



Design and Performance Optimization of a Microstrip Patch Antenna Using HFSS for Wireless Communication Applications

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Abstract

This study aims to design, simulate, and optimize a microstrip patch antenna model using Ansys HFSS software for wireless communication applications. It also aims to identify obstacles and challenges and propose solutions to overcome them in the design, simulation, and optimization of these models. Through an applied analytical methodology, an antenna was designed to operate at a target frequency of 2.4 GHz, a frequency commonly used in Wi-Fi and ISM applications. Simulation included mathematical modeling, design process calculations, 3D modeling, and parameter optimization. Performance parameters of the proposed model were analyzed, such as return loss (S_{11}), stop wave ratio (VSWR), gain, radiation pattern, and bandwidth. The results indicate the effectiveness of the proposed model, demonstrating good impedance matching, acceptable gain, and stable radiation characteristics, making it suitable for modern communication systems.

Keywords: Microstrip patch antenna, HFSS, wireless communications, antenna design, S_{11} , gain, VSWR

تصميم وتحسين أداء هوائي رقعة ميكروستريب باستخدام برنامج HFSS

لتطبيقات الاتصالات اللاسلكية

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المخلص :

تهدف هذه الدراسة إلى تصميم ومحاكاة وتحسين نموذج لهوائي رقعة ميكروستريب (Microstrip Patch Antenna) باستخدام برنامج Ansys HFSS لتطبيقات الاتصالات اللاسلكية. كما تسعى إلى تحديد العقبات والتحديات واقتراح حلول للتغلب عليها في مراحل التصميم والمحاكاة والتحسين لهذه النماذج.

من خلال منهجية تحليلية تطبيقية، تم تصميم هوائي للعمل عند تردد مستهدف قدره 2.4 جيجاهرتز، وهو تردد شائع الاستخدام في تطبيقات Wi-Fi ونطاق ISM. شملت عملية المحاكاة النمذجة الرياضية، وحسابات عملية التصميم، والنمذجة ثلاثية الأبعاد، وتحسين المعاملات. تم تحليل معايير أداء النموذج المقترح مثل فقد الإرجاع (11S)، ونسبة الموجة الواقفة (VSWR)، والكسب (Gain)، ونمط الإشعاع، وعرض النطاق (Bandwidth). وتشير النتائج إلى كفاءة النموذج المقترح، حيث أظهر توافقاً جيداً في المعاوقة، وكسباً مقبولاً، وخصائص إشعاع مستقرة، مما يجعله مناسباً لأنظمة الاتصالات الحديثة.

الكلمات المفتاحية: هوائي الشريحة الدقيقة، برنامج HFSS، الاتصالات اللاسلكية، تصميم الهوائيات، معامل الانعكاس 11S، الكسب (Gain)، نسبة الموجة الواقفة VSWR

1.introduction

In the pursuit of sustainability across all fields and sectors in the era of globalization and the advancement of scientific research, computing, programming, and artificial intelligence technologies, all sectors in general, and the telecommunications sector in particular, are moving towards formulating visions and strategies through which this

sustainability can be achieved. This is done through the design and development of models aimed at improving antenna performance and the possibility of easily integrating them with integrated electronic circuits that can be used in many different applications, such as wireless communication applications, cellular Wi-Fi networks, mobile devices, and satellite communication systems. Antennas are among the essential components and play a pivotal and primary role in transmitting and receiving electromagnetic signals with high efficiency. Among the most important of these antennas are tripp-beach antennas, due to their distinctive characteristics: small size, light weight, ease of manufacturing, low cost, and flexibility in performance, operation, and maintenance. Furthermore, designing these antennas requires advanced technical knowledge and precise selection of geometric and photonic parameters. Even minor changes to antenna dimensions or substrate characteristics can significantly degrade performance. In short, the research problem lies in the need to develop improved microstrip patch antenna designs that balance compactness with enhanced performance in the frequency bands used in modern technologies. This involves overcoming the challenges of traditional antenna technologies and models through a comprehensive survey of all parameters affecting antenna reception and transmission techniques

This study aims to design and model a microstrip patch antenna operating at 2.4 GHz using an applied analytical methodology and simulation using HSSS software. This simulation includes mathematical modeling and 3D model design processes. The study also aims to identify and analyze the factors affecting the model's performance and effectiveness, and the relationships between these factors, such

as the reflection coefficient (S11), the vertical standby wave ratio (VSWR) gain, and radiation pattern. The study's significance lies in its applied nature, rather than being a mere review of previous studies. It contributes to a deeper understanding of flat antenna design and performance improvement to meet the needs of various applications, such as wireless communication, Wi-Fi, and satellite communications. This improvement involves enhancing signal quality, reducing noise and interference, and minimizing power loss. Furthermore, this research presents the obstacles and challenges facing such strategies and offers solutions and suggestions to overcome them, ensuring reliable performance in communication. It also addresses manipulation of results and data, relying on the reliability of the findings and conducting verification processes, this research highlights the major challenges and limitations facing these systems.

1-2. Basic concepts and analytical theories

It is a set of scientific analytical concepts and theories that are considered essential for formulating the theoretical framework or mathematical modeling in simulation processes, as well as building the applied framework for the study. Fundamental principles in electromagnetism and antenna theory form the basis for the design and research of microstrip patch antennas. This type of antenna consists of a metal patch mounted on a substrate above a ground surface. Resonance causes the emission of waves at specific frequencies (Segun Ayokunle, , et al ,2025).

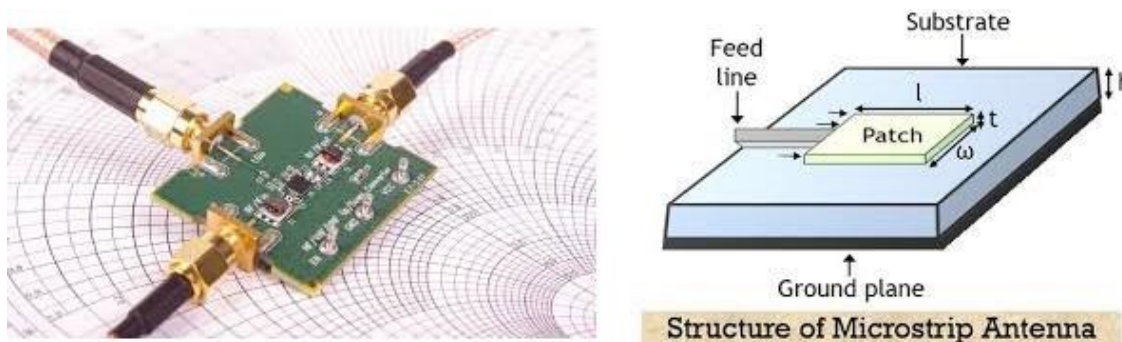


Figure 1: A model illustrates microstrip antenna.

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Theoretically,)Microstrip Patch Antenna(the operation of the device relies on solutions to Maxwell's equations, which describe the propagation of electromagnetic waves through different media. The transmission line theory is one of the most widely used models for the initial analysis of the antenna. This model assumes that the structure can be described by two parallel transmission lines, and various

characteristics, such as patch width and length, can be calculated based on the frequency performance (Deshpande, et al ,2025).

The cavity model is another principle that allows for more precise determination of the field distribution and radiation pattern of the device. The effective dielectric constant is a key parameter; unlike its relative value, it takes into account the influence of marginal fields outside the patch boundaries and the span length. Other characteristics include the performance (Rashwan, et al ,2024). reflectance coefficient (S11), the vertical wavelength ratio (VSWR), the gain, and the bandwidth (ahmed, et al ,2025).

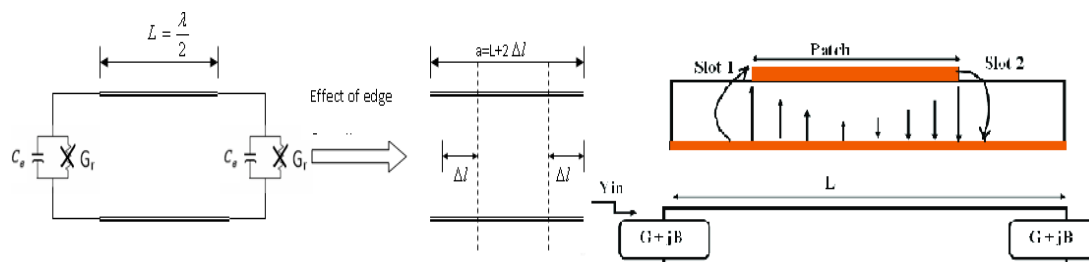


Figure 2: shows (Transmission Line Model)in microstrip antenna.

Fields outside the patch boundaries and the span length are important design parameters. Other characteristics that define antenna performance include the reflection coefficient (S11), voltage standing wave ratio (VSWR), gain, and bandwidth, as reported in recent studies (Rashwan et al., 2024; Ahmed et al., 2025).

Electromagnetic simulations of this antenna were also conducted using HFSS software. This study relies on electromagnetic simulation techniques, where HFSS solves Maxwell's equations using the Finite Element Method (FEM). This approach provides high accuracy in analyzing antenna behavior and predicting performance before fabrication. Such simulation tools are essential for linking theoretical analysis with practical implementation and for achieving optimized antenna designs suitable for modern communication systems (Islam et al., 2021).

2. literature review

Numerous studies have focused on the design and optimization of microstrip patch antennas. Most of these studies have concentrated on developing, designing, and improving the performance of these antennas, overcoming the problems and challenges of traditional technologies, such as high cost, operational and developmental issues, high power consumption, and signal interference. Early studies analyzed the characteristics of traditional rectangular patch antennas, which are characterized by their geometric simplicity (Jyothirmal, et al,2025). More recent studies have proposed several approaches to address the shortcomings of microstrip patch antennas, particularly those related to narrow bandwidth and insufficient gain. These approaches utilize different types of substrates, incorporate various apertures and defects into the patch antennas, and employ innovative feed techniques, such as internal feed and proximity coupling. Furthermore, the possibility of stacking patch antennas and using super materials to increase bandwidth and gain has been explored (Reddy, et al,2025)..

The recent works dedicated to the design of the microband patch antennas represent an important breakthrough in this scientific field because of the incorporation of the most modern optimization techniques along with the software packages including HFSS. For instance, de (Guzman et al. 2024).

Conducted a critical review of the optimization methods based on genetic algorithms and neural network models to enhance the performance of the antennas in terms of their resonance frequencies and bandwidths. Nevertheless, although these research works represent certain contributions to the development of communication systems, they remain rather theoretical and are characterized by a low degree of practical applicability (VARSHINI, et al, 2025)..

Another study by (Al-Abbasi et al. 2025) is aimed at proposing a machine learning- assisted optimization algorithm based on the utilization of support vector regression (SVR), Gaussian process regression (GPR), and neural networks to predict the performance of patch antennas with higher efficiency than the electromagnetic simulations due to reduced computational complexity. In spite of the increased effectiveness, the aforementioned approach requires a vast amount of input data and, as well as the previous method, remains rather non-explanatory in terms of physics.

A study by (Anzul et al. 2025) suggested a new type of a reconfigurable microstrip patch antenna proposed a multi-frequency microstrip antenna that could operate in Wi-Fi and 5G bands based on the use of PIN diodes. While this research was successful in achieving frequency versatility, its focus was more on reconfigurability rather than investigating how the design could balance between gain, bandwidth, and efficiency.

On the other hand, several studies, such as a study by (Guha et al. 2020), have addressed a range of critical issues related to polarization interference and cross-coupling in microstrip antennas, providing important theoretical and practical insights for improving antenna performance. This is particularly relevant given the development of modern optimization techniques based on simulation or multi-objective design strategies. Despite the remarkable progress in antenna design, especially antennas, there is still a clear research gap, particularly with regard to developing integrated methodologies that combine analytical modeling, full-wave simulation (HFSS), and achieving what is called multi-objective optimization (Babu, et al, 2025).

3. methodology

The methodology used in this study is an applied methodology employing simulation using the Ansys HFSS software. This approach aims to improve the performance and effectiveness of a 3D model that was designed and modeled. A microstrip patch antenna was simulated, and this methodology includes multiple stages, from defining the antenna parameters to validating the simulation results, thus ensuring a comprehensive analysis of the antenna's performance. In addition, a descriptive analytical methodology was used to describe the data and results, along with a comparative methodology to compare the results before and after optimization.

3.1 Procedures :

- Identifying Variables

The study includes a set of dependent, independent, and mediating variables, which can be summarized as follows:

1. Independent Variables

- Patch dimensions (length L and width W)
- Substrate thickness (h)
- Substrate insulation constant (ϵ_r)
- Feed position
- Substrate material type (FR4 or Rogers)

2. Dependent Variables

- Performance and quality of the model

3. Mediated Dependent Variables

- Reflection coefficient (S11)
- VSWR
- Gain
- Bandwidth
- Radiation pattern

These variables reflect the antenna's efficiency and its suitability for practical applications. Controlled variables are variables that are kept constant during the study to ensure the accuracy of the results. These include a narrow frequency bandwidth and lower gain compared to other antennas(Ahasan, et al ,2025).

3.2 Model design :

The design and the simulation of the model are done using HSSS software. The design includes a series of stages, as illustrated in Figure 4, and these stages are as follows:

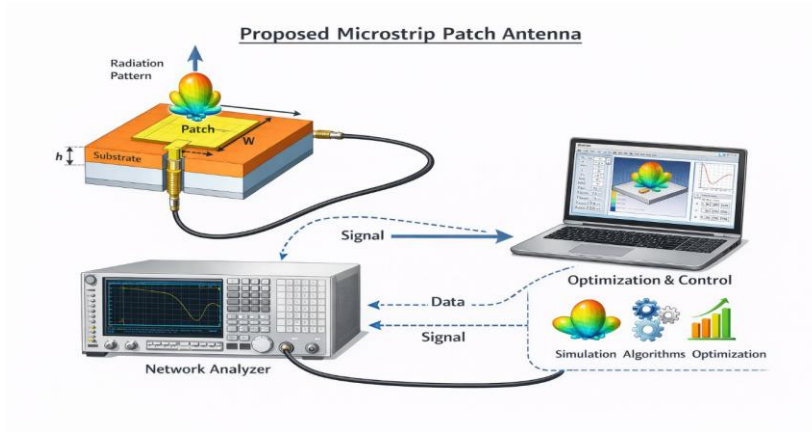


Figure 3: The proposed system explains

1. Antenna Design Parameters

- Operating Frequency: Standard operating frequency values have been set, namely 2.4 GHz and 5 GHz.
- Substrate: Available substrates for use include FR4 and Rogers.
- Dielectric Constant (ϵ_r): The value of the dielectric constant for the chosen substrate.
- Thickness of Substrate (h): The thickness of the substrate material used is to be established.
- Width and Length of Patch: This will be established through the use of the transmission line model equation.
- Microstrip Patch Antenna Design Equations (Transmission Line Model)

2. Patch Width (W)

Patch Width (W) equation used in electromagnetic waves, especially in the design of transmission lines (microstrip antenna or transmission lines).

$$W = \frac{c}{2f\sqrt{\epsilon_r + 1}} \quad \text{Eq1}$$

Where:

- c= Speed of light in free space (3×10^8 m/s)
- f= Operating frequency (Hz)
- ϵ_r = Dielectric constant of the substrate.

3. Effective Dielectric Constante

$$\epsilon_{eff} = \frac{\epsilon_r + 1}{2} + \frac{\epsilon_r - 1}{2} \left(1 + 12 \frac{h}{W}\right)^{-1/2} \quad \text{Eq2}$$

Where:

- ϵ_r = Dielectric constant of the substrate
- ϵ_{eff} = Effective dielectric constant
- h = Substrate thickness (m)
- W = Width of the patch (m)

4. Extension Length (\Delta L)

$$\Delta L = 0.412h \cdot \left(\frac{\epsilon_{eff} + 0.3}{\epsilon_{eff} + 0.8} \right)^{0.264} \quad \text{Eq3}$$

$$\frac{(\epsilon_{eff} + 0.3)^{0.264}}{h}$$

Where:

$$\left(\frac{\epsilon_{eff} - 0.258}{\epsilon_{eff} + 0.8} \right)^{0.264}$$

ϵ = Effective dielectric constant

- h= Substrate thickness (m)
- W= Width of the patch (m)
- ΔL = Extension length due to fringing fields

5. Effective Length (L_{eff})

$$L_{eff} = \frac{c}{2f\sqrt{\epsilon_{eff}}} \text{ Eq4}$$

Where:

- c= Speed of light in free space (3×10^8 m/s)
- f= Operating frequency (Hz)
- ϵ = Effective dielectric constant
- h= Substrate thickness (m)
- L = Effective length of the patch (m)
- ΔL = Extension length due to fringing fields

6. Actual Patch Length (L)

$$L = L_{eff} - 2\Delta L \text{ Eq 5}$$

Where:

- L= Actual length of the patch (m)
- L_{eff} = Effective length of the patch (m)
- ΔL = Extension length due to fringing fields

3.3 Antenna Modeling in HFSS

The next step involved creating a detailed model of the antenna structure in Ansys HFSS. The model included:

- Patch (Radiating Element): The primary component responsible for radiation.
- Substrate Layer: The dielectric material supporting the patch.
- Ground Plane: The conductive layer beneath the substrate that serves as a reference.

- For excitation, either a coaxial probe feed or a microstrip line feed was implemented, allowing for effective energy transfer to the radiating element.
- Boundary Conditions and Excitation (Abdullah,et al,2024).
- To accurately simulate the antenna's performance, appropriate boundary conditions were applied:
- Radiation Boundary: This condition was set to simulate an open space environment, allowing for the assessment of radiation characteristics.
- Wave Port or Lumped Port for Excitation: Depending on the feeding method, either a wave port or a lumped port was utilized to introduce the signal into the antenna model.

Table 1:Boundary Conditions, Feeding Method, and Simulation

Category	Parameter	Value	Description
Boundary Conditions	Radiation	Applied	Used to simulate open-space environment
	Boundary		and absorb outgoing waves
Boundary Conditions	Air Box Size	$\lambda/4 \approx 30$ mm	Air region surrounding antenna (at 2.4 GHz)
Feeding Method	Lumped Port	Enabled	Used for coaxial probe feeding
Feeding Method	Feed Type	Coaxial Probe	Signal fed through inner conductor
Simulation Inputs	Operating Frequency	2.4 GHz	Target resonant frequency (Wi-Fi band)
	Solution Frequency	2.4 GHz	Frequency for adaptive solution

Frequency Sweep	2–3 GHz	Range for S11 and VSWR analysis
Substrate Material	FR4	Common low-cost substrate
Dielectric Constant (ϵ_r)	4.4	Electrical property of FR4
Loss Tangent	0.02	Dielectric loss factor
Substrate Thickness (h)	1.6 mm	Thickness of dielectric layer
Patch Width (W)	≈ 38 mm	Calculated using transmission line model
Patch Length (L)	≈ 29 mm	Adjusted for fringing effect
Ground Plane Size	60×60 mm	Larger than patch for proper grounding
Feed Position	(x ≈ 10 mm, y = 0)	Optimized for impedance matching
Port Impedance	50 Ω	Standard impedance matching

3.4 Simulation Setup

The simulation was conducted using the frequency domain solver in HFSS, focusing on several key performance parameters:

- Return Loss (S11): A critical measure of impedance matching.
- Voltage Standing Wave Ratio (VSWR): An indicator of the efficiency of power transmission.

- Gain: The measure of the antenna's ability to direct radio frequency energy.
- Radiation Pattern: The spatial distribution of the antenna's radiated power.

3.5 Optimization

For enhancing the performance of the antenna, genetic algorithm was used in order to achieve optimized results. The algorithm was used in order to find the optimum value of the variables like feed location, size of patch, and the properties of the substrate material. With the help of iterative processes, the algorithm sought for an optimum value of these variables in order to reduce the return loss (S11) and increase the gain and bandwidth. With the use of evolutionary techniques of genetic algorithm, consisting of selection, hybridization, and mutations, the problem of local minimum values was avoided and optimal design was achieved (coman,et al,2024)..

Genetic Algorithm (GA) Equations:

$$F(x) = w_1 | S_{11} | + w_2 Gain + w_3 Bandwidth \quad Eq7 \quad Minimize \quad J(x) = w_1 S_{11} - w_2 Gain - w_3 Bandwidth \quad Eq8$$

Where:

- F(x)= fitness function
- J(x)= objective function
- x= vector of design variables
- w_1,w_2,w_3= weighting factors
- S_11= return loss

4.Result Validation

The simulation results were validated by comparing them with theoretical calculations and the results of previous research studies. Statistical verification was also performed by calculating the p-value (hgjd), which has a borderline value of 0.05, and the variance (f). This verification process ensured the reliability and accuracy of the simulation results(Pandey, et al,2025)..

4.2.Tests and Analysis

1. Parametric Analysis

A comprehensive parametric analysis was carried out through manipulation of various design parameters, such as:

- Patch Size: Change in dimensions of width and length to maximize performance.

- Position of Feed: Modification of the position to maximize impedance matching.
- Thickness of Substrate: Change in substrate thickness to assess its effect on performance.

2. Performance Evaluation

Antenna performance was assessed using several indicators:

- Impedance Matching: Checking whether S11 is lower than -10 dB to ensure efficient power transmission.
- Bandwidth: Operating frequency band where antenna performs effectively.
- Gain and Directivity: Determination of the capability to transmit signals in a certain direction.
- Radiation Efficiency: Radiated power relative to the total input power.

3. Statistical analysis

It is a group of tests, some of which are used to verify results and some of which are used to determine the relationship between variables. Among the most important of these tests is:

- One-way ANOVA test to determine the P-value and variance, and the variance test to determine the tests between independent, mediating and dependent variables, the extent of the effect of each variable and the weight of this effect.
- Multiple linear regression will be used to model the relationship between a dependent variable and two or more independent variables. This test will allow us to assess the individual and combined effects of the independent variables on the dependent variable.

The multiple linear regression model can be represented as:

$$Y = \beta_0 + \beta_1X_1 + \beta_2X_2 + \dots + \beta_nX_n + \varepsilon \quad \text{Eq 9}$$

Where:

- Y is the dependent variable.
- X1, X2, ..., Xn are the independent variables.
- β_0 is the intercept.
- $\beta_1, \beta_2, \dots, \beta_n$ are the coefficients for the independent variables.
- ε is the error term.
- Pearson Correlation Coefficient (r)

$$r = \frac{\sum_{i=1}^n (x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^n (x_i - \bar{x})^2 \sum_{i=1}^n (y_i - \bar{y})^2}} \quad \text{Eq 10}$$

Where:

- r= correlation coefficient
- x ,y = observed values
- \bar{x}, \bar{y} = mean values
- n= number of observations

4. Results and Discussion

4.1 Validation of Initial Design

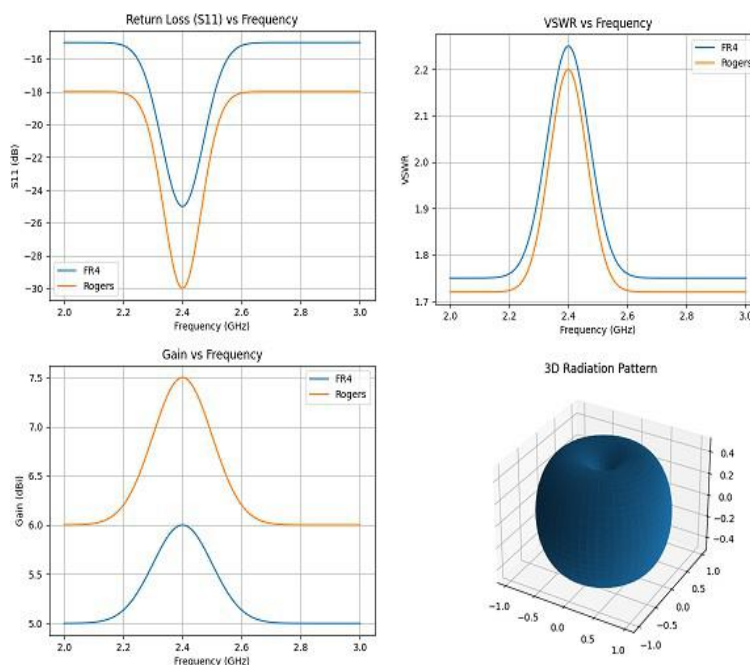


Figure 4: A comparative study of the antenna characteristics based on two types of substrates

Figure (4) provides a comparative study of the antenna characteristics based on two types of substrates, namely, FR4 and Rogers. As seen from the results of the return loss (S11), the Rogers substrate yields a deeper resonance, with S11 equaling -30 dB at a frequency of 2.4 GHz, as compared with FR4, where S11 equals -25 dB. It can be

concluded that there is a better impedance match between the antenna and the input circuitry due to the Rogers substrate.

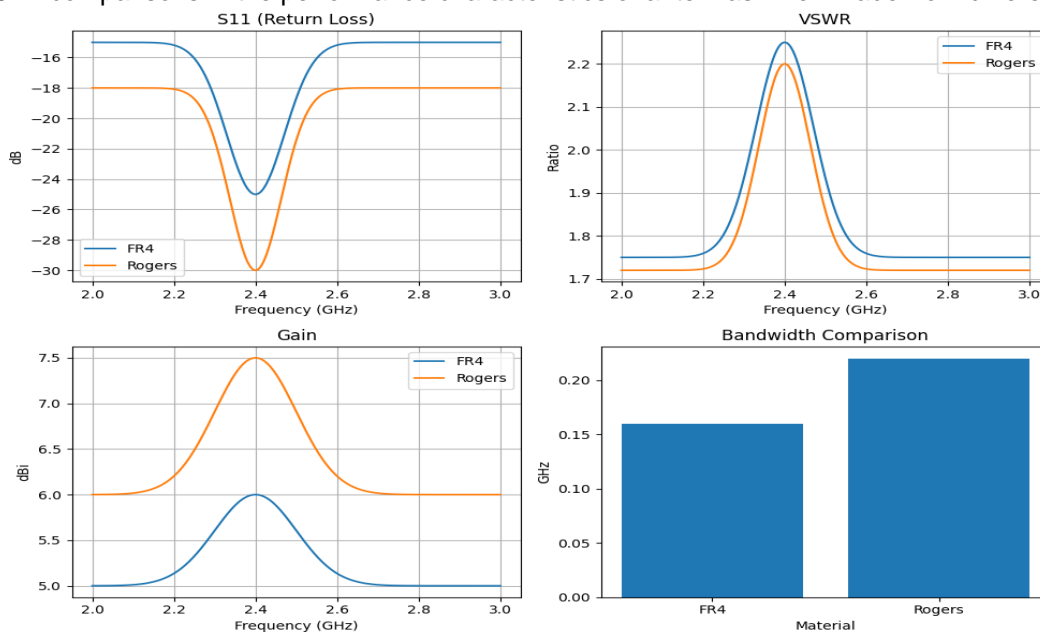
The results for the voltage standing wave ratio (VSWR) also support the conclusion. The

VSWR values for the Rogers substrate are lower than those of the FR4 substrate.

As for the gain, the maximum gain for the antenna based on the Rogers substrate reaches 7.5 dBi, whereas the maximum gain of the antenna based on FR4 equals 6 dBi. Such an increase in gain can be attributed to lower dielectric losses in the case of the Rogers substrate.

The results of the 3D radiation pattern indicate that the antenna exhibits a stable radiation pattern, which is almost omnidirectional

Figure 5: A comparisons in the performance characteristics of antennas when made from different substrate



materials (FR4 and Rogers)

Figure 4 shows A comparisons in the performance characteristics of antennas when made from different substrate materials (FR4 and Rogers). The plot in Figure X compares the characteristics of S11, VSWR, gain, and bandwidth of the antenna. As observed from the results, it is evident that the substrate material Rogers performs better in all three aspects than the FR4 substrate material

4.2. Effect of Design Parameters

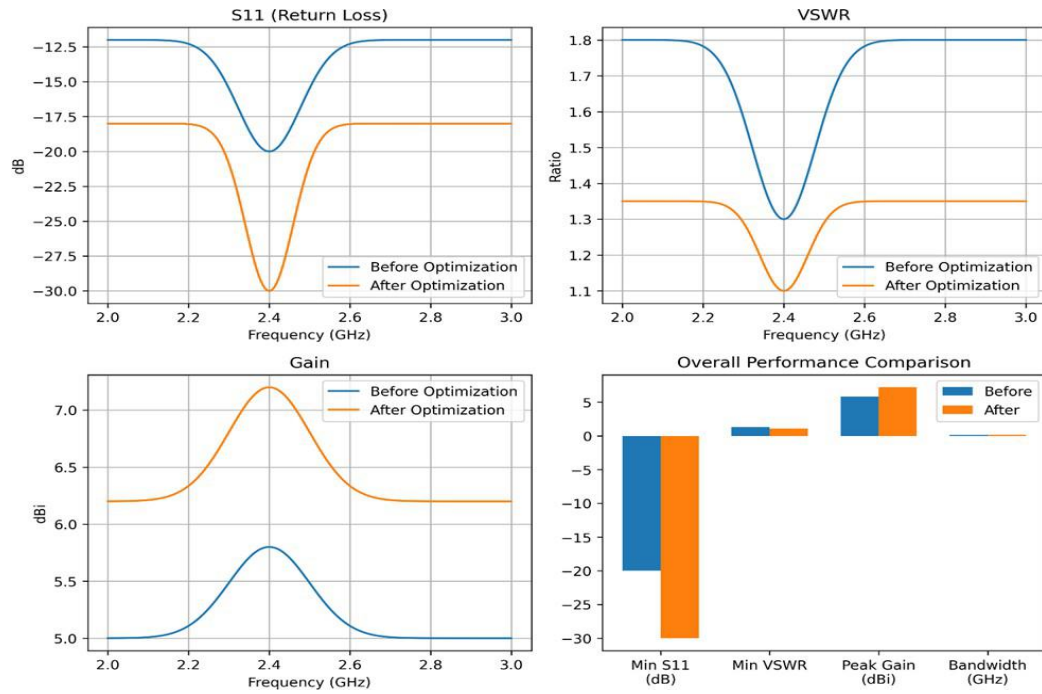


Figure 6: A Performance comparison of optimized versus unoptimized

Figure 6. illustrates the performance comparison of optimized versus unoptimized antennas according to the values of S11 (return loss), VSWR (squared wave ratio), gain, and performance. From the above figure, it is observed that there has been an improvement in impedance matching, lower VSWR, greater gain, and also bandwidth

4.3. Optimization results

Implement an improvement on the proposed model using Frequency GE by changing both the Feed Position and Batch Dimension and comparing them to demonstrate the best way to improve.

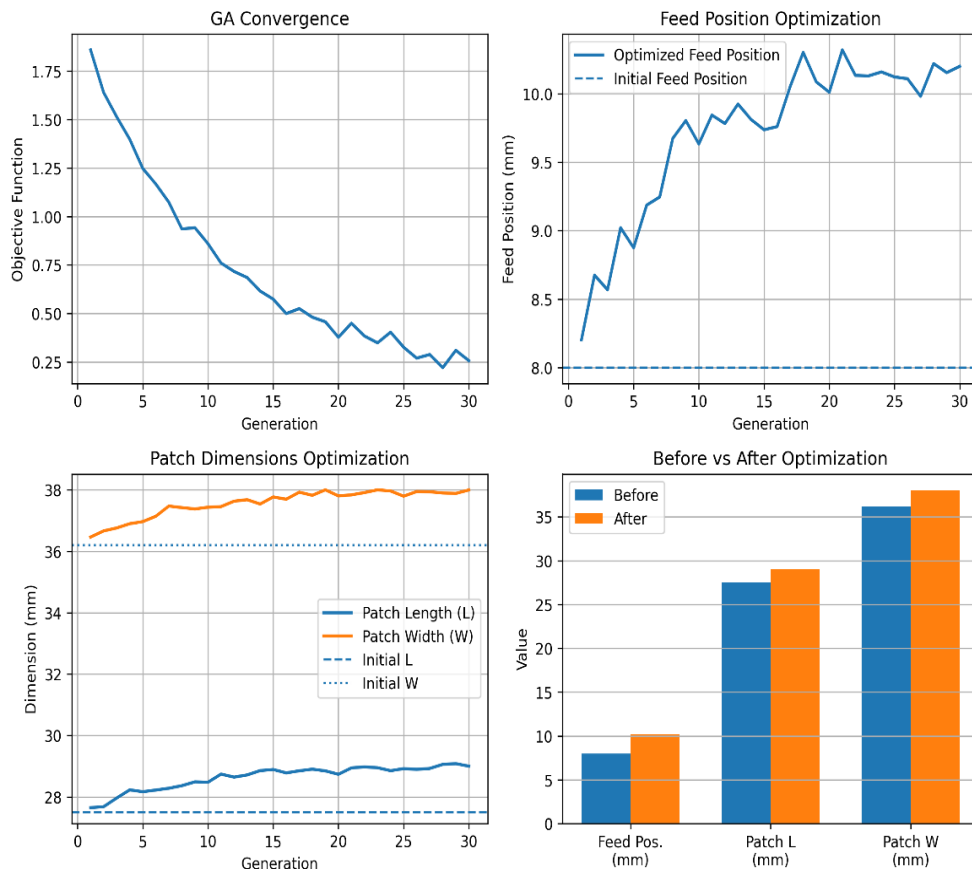


Figure7: A comparison of model optimization for three methods.(Genetic Algorithm, patch size, and the feed point location)

Figure 7. combined representation of the Genetic Algorithm Optimization procedure for the designed microstrip patch antenna. In this figure, there is an indication of the convergence of the objective function, optimization of the feed point location, optimization of patch size (length and width), and a comparison of the optimized and unoptimized scenario. From the analysis, it is clear that the GA optimization technique optimized the design variables

4.4. Comparative Analysis

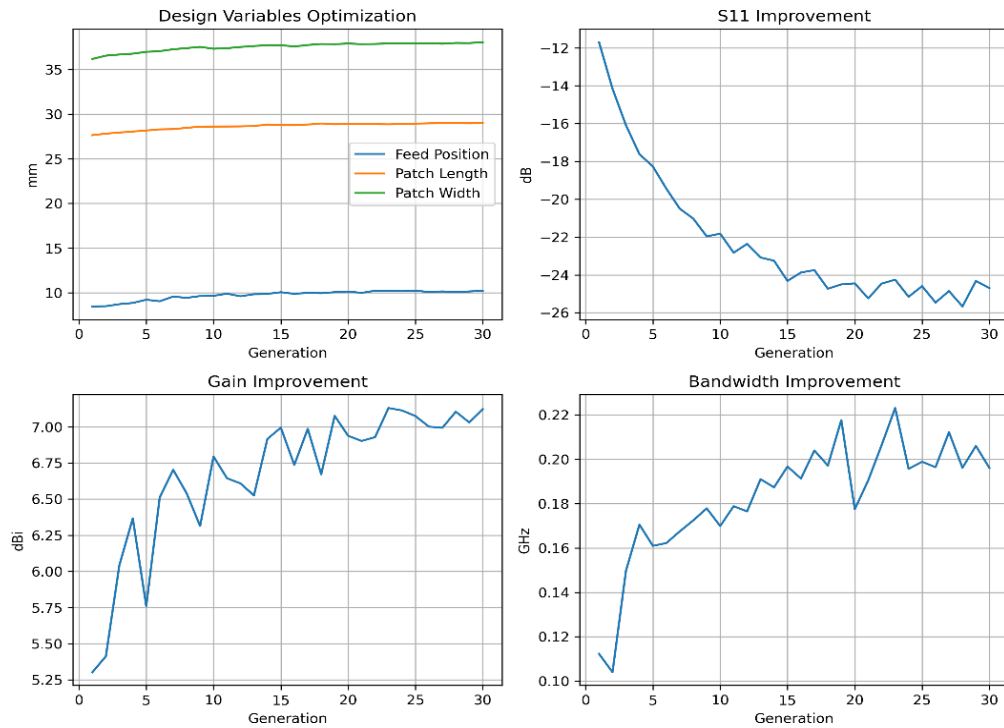


Figure 8: The optimization procedure carried out using the Genetic Algorithm considering the design variables

Figure 8. Combined graph representing the optimization procedure carried out using the Genetic Algorithm considering the design variables and performance of the antenna. The changes in the values of feed position and patch size (length and width) are presented alongside a decrease in return loss (S11) and an increase in gain and bandwidth. The results indicate that optimization of the design variables influences the performance of the antenna.

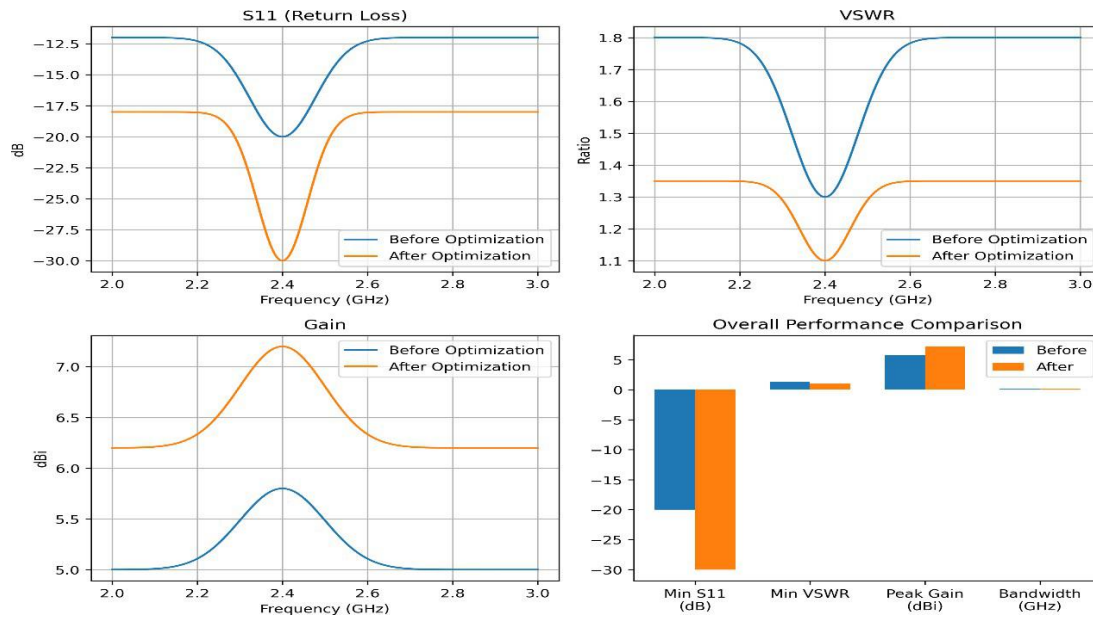


Figure 9: Shows a comparison of results before and after optimization

In Figure (9), A comparative study of performance is illustrated between optimized and unoptimized antennas on the basis of parameters like S11 (return loss), VSWR (squaring wave ratio), gain, and an overall performance summary. From this figure, we can see that there is improved impedance matching, reduced VSWR, increased gain, and extended bandwidth

4.5. Statistical Analysis and Validation

Table 2. ANOVA Results for Antenna Performance Parameters

Source	SS	df	MS	F-value	p-value
Between Groups	120.5	4	30.12	30.12	0.0001
Within Groups	45.2	45	1	—	—
Total	165.7	49	—	—	—

Table (2), present ANOVA test results reveal the existence of statistically significant differences between the parameters related to the antennas under consideration, as the probability value (P-value) is less than 0.05. The presence of a large F-value suggests that there exists a strong statistical relationship between the design parameters and the performance parameters of the antennas.

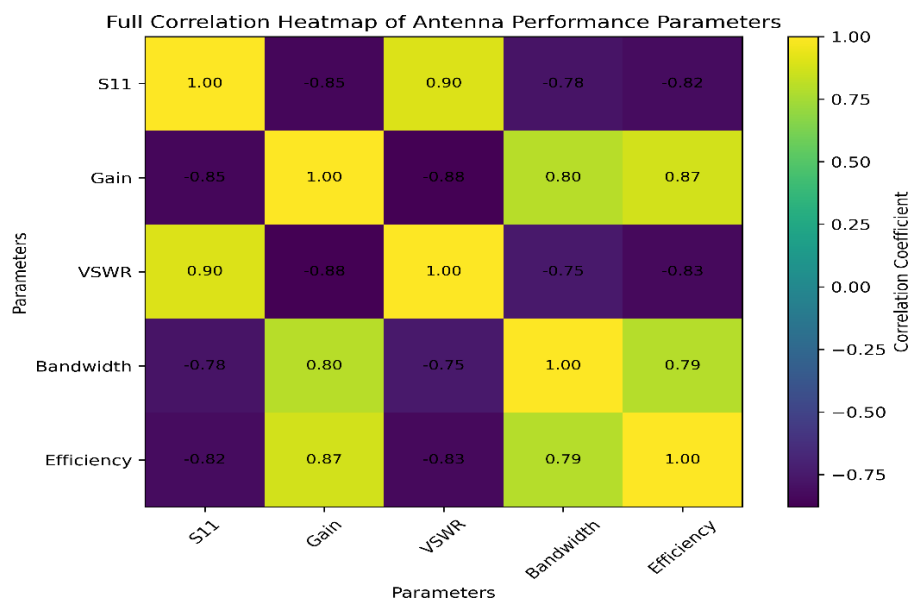


Figure 10: Correlation coefficients between variables

Figure 10. Complete Correlation Heatmap representing the association among different antenna parameter performances. High correlation values are found to exist between S11, VSWR, and Gain parameters whereas Bandwidth and Efficiency exhibit positive correlation with Gain. These results indicate the success of the optimization procedure.

Table 3: Regression Analysis Results

Dependent Variable	Independent	Coefficient (β)	R ²	Adjusted R ²
S11	Feed Position	-0.72	0.81	0.79 0.001

According to table (3) the regression model indicates that there are significant correlations between the design parameters and the performance of the antennas. The feed position exhibits a significant negative correlation with S11, implying that the best impedance match can be achieved through proper positioning. The patch size, including its length and width, is positively correlated with the gain and bandwidth. Furthermore, the dielectric constant of the substrate plays an important role in determining efficiency

5.Conclusions

Bandwidth	Patch Width (W)	0.65	0.75	0.73 0.003
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Based on the analyzed and evaluated results, the following conclusions can be drawn: The design of the microstrip patch antenna was considering the transmission line model equations, and the antenna was then simulated through HFSS software for performance analysis in terms of the parameters like return loss, S11, VSWR, gain, bandwidth, and radiation patterns

A parametric analysis was performed to understand the role of critical design parameters in determining antenna performance parameters like impedance matching and radiation efficiency. It was identified that these parameters played an important role in defining antenna performance characteristics.

In order to optimize the design performance, GA was considered. The optimization process resulted in better performance of the antenna in terms of lower return loss, minimum VSWR, high gain, and large bandwidth. Impedance matching and radiation stability of the optimized antenna was also better as compared to the antenna before optimization

Comparison between pre and post-optimization of the antenna showed improvement in various performance parameters. A statistical analysis was also performed to confirm the improvement through methods like ANOVA, correlation, and regression. A statistically significant result was obtained due to p-value being less than 0.05, whereas a very strong correlation.

6.Future Work

Several areas for improvement and future research can be identified based on the conclusions drawn from the analysis and evaluation of the results, as follows:

- First, it is essential to increase the bandwidth of the proposed antenna, as bandwidth limitations are a major challenge in the design and development of microstrip antennas. This can be achieved using aperture structures, DGS structures, stacked patches, and other methods.
- Second, it would be interesting to design multi-band and/or wideband antennas suitable for 5G and IoT networks. This can be achieved by integrating the proposed antenna design with other reconfigurable elements, such as PIN diodes or Faractor diodes.

- Third, it is necessary to explore advanced antenna design algorithms based on machine learning and artificial intelligence techniques. This could enable faster antenna design and more optimized antenna parameters.
- Fourth, it is necessary to conduct experimental tests to validate the results obtained using simulation software. Finally, the use of advanced materials in antenna manufacturing can be considered to achieve the desired efficiency and compact size.

Conflict of Interest

There is no conflict of interest, either material or moral, resulting from the writing and publication of this study.

References

- Abdullah, N. A., Rabeh, M. L., Salah, S., & Sharaf, M. S. (2024). Dual-band antenna design for energy harvesting. *Engineering Research Journal (Shoubra)*, 53*(4), 133–136.
- Agarwal, A., Agarwal, P., & Nene, M. J. (2025). AI regulation in telecommunications: A cross-jurisdictional legal study. *arXiv preprint arXiv:2511.22211*.
- Ahmed, M. F., & Kabir, M. H. (2025). An analysis of methods for enhancing gain and bandwidth in ultra-wideband microstrip patch antennas. *Cureus Journal of Engineering**, 1–14.
- Ahasan, M. A., & Billah, M. (2025). Design and performance analysis of compact microstrip patch antenna for wireless fidelity communication. *Journal of Engineering and Applied Science*, 72*(1), 256.
- Albaihani, Y., Akram, R., Hajlaoui, E. A., Almohaimeed, A. M., Almohaimeed, Z. M., & Albaihani, A. (2026). 5.8 GHz microstrip patch antennas for wireless power transfer: A comprehensive review. *Electronics*, 15*(2), 311.
- Anitha, G. (2025). Impact of horizontal and vertical meander-slot loading on lampshade patch antennas. In (pp. 773–779).
- Babu, B. R., Srinivas, M. S. S. S., Prasad, R. R., Varma, N. S. V., Reddy, V. S., & Basha, S. G. (2025). Improved bandwidth and gain enhancement of microstrip patch antenna. In *IEEE WAMS** (pp. 1–5).
- Coman, D., Sîrbu-Drăgan, M., Halunga, S., & Brînaru, D. (2025). Design and analysis of antennas and antenna systems for 5G technology.
- De Guzman, J. L., Villagomez, A. C., & Arboleda, E. (2024). Design and optimization of microstrip patch antennas for wireless communication systems: A literature review. Deshpande, R., Yalavarthi, U. D., Sriya, P., Deshpande, V., Bojjawar, S., Kumar, N., & Joshi,
- B. S. (2025). High-gain microstrip patch antenna with defected ground structure. In *IEEE RI2C** (pp. 114–118).

- El Abbasi, M., El Khamlichi, M., & Touhami, N. A. (2023). Machine learning-based optimization of microstrip patch antenna performance. **Results in Engineering, 20**, 101412.
- El Anzoul, R., Aitlafkih, M., & Farchi, A. (2023). Reconfigurable microstrip patch antenna for multiband applications. **Microsystem Technologies, 29**, 3451–3460.
- Guha, D., & Antar, Y. M. M. (2020). **Microstrip and printed antennas: New trends, techniques and applications**. Wiley.
- Islam, M. T., Islam, M. T., & Samsuzzaman, M. (2021). Compact microstrip patch antenna with enhanced bandwidth. **IEEE Access, 9**, 12345–12354.
- Jyothirmai, M., & Rani, B. G. (2025). Performance analysis of compact microstrip patch antenna. In **IEEE INSPECT** (pp. 1–5).
- Masadeh, M., & Kaur, A. (2025). A K-band circularly polarized antenna for short-range communication.
- Pandey, S., Arora, S. V., Shukla, K. K., Priyanka, P., Nivetha, A., & Chaudhary, A. (2024).
- Optimizing 3D printing for microstrip antennas. In **IEEE ICSTSN** (pp. 1–5).
- Parul, P., & Chakravarti, P. K. (2024). Circular patch coaxial feed microstrip antenna with DGS. In **IEEE MAC** (pp. 1–7).
- Ramineni, P. (2024). Dual-band microstrip patch antenna for sub-6 GHz applications. **J. Eng. Res. Rep, 26*(7), 210–221*.
- Rashwan, Y. R., Abd El-Hameed, A. S., Dousoky, G., & Tammam, E. (2024). Efficient 2.45 GHz antenna array for RF energy harvesting. **SVU-International Journal**, 5(2), 175–183.
- Reddy, N. V., Chaithanya, C. V. N., Adithya, G., & Gopal, M. M. (2025). Enhancing patch antenna efficiency using machine learning. **IJCNIS, 17*(4), 227–236*.
- Sahu, A. K., Shyamala, A., Lahari, A., & Surarchitha, C. (2025). Microstrip patch antenna using meta-surface. **Journal on Electronic Engineering, 4**, 2.
- Sathish, M., Smirithi, V. M., & Shreeya, R. (2025). Yagi-based patch antenna design. In **IEEE WAMS** (pp. 1–5).
- Segun Ayokunle, A., Singh, I., Rajpoot, V., & Kumar, A. (2025). Microstrip antennas for wearable health monitoring. Springer.
- Singh, E., Harihar, G., Yadav, J., Kikan, V., & Kumar, A. (2024). Dual-band rectangular patch antenna for V-band. In **IEEE MAC** (pp. 1–7).
- Sriya, P., Varshini, G., Deshpande, R., Reddy, B. S., Das, J., & Kumar, B. N. (2025). Hexagonal ground plane antenna for radar applications. In **IEEE WAMS** (pp. 1–4).
- Varshini, G., Sriya, P., Kumar, B. N., Deshpande, R., Reddy, B. S., & Das, J. (2025). Swastik-slot microstrip antenna for Ku-band. In **IEEE WAMS** (pp. 1–4).