Design Optimization of Microstrip Patch Antenna Using Fuzzy Logic for S-Band Communication: AI Approach

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***Abstract*—Satellite communication, mobile networks, Bluetooth, and WiFi demand compact, high-performance antennas in the S-band (2–4 GHz). Conventional Microstrip Patch Antenna (MSPA) designs struggle to optimize return loss, gain, and bandwidth simultaneously. This paper presents an intelligent optimization framework based on Artificial Intelligence (AI) and Fuzzy Logic (FL) to enhance S-band MSPA design. A fuzzy inference system adaptively adjusts key parameters such as patch dimensions, feed line size, substrate properties, and feed point position. Implemented in MATLAB, the Fuzzy Logic Controller (FLC) improves antenna performance, achieving at 2.4 GHz a return loss below –30 dB, bandwidth above 100 MHz, and gain up to 8.9 dBi. The proposed FL-based method outperforms traditional approaches, offering a robust and flexible tool for intelligent MSPA optimization.**

***Index Terms*—S-band, Microstrip Patch Antenna (MSPA), Fuzzy Logic (FL), Artificial Intelligence (AI), antenna optimization, MATLAB.**

I. INTRODUCTION

Microstrip Patch Antennas (MPAs) are widely used in modern wireless communication due to their low profile, lightweight design, ease of fabrication, and integration capability. The S-band (2-4 GHz) is especially significant, supporting applications such as satellite communication, radar, Wi-Fi, Bluetooth, and telemetry, while offering an effective balance of penetration, resolution, and coverage. Despite their advantages, MPAs face challenges such as narrow bandwidth, low gain, and sensitivity to design parameters. Traditional analytical and manual tuning methods are often inadequate to optimize multiple interdependent variables. To address these issues, intelligent techniques are increasingly applied. Fuzzy logic, a branch of Artificial Intelligence (AI), is particularly effective as it uses approximate reasoning and rule-based control to manage uncertainty and nonlinear dependencies.

This study applies fuzzy logic to optimize S-band MPAs by tuning patch dimensions, substrate properties, and feed position. A fuzzy logic controller, implemented in MATLAB, efficiently explores the design space, resulting in improved return loss, impedance matching, gain, and bandwidth. The approach demonstrates the potential of fuzzy logic to overcome traditional limitations and enable intelligent, high-performance antenna design.

II. LITERATURE REVIEW

Microstrip Patch Antennas (MPAs) are crucial to modern wireless communication systems, notably in the S-band frequency range (2-4 GHz). Their popularity stems from desirable qualities like their low profile, light weight, and ease of integration into compact, portable gadgets. But variables like restricted bandwidth, low gain, and high return loss often restrict traditional MPA design methods. These challenges are primarily caused by the complex interdependence of design factors such as patch size, substrate properties, and feeding methods. In order to overcome these limitations, researchers have looked at a variety of smart optimization methods. Due to its capacity to handle nonlinearity and uncertainty in system behavior, Fuzzy Logic (FL) has emerged as a useful optimization approach. To simulate human decision-making, FL systems employ linguistic variables and rule-based reasoning, which allow adaptive control over important design parameters.

Several researchers have demonstrated the effectiveness of fuzzy logic in optimizing antenna performance.

Patel and Kumar (2019) and Mishra et. al. (2016) both showed in their research publications that Fuzzy Logic-based methods can significantly improve antenna performance characteristics. via dynamic parameter tweaking, such as bandwidth and return loss. By facilitating implementation and analysis, the integration of FL with simulation platforms like MATLAB enhances its usefulness. Fuzzy logic is a great option for real-time, multi-objective optimization issues because of its simplicity, adaptability, and transparency. Based on earlier studies, this study proposes a fuzzy logic-based optimization framework that is particularly tailored to S-band MPAs. The goal is to make the design easier while simultaneously improving gain, bandwidth, and return loss.

III. MSPA DESIGN METHODOLOGY

The design of a Microstrip Patch Antenna (MSPA) begins by selecting the operating frequency in the S-band (2–4 GHz) and choosing a suitable substrate, such as FR-4, based on its dielectric constant, thickness, and loss tangent. Rectangular patch geometry is adopted for its simplicity, with dimensions determined using standard transmission

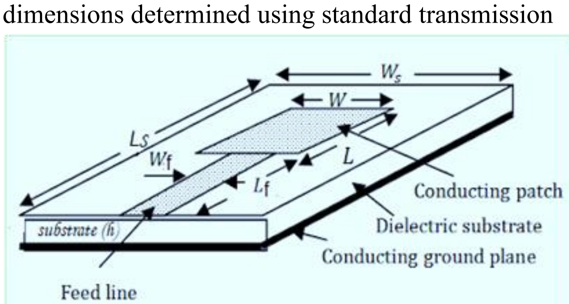

Fig.(1): Design structure of MSPA

line models to ensure resonance. Feed techniques like coaxial probe or microstrip line feed are optimized for 50 Ω impedance matching, while substrate and ground plane sizes are chosen to minimize diffraction and surface wave losses. The initial design structure is as shown in the Figure (1) accordingly it is simulated in MATLAB to evaluate key parameters including return loss, VSWR, gain, bandwidth, and radiation patterns.

To overcome the limitations of manual trial-and-error tuning, a fuzzy logic–based optimization approach is employed. Critical parameters -substrate height, dielectric constant, feed position, and patch dimensions- are adaptively tuned using a fuzzy inference system (FIS) built on linguistic rules. The FIS iteratively adjusts design variables during MATLAB simulations to achieve target metrics: return loss below –20 dB, gain above 7 dBi, bandwidth covering the S-band, and 50 Ω impedance matching. Final electromagnetic simulations validate improved performance over conventional methods. This AI-driven fuzzy optimization provides a systematic, intelligent, and efficient methodology for high-performance S-band antenna design.

IV. MICROSTRIP PATCH CONVENTIONAL ANTENNA (MSPCA) DESIGN FRAMEWORK

The design parameters of the Microstrip Patch Antenna (MSPA) have been derived using equations (1) through (7), targeting the 2–4 GHz frequency range, which corresponds to the S-band spectrum commonly employed in wireless or mobile communication applications. The antenna design and simulation were implemented using MATLAB R2013a. The developed mathematical model has been validated for a resonant frequency (fr) of 2.4 GHz. All antenna prototypes have been designed using flame retardant-4 (FR-4) substrate material with a relative dielectric constant (εr) of 4.4 and a uniform substrate height (h) of 1.60 mm. The speed of light was considered as $c=3\times10^8$ m/s in all calculations.

Width of Patch $(W)=\frac{C}{2fr\sqrt{\frac{(\varepsilon r+1)}{2}}}$ ----------- (1)

$$\varepsilon_{eff}=\left[\frac{\varepsilon_r+1}{2}\right]+\left[\frac{\varepsilon_r-1}{2}\right]\left[1+\frac{12h}{W}\right]^{-\frac{1}{2}},\ \frac{W}{h}>1 \quad \text{--- (2)}$$

$$L_{eff}=\frac{C}{2fr\sqrt{\varepsilon\,\text{eff}}} \quad \text{-------------------- (3)}$$

$$\Delta L = 0.412h\,\frac{(\varepsilon reff+0.3)(\frac{W}{h}+0.264)}{(\varepsilon reff-0.258)(\frac{W}{h}+0.8)} \quad \text{-------------- (4)}$$

Length of the patch (L) = L_{eff} - 2ΔL ------------ (5)
Length of the substrate (L_g)= 6h+L ------------ (6)
Width of the substrate (W_g) = 6h+W -------------- (7)
Where,

h- is the height of the substrate i.e. FR-4 epoxy material,
W- is width of the patch,
L- is the length of the patch,
ε_r -is the dielectric constant of the substrate.

This paper presents an optimized design methodology for Microstrip Patch Antennas (MSPAs) employing line feed in the S-band (2–4 GHz). Six FR-4 substrate-based designs (εr=4.4, h=1.6 mm) demonstrate a return loss of –30 dB, an almost ideal VSWR (≈1.0), a bandwidth exceeding 100 MHz, and compact, which shows stable performance.

MSPCA- Optimization Technique Based on Expert Knowledge:
This work presents a MATLAB based approach for designing Microstrip Patch Antennas (MSPCAs) using conventional optimization guided by expert knowledge. The antennas are designed with the line feed method, where a microstrip transmission line directly connects to the patch, and impedance matching is optimized by adjusting the feed point. Initial dimensions are derived from analytical equations and refined iteratively to improve return loss, VSWR, bandwidth, and radiation performance. Simulation results show excellent performance across the 2–4 GHz S-band: return loss between –112 dB and –124 dB, bandwidth improving from 34.85 MHz at 2 GHz to 176.59 MHz at 4 GHz, and stable gain (~–6.4 dBi) on a low-cost FR-4 substrate. The designs meet key benchmarks for WLAN, Bluetooth, and IoT applications. While AI-driven methods like Fuzzy Logic can automate optimization, this study demonstrates that expert-guided, conventional design remains precise, efficient, and cost-effective.

The Test Run: The test run at the resonant frequency of 2.4 GHz yielded the following optimized design parameters: patch size (PS) of 39.94 mm (width) × 28.85 mm (length), ground plane size (GPS) of 49.54 mm × 38.45 mm, feed line dimensions (FLD) of 3.06 mm (width, Wf) × 5.00 mm (length, Lf), and feed point offset (FPO) of 15.98 mm. Accordingly output designed MSPCA is as shown in the Figure (2).

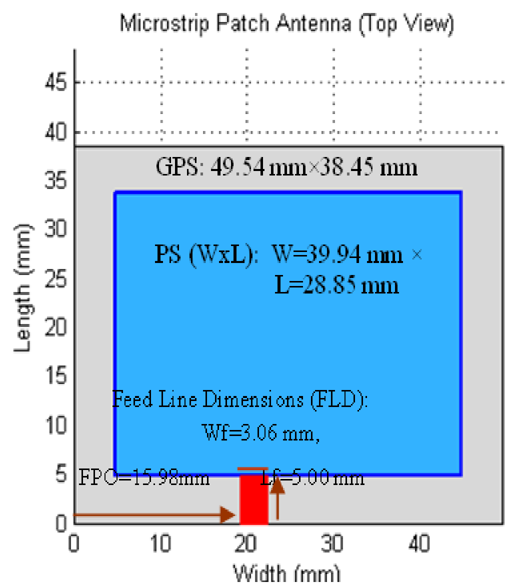

Fig. (2): Conventional Design of MSPA

Performance Analysis: The conventional Microstrip Patch Antenna (MSPCA) was designed and optimized for 2.4 GHz using an FR-4 substrate with dimensions: patch 39.94 mm × 28.85 mm, ground plane 49.54 mm × 38.45 mm, feed line 3.06 mm × 5.00 mm, and feed offset 15.98 mm. Simulation results achieved a return loss of –115.19 dB, VSWR of 1.00, and a bandwidth of 53.05 MHz, confirming near-perfect impedance matching, minimal reflection, and efficient power transfer.

The normalized E-plane radiation pattern exhibits a symmetric, broadside dumbbell profile, validating stable and directional performance. The return loss (S11), voltage standing wave ratio (VSWR), and radiation pattern are illustrated in the Figure (3, 4, 5).

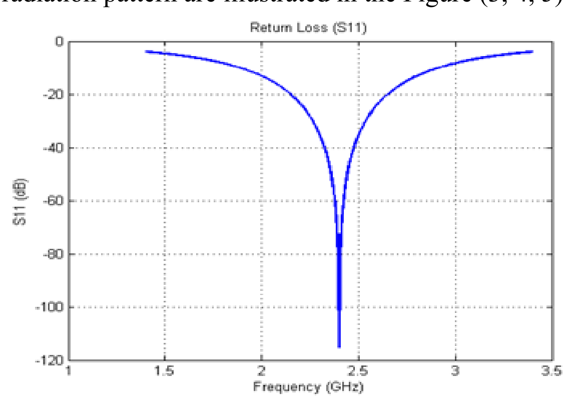

Fig. (3): Return Loss (S11)

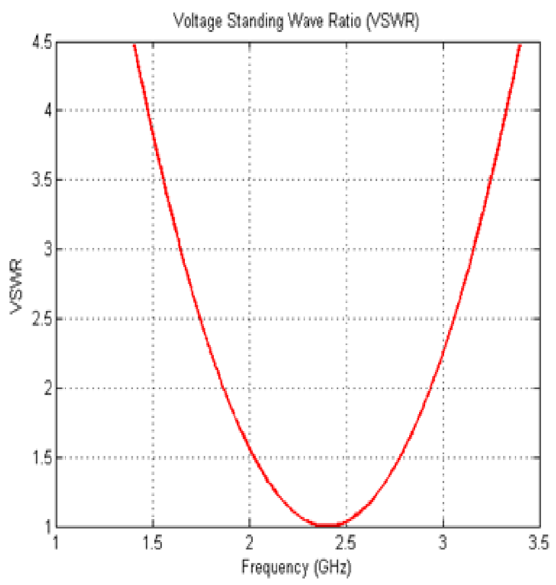

Fig. (4): VSWR

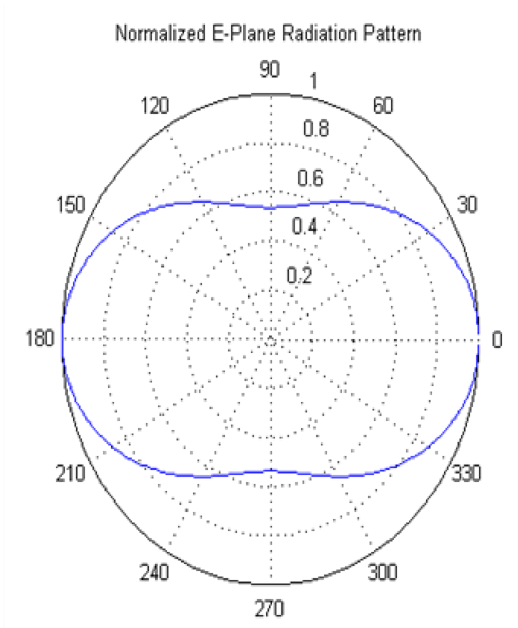

Fig. (5): E-Plane Radiation Pattern

These results confirm the suitability of the MSPCA for WLAN, Bluetooth, and IoT applications, while performance across the S-band further demonstrates the effectiveness of conventional design optimization, with representative results summarized in Table-1.

Table-1 : MSPCA design and performance results for S-band frequencies (2 & 2.4 GHz).

Sr. No.	Design Frequency Fr (GHz)	2.0	2.4
	Effective Dielectric Constant (εeff)	4.13	4.09
	Fringing Extension ΔL (mm)	0.74	0.74
	Patch Width W (mm)	47.93	39.94
	Patch Length L (mm)	34.73	28.85
	Ground Plane Width Wg (mm)	57.53	49.54
	Ground Plane Length Lg (mm)	44.33	38.45
	Feed Line Width Wf (mm)	3.06	3.06
	Feed Line Length Lf (mm)	5.00	5.00
	Feed Point Offset X-feed (mm)	19.17	15.98
	Return Loss S11 (dB)	-112.02	-115.19
	VSWR	1.00	1.00
	Gain (dBi)	-6.39	-6.40
	Bandwidth (MHz)	34.85	53.05

The results confirm that conventionally optimized MSPA designed model is a robust and effective which, offering precise control over performance parameters with minimal iterative effort.

V. MICROSTRIP PATCH FUZZY ANTENNA (MSPFA) DESIGN FRAMEWORK:

Fuzzy logic provides an effective method for handling uncertainties and nonlinearities in antenna design, especially when analytical models are complex or unavailable. It integrates empirical design knowledge with simulation-based validation, enabling adaptive and flexible antenna development. This research aims to establish a smart, semi-automated design methodology that minimizes manual calculations while ensuring high accuracy and performance for S-band applications such as WLAN, radar, and satellite communication.

The proposed work applies fuzzy logic to optimize Microstrip Patch Antenna (MSPA) parameters, focusing on patch size for improved performance. The design is simulated and analyzed using MATLAB R2013a (Fuzzy Toolbox) with the line feed method. Future stages include fabrication, experimental validation, and a comparative analysis between conventional MSPA and fuzzy logic–based MSPA (FLMSPA) in terms of return loss, VSWR, bandwidth, and gain.

Fuzzy Logic Design Methodology:

This study presents a fuzzy logic-based methodology for the intelligent design of Microstrip Patch Antennas (MSPAs), aiming to optimize patch dimensions for improved return loss, VSWR, bandwidth, and gain. Fuzzy logic, applied as a soft computing technique, models the nonlinear relationship between antenna geometry and resonant frequency through a rule-based system, enabling rapid and adaptive parameter estimation.

Once optimized parameters are obtained, the antenna is fabricated and tested, followed by comparative analysis with a conventional MSPA to validate performance improvements. The fuzzy inference system employs triangular membership functions to manage nonlinearities and uncertainties in design. The optimized antenna operates at 2.4 GHz with an FR-4 substrate (thickness 1.60 mm, dielectric constant 4.40). Key design parameters include a fringing extension of 0.7351 mm, effective dielectric constant of 4.0094, ground plane size of 37.60 mm × 29.60 mm, patch size of 28.00 mm × 20.00 mm, feed line of 3.06 mm × 5.00 mm, and a feed point offset of 11.20 mm. This approach demonstrates the potential of fuzzy optimization in developing adaptive, high-performance antennas for wireless applications.

Test Run:

A test run was carried out for a resonant frequency of 2.4 GHz using a Mamdani-type Fuzzy Inference System (FIS) for conventional MSPA design optimization. The fuzzy system uses two input variables patch width (W) and patch length (L) that determine the output parameter, resonant frequency (rf) in GHz. All variables are modelled with triangular membership functions to cover realistic ranges and ensure smooth transitions between linguistic states.

In the FLMSPA design, patch width (W) is defined over 28–38 mm and classified into three linguistic terms: Small [28, 28, 32], Medium [30, 33, 36], and Large [34, 38, 38].

Similarly, patch length (L) is defined over 20–32 mm with three categories: Short [20, 20, 24], Medium [22, 26, 30], and Long [28, 32, 32]. The output resonant frequency ranges from 2.2–2.6 GHz and is described by three linguistic terms: Low [2.2, 2.2, 2.3], Mid [2.25, 2.4, 2.55], and High [2.4, 2.6, 2.6].

These input-output relationships enable the fuzzy system to estimate the appropriate resonant frequency based on the selected patch dimensions. The graphical representation of applied fuzzy membership functions are as illustrated in the Figure (6), (7) and (8).

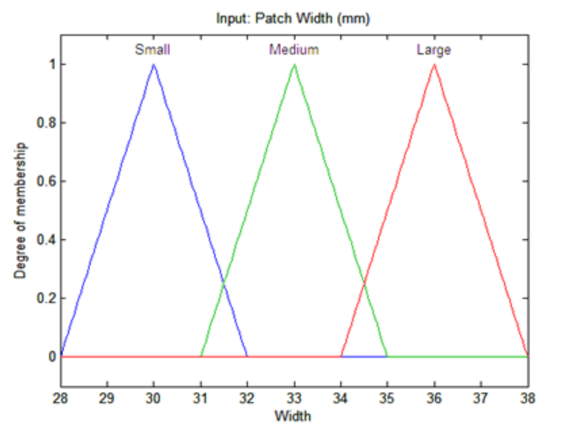

Fig. (6): Fuzzy Input Membership Function-Patch Width (w).

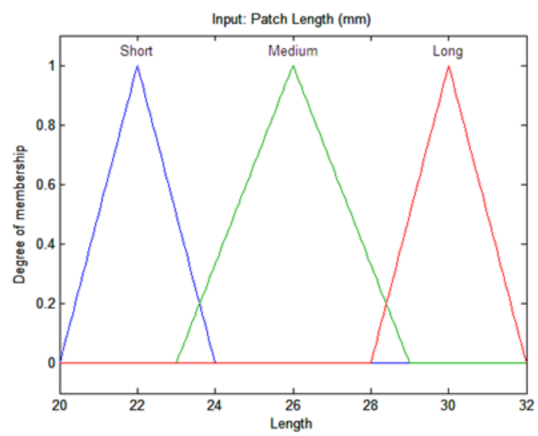

Fig. (7): Fuzzy Input Membership Function-Patch Length (L).

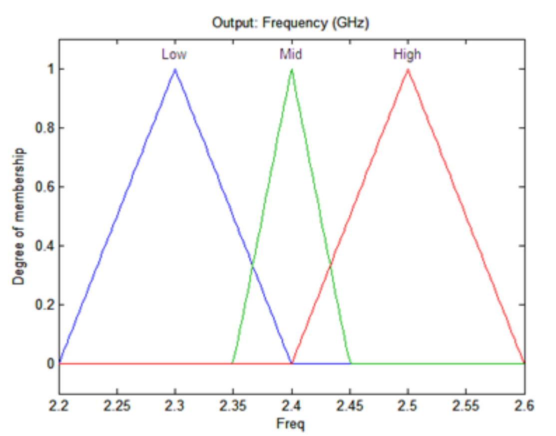

Fig. (8): Fuzzy Output Membership Function-Resonance Frequency (Fr).

Fuzzy Rule Base and Inference Strategy:
The fuzzy inference engine is driven by a set of nine linguistic rules that relate combinations of patch width and length to the expected resonant frequency.

These rules are developed based on electromagnetic theory and empirical design knowledge, reflecting how changes in physical dimensions influence antenna behaviour. Specifically, the rule base captures the fact that smaller patch sizes typically resonate at higher frequencies, while larger patch dimensions shift the resonant frequency downward. Furthermore, increasing the patch length tends to lower the operating frequency due to the extension of the electrical (power) path.

The nine fuzzy rules used in the system are as follows:

1. If patch width is *Small* and patch length is *Short*, then resonant frequency is *High*.
2. If patch width is *Small* and patch length is *Medium*, then resonant frequency is *Mid*.
3. If patch width is *Small* and patch length is *Long*, then resonant frequency is *Low*.
4. If patch width is *Medium* and patch length is *Short*, then resonant frequency is *High*.
5. If patch width is *Medium* and patch length is *Medium*, then resonant frequency is *Mid*.
6. If patch width is *Medium* and patch length is *Long*, then resonant frequency is *Low*.
7. If patch width is *Large* and patch length is *Short*, then resonant frequency is *Mid*.
8. If patch width is *Large* and patch length is *Medium*, then resonant frequency is *Low*.
9. If patch width is *Large* and patch length is *Long*, then resonant frequency is *Low*.

These rules form the core of the fuzzy inference system and are used to generate output membership values based on the given inputs. The inference mechanism aggregates the contributions from all applicable rules and computes a combined fuzzy output. Defuzzification is then performed using the centroid (center of gravity) method, which provides a crisp output value representing the predicted resonant frequency. This method is widely used in *Mamdani systems* for its balance between accuracy and interpretability.

Fuzzy Reasoning: As Width and Length increase, the resonant frequency decreases this is consistent with microstrip antenna physics. These rules form a Sugeno-type fuzzy system with Mamdani inference and help estimate the resonant frequency based on patch dimensions.

Fuzzy System Implementation and Performance:
The complete fuzzy system is developed for MSPFA using MATLAB R2013a with the built-in Fuzzy Logic Toolbox. Once designed, the FIS is exported for further use and performance of the designed MSPFA. This export creates a .fis file that encapsulates the fuzzy inference rules, membership functions, and system structure. The file can be imported into GUI-based design tools or extended for further optimization tasks. This modularity enhances reusability and streamlines integration with broader design workflows. The advanced complete Fuzzy Logic (FL) based designed structure of the MSPFA is as shown in the Figure (9).

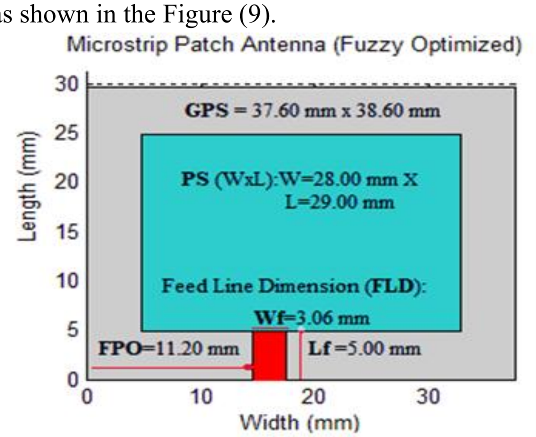

Fig.(9): MSPFA-Design using Fuzzy Logic

MSPFA: Performance Analysis:
With a Voltage Standing Wave Ratio (VSWR) of 2.10 and a return loss (S11) of -9.01 dB at 2.4 GHz, the optimized antenna exhibits reasonable impedance matching. The bandwidth of the fuzzy logic–based design is 1589.01 MHz (66.21% fractional), which is much higher than that of Standard Microstrip Patch Antennas (MSPA). It is appropriate for long-range wireless transmission and broadband because it has a gain of 7.77 dBi. Figures (10 and 11) illustrate the VSWR, E-plane features, and S11.
In conclusion, Fuzzy logic (FL) offers a valuable framework for improving the design of Microstrip Patch Fuzzy Antennas (MSPFAs) by allowing for

intelligent parameter tuning achieving a wide range of results. large bandwidth and significant gain at 2.4 GHz.

The results demonstrate the promise of fuzzy logic in handling nonlinearities and uncertainties in antenna engineering, even if impedance matching needs additional improvement. Future research might look at hybrid strategies that combine fuzzy logic with evolutionary algorithms or machine learning in order to improve impedance matching, radiation efficiency, and multiband operation.

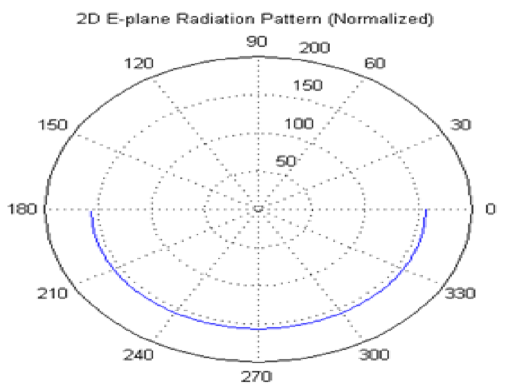

Fig.(11): MSPFA: E-Plane Radiation Pattern

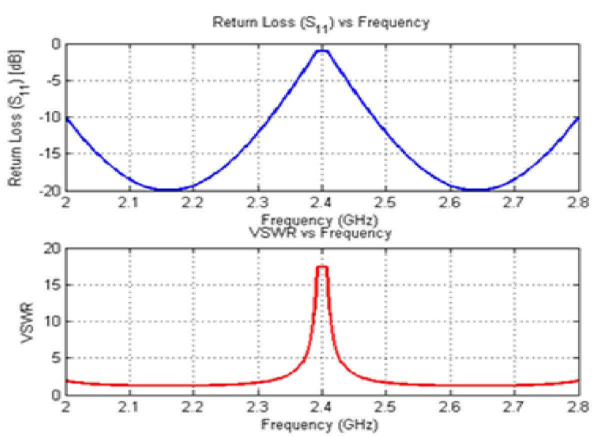

Fig.(10): Return Loss (S_{11}) and VSWR

VI. COMPARATIVE RESEARCH STUDY BETWEEN MSPCA AND MSPFA

A comparative study was conducted between the conventional Microstrip Patch Antenna design method (MSPCA) and the fuzzy logic–based design method (MSPFA), both designed at a resonance frequency of 2.4 GHz with a dielectric constant (εr = 4.4) and substrate height (h = 1.60 mm). The design and performance parameters are summarized in Table-2.

Table-2. Comparison of MSPA design parameters obtained by conventional and fuzzy logic–based optimization methods.

Sr. No.	Design & Performance Parameters	MSPCA	MSPFA
1	Design Frequency Fr (GHz)	2.4	2.4
2	Effective Dielectric Constant (εeff)	4.09	4.01
3	Fringing Extension ΔL (mm)	0.74	0.73
4	Patch Width W (mm)	39.94	28.00
5	Patch Length L (mm)	28.85	29.00
6	Ground Plane Width Wg (mm)	49.54	37.60
7	Ground Plane Length Lg (mm)	38.45	38.60
8	Feed Line Width Wf (mm)	3.06	3.06
9	Feed Line Length Lf (mm)	5.00	5.00
10	Feed Point Offset X-feed (mm)	15.98	11.20
11	Return Loss S11 (dB)	–115.19	–9.01
12	VSWR	1.00	2.10
13	Gain (dBi)	–6.40	7.77
14	Bandwidth (MHz)	53.05	1589.01

Comparative Analysis:

1. Frequency Accuracy: Both MSPCA and MSPFA achieve the target resonance frequency of 2.4 GHz. However, MSPFA directly predicts patch dimensions using fuzzy rules, avoiding the repeated tuning required in MSPCA optimization.
2. Impedance Matching: MSPCA shows extreme values of S11 = –115 dB, and VSWR = 1.0, that are ideal but not practical. MSPFA provides more realistic results (S11 ≈ –9 dB, VSWR ≈ 2.1), ensuring stable performance in real applications.
3. Bandwidth: MSPFA offers a major improvement in bandwidth, reaching 1589 MHz compared to only 53 MHz in MSPCA. This makes it more suitable for wideband and multi-standard wireless systems.
4. Gain: MSPCA gives a negative gain (–6.40 dBi), limiting its use, while MSPFA achieves a high gain of 7.77 dBi, supporting efficient radiation for WLAN and S-band applications.
5. Compactness & Miniaturization: MSPFA reduces patch and ground plane sizes (W = 28 mm, Wg = 37.6 mm) compared to MSPCA (W = 39.94 mm, Wg = 49.54 mm). This makes MSPFA better for compact and portable devices.

6. Trade-Offs: MSPFA provides compact size, higher gain, and wider bandwidth, though its VSWR (≈ 2.1) shows some mismatch compared to the ideal 1.0 of MSPCA. In some fuzzy designs, bandwidth may be slightly reduced, but this is balanced by better efficiency, directivity and miniaturization.

Advantages of Fuzzy Logic (FL) Optimization in MSPFA Design:
FL based optimization makes antenna design easier by removing manual trial-and-error through smart rules. It can quickly adapt to different frequencies, materials, and design needs. This method saves time and effort by reducing heavy simulations in the early stages. It also improves performance with higher gain, compact size, and wider bandwidth, which is useful for modern communication systems.

VII. CONCLUSION

The comparative study clearly shows that the fuzzy logic–based design (MSPFA) offers substantial improvements in bandwidth, gain, and design compactness compared to the conventional approach (MSPCA). Although MSPCA provides excellent theoretical impedance matching, its negative gain and limited bandwidth reduce its real-world applicability.

MSPFA, on the other hand, delivers a practical, high-gain, and adaptive design well-suited for modern wireless applications, particularly WLAN and S-band communication systems. Ultimately, the choice between MSPCA and MSPFA depends on design priorities: MSPCA for conventional stability and impedance matching, or MSPFA for advanced, compact, and high-performance solutions.

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