed Microstrip Antenna Array Design

To boost gain further, a 2×1 antenna array configuration was developed. Two identical inset-fed patches were arranged with a spacing of $\lambda/2$. The patch dimensions were reduced to maintain resonance at 3.5 GHz.

The simulation results show:

- Return loss = -18.49 dB
- Bandwidth = 186 MHz
- VSWR = 1.268
- Gain = 8.627 dB

As seen in Table 5 and Figures 5(b)-(d), the array design improves gain compared to single-element antennas.

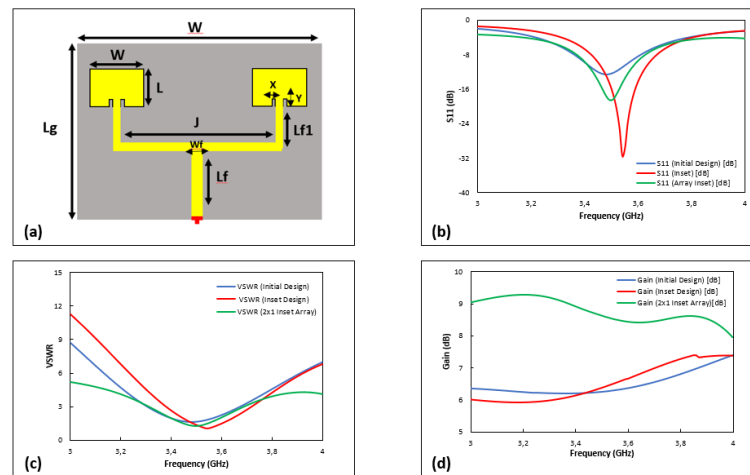


Figure 5. (a) Structure and Dimensions of the 2×1 Inset-Fed Microstrip Antenna Array, (b) Return Loss Simulation Result, (c) VSWR Simulation Result, (d) Gain Simulation Result

Table 5. Simulation Results for the 2×1 Inset-Fed Microstrip Antenna Array

Design Type	Parameter			
	Return Loss (dB)	Bandwidth (MHz)	VSWR	Gain (dB)
Rectangular Single	-12,67dB	160	1,626	5,702
Inset Single	-31,61	190	1,367	6,383
Array Inset	-18,49	186	1,268	8.627

Table 5 demonstrates that the 2×1 inset-fed array antenna design successfully improves the gain, while the addition of slits contributes to reducing return loss and axial ratio. The best performance is observed at an inset length of $X = 3$ mm, achieving a return loss of -18.49 dB, bandwidth of 186 MHz, VSWR of 1.268, and gain of 8.627 dB at 3.5 GHz.

5. 2×1 Inset-Fed Microstrip Antenna Array with U-Slot

The final configuration combines the 2×1 array structure with U-slot on each patch. Patch and slot dimensions were optimized across three iterations ($\Delta E = 1$ mm, 2 mm, 3 mm).

The optimal performance was achieved at $\Delta E = 3$ mm:

- Return loss = -36.75 dB
- Bandwidth = 169 MHz
- VSWR = 1.115
- Gain = 9.246 dB

These results, summarized in Table 6 and Figures 6(b)-(d), confirm that combining array configuration and U-slot modification yields significant improvement in gain and return loss.

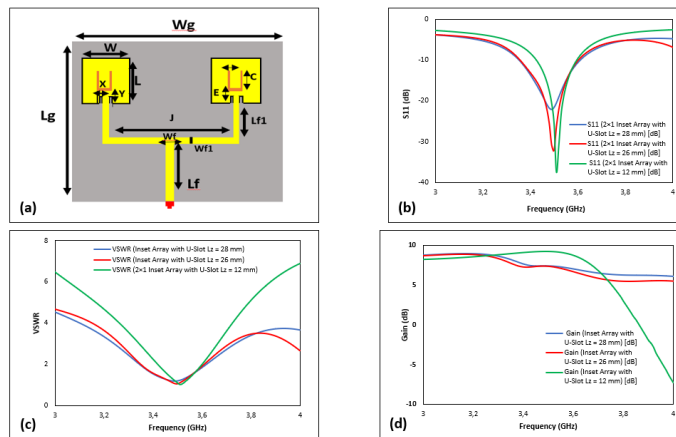


Figure 6. (a) Structure and Dimensions of the 2×1 Inset-Fed and U-Slot Microstrip Antenna Array, (b) Return Loss Simulation Result, (c) VSWR Simulation Result, (d) Gain Simulation Result

Table 6. Simulation Results for the 2×1 Inset-Fed and U-Slot Microstrip Antenna Array

Iteration ΔE	Parameter			
	Return Loss (dB)	Bandwidth (MHz)	VSWR	Gain (dB)
Iteration 1	-21,57	259	1,186	7,420
Iteration 2	-32,12	245	1,05	7,392
Iteration 3	-36,75	169	1,115	9,246

As shown in Table 6, the implementation of a 2×1 microstrip antenna array with inset feed and U-slot integration significantly improves the antenna's gain performance. Furthermore, the addition of the U-slot contributes to a reduction in return loss and VSWR. The optimal performance was recorded in the third iteration ($\Delta E = 3$ mm), achieving a return loss of -36.75 dB, a bandwidth of 169 MHz, a VSWR of 1.115, and a gain of 9.246 dB at the operating frequency of 3.5 GHz.

3.3 Antenna Simulation Analysis

Upon completion of all design and simulation phases, the analysis of key performance parameters—including return loss, VSWR, gain, and bandwidth—demonstrates that the integration of inset feeding, U-slot modification, and a 2×1 array configuration substantially enhances the overall performance of the microstrip antenna.

1. Inset Length Determination Process

Figure 7 and Table 7 provide a comparative overview of the return loss simulation results across the different antenna designs evaluated in this study.

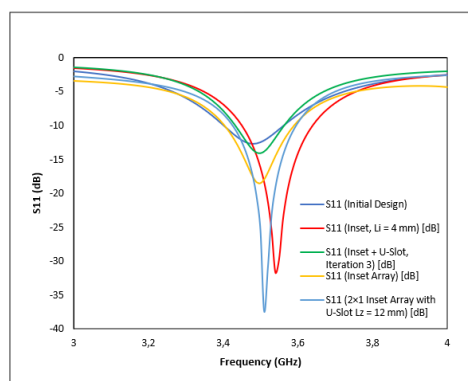


Figure 7. Comparison of Return Loss Simulation Results for Antenna Designs

Table 7. Comparison of Return Loss and Bandwidth Simulation Results

Antenna Design	Return loss (dB)	Bandwidth (MHz)
Rectangular Patch Single	-12,67	160
Inset Single	-31,61	190
Inset dan U-Slot Single	-14,01	132
Array 2x1 Inset	-18,49	186
Array 2x1 Inset dan U-Slot	-36,75	169

The integration of the inset feed and U-slot techniques in the 2×1 array configuration significantly reduces return loss and enhances bandwidth. The improvement in return loss is likely due to better impedance matching and increased surface current path introduced by the U-slot structure, which minimizes reflection. Meanwhile, the bandwidth enhancement can be attributed to the multiple resonant modes enabled by the slot, which broadens the frequency response [15].

$$\text{Return Loss Reduction} = \frac{-36,75 - (-12,76)}{-12,76} \times 100\% = 188\%$$

$$\text{Bandwidth Improvement} = \frac{169 - (160)}{160} \times 100\% = 5,625\%$$

2. VSWR Analysis

Figure 8 and Table 8 compare the VSWR simulation results of the designed antennas.

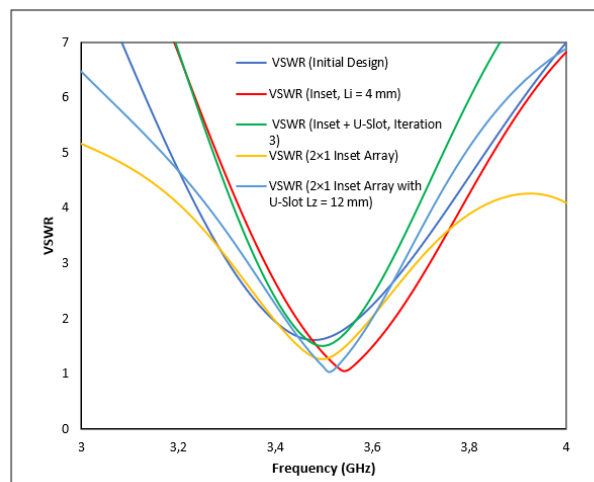


Figure 8. Comparison of VSWR Simulation Results for Antenna Designs

Table 8. Comparison of VSWR Simulation Results

Antenna Desgin	VSWR
Rectangular Patch Single	1,626
Inset Single	1,367
Inset dan U-Slot Single	1,494
Array 2x1 Inset	1,268
Array 2x1 Inset dan U-Slot	1,115

The 2×1 Inset and U-Slot Array achieves the lowest VSWR value of 1.115. This result indicates excellent impedance matching between the feed line and the antenna, which contributes to higher transmission efficiency and minimal signal reflection [16][17].

$$\text{VSWR Reduction} = \frac{1,115 - (1,626)}{1,626} \times 100\% = -31.42\%$$

3. Gain Analysis

Figure 9 and Table 9 present a comparison of gain simulation results from the antenna designs.

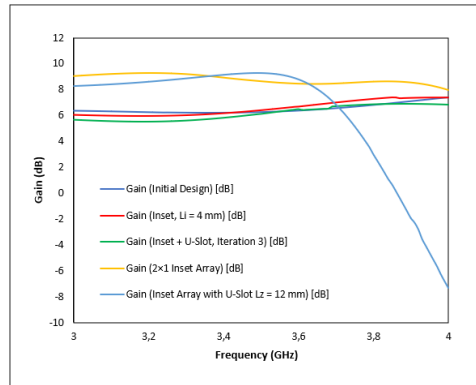


Figure 9. Comparison of Gain Simulation Results for Antenna Designs

Table 9. Comparison of Antenna Gain

Antenna Design	Gain (dB)
Rectangular Patch Single	5,702
Inset Single	6,383
Inset dan U-Slot Single	6,123
Array 2x1 Inset	8,627
Array 2x1 Inset dan U-Slot	9,246

The 2×1 Inset and U-Slot Array provides the highest gain of 9.246 dB. This enhancement in gain is attributed to the array configuration that increases the effective aperture, as well as the U-slot that contributes to better radiation efficiency by shaping current distribution on the patch [18],[19],[20].

$$\text{Gain Improvement} = \frac{9,246 - (5,702)}{5,702} \times 100\% = 62,15\%$$

4. Comparison with Previous Research

Table 10 presents a comparative analysis between the results obtained in this study and those reported in previous research works.

Table 10. Comparison with Previous Research

Reference	Method	Resonant Frequency	S11 (dB)	VSWR	Bandwidth (MHz)	Gain (dB)	Polarization	Patch Dimensions (mm)
[7]	Rectangular Patch Array 2x1 with Inset & Slit (2)	3.5 GHz	-24	<2	360	10	Unknown	28.3 x 35
[8]	Rectangular Patch Array 1x2 for 5G Communication (1)	3.5 GHz	-12.54	1.6	66.5	5.5	Vertical or Unidirectional	19.5 x 26.5
[9]	MIMO Patch Array 2x1 with Slit & Inset	3.5 GHz	-25	≤2	220	≥6	Directional	35 x 28.3
This Research	Rectangular Patch 2x1 with Inset & U-Slot	3.5 GHz	-36.75	1.115	169	9.246	Unidirectional	18.2 x 22.3

This comparison reveals that the proposed 2×1 array antenna using inset feed and U-slot techniques achieves a significantly better return loss and gain compared to the references, with competitive VSWR and bandwidth. However, it is important to note that polarization characteristics (such as axial ratio or polarization purity) were not simulated. Although the gain improvement may suggest improved radiation behaviour, future research should include explicit polarization analysis to validate this claim.

4. CONCLUSION

The determination of the inset length and the progressive optimization of the microstrip antenna design across multiple stages have demonstrated substantial performance enhancements. Simulation outcomes validate the adoption of the inset feed, U-slot, and 2×1 array configuration as effective strategies for achieving optimal values in return loss, VSWR, gain, and bandwidth, while also contributing positively to radiation behavior.

The finalized 2×1 microstrip antenna array, operating at 3.5 GHz with inset feed and U-slot integration, achieved a return loss of -36.75 dB, a gain of 9.246 dB, a VSWR of 1.115 , and a bandwidth of 169 MHz. These results confirm the antenna's suitability for 5G communication systems, offering improved gain and directivity in line with modern microstrip antenna requirements.

References Acknowledgement

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