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Enhancement of Microstrip Patch Antenna Design and Performance for S-Band Applications Using Fuzzy Logic

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Abstract: S-band (2-4 GHz) antennas play a critical role in modern wireless systems such as satellite communication, Wi-Fi, Bluetooth, and mobile networks. Microstrip Patch Antennas (MSPAs) are widely preferred for these applications due to their compact size, low profile, and ease of fabrication. However, conventional MSPA designs often exhibit narrow bandwidth, low gain, and reduced radiation efficiency because of strong nonlinear coupling among design parameters. This paper presents an Artificial Intelligence (AI) based optimization approach using Fuzzy Logic (FL) to enhance the performance of S-band MSPA. A Fuzzy Inference System (FIS) is developed to intelligently tune critical antenna parameters including patch dimensions and feed location. The paper proposes the design is implemented in MATLAB R2013a [8] and evaluated at a target frequency of 2.6 GHz. Simulation results demonstrate considerable improvement in antenna performance, achieving enhanced bandwidth, improved gain, and acceptable impedance matching. Comparative analysis confirms that the fuzzy logic optimized MSPA outperforms the conventionally designed antenna in terms of bandwidth, compactness, and radiation characteristics, making it suitable for modern S-band wireless communication applications in the current scenario.

Keywords: S-band, Microstrip Patch Antenna, Fuzzy Logic, Artificial Intelligence, Antenna Optimization, Bandwidth, Gain.

I. INTRODUCTION

The line feed Microstrip Patch Antennas (MSPAs) have become an essential electronic component of modern wireless communication systems due to their low cost, lightweight structure, planar configuration, and compatibility with integrated circuits. These features make them particularly attractive for compact and portable wireless devices. Among various operating frequency ranges, the S-band (2-4 GHz) is extensively utilized for applications such as satellite communication, radar systems, Wi-Fi, Bluetooth, WLAN and telemetry because of its favourable propagation characteristics and moderate atmospheric attenuation. Despite their advantages, MSPAs suffer from inherent limitations including narrow impedance bandwidth, low gain, and limited radiation efficiency. These drawbacks become more pronounced when low-cost dielectric substrates such as FR-4 are employed. Conventional antenna design techniques rely on analytical models and iterative manual optimization, which are often insufficient to simultaneously optimize multiple conflicting performance parameters. The nonlinear relationship between antenna geometry, substrate properties, and feeding configuration further complicates the design process.

To address these challenges, Artificial Intelligence (AI) based optimization techniques have gained increasing attention in antenna engineering. Among these techniques, Fuzzy Logic (FL) offers a robust and interpretable framework for handling uncertainty, imprecision, and nonlinear interactions among design variables. Unlike data intensive approaches such as Artificial Neural Networks, FL incorporates expert knowledge through linguistic rules, making it well suited for electromagnetic design problems. This work proposes a fuzzy logicbased optimization framework to enhance the performance of an S-band Microstrip Patch Antenna, focusing on bandwidth enhancement, gain improvement, and antenna miniaturization.

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II. LITERATURE REVIEW

Microstrip Patch Antennas (MSPAs) have been the subject of extensive research for several decades due to their inherent advantages such as low profile, ease of fabrication, and compatibility with planar microwave circuits. Foundational work by Pozar and Schaubert [1] established the theoretical basis for microstrip antenna analysis using cavity and transmission-line models, clearly identifying the fundamental performance limitations of MSPAs, particularly narrow bandwidth and moderate gain. Garg *et al.* [2] and James and Hall [3] further expanded on practical design considerations, emphasizing that antenna performance is strongly governed by interdependent parameters such as patch dimensions, substrate permittivity, substrate thickness, and feeding technique. These early studies collectively highlighted that improving one performance metric often degrades another, thereby motivating the need for systematic optimization techniques. Several conventional approaches have been proposed to overcome these limitations, including the use of thicker substrates, low permittivity dielectric materials, stacked patches, parasitic elements, and defected ground structures. Although such techniques can enhance bandwidth and gain, they often increase fabrication complexity, cost, and overall antenna size, making them less suitable for compact and low-cost wireless devices. Furthermore, these approaches typically rely on extensive electromagnetic simulations and manual parametric sweeps, which are time-consuming and design specific.

With the advancement of computational intelligence, Artificial Intelligence (AI) based optimization techniques have gained significant attention in antenna engineering. Among these, Genetic Algorithms (GA), Particle Swarm Optimization (PSO), and Artificial Neural Networks (ANN) have been widely applied to improve antenna dimensions and performance. However, as discussed by Deb *et al.* [7], evolutionary algorithms, while powerful, require large computational resources and careful parameter tuning to validate convergence. ANN-based approaches, on the other hand, demand extensive training data and often behave as black-box models, limiting physical interpretability and generalization capability.

Fuzzy Logic (FL) has emerged as an attractive alternative due to its rule-based reasoning, transparency, and ability to handle uncertainty and nonlinear relationships. Mishra *et al.* [4] demonstrated that a fuzzy logic controller can effectively optimize microstrip antenna parameters to improve return loss and impedance matching without requiring complex mathematical formulations. Similarly, Mishra and Gupta [5] compared ANN and FL-based optimization techniques and reported that fuzzy logic offers comparable or superior characteristics with significantly decreased computational complexity and enhanced interpretability. Patel and Kumar [6] applied fuzzy logic optimization to microstrip antennas and showed that linguistic rule-based tuning of patch dimensions can lead to substantial enhancement in bandwidth and operating frequency accuracy. Their work highlighted that fuzzy systems are particularly effective when precise analytical relationships between design variables and performance metrics are very tough to achieve. Moreover, fuzzy logic allows the incorporation of expert electromagnetic knowledge directly into the optimization process through intuitive IF–THEN rules.

Despite these advancements, most reported fuzzy logic based antenna designs focus on specific frequency bands or isolated performance improvements, such as return loss or resonant frequency tuning. Limited research has addressed comprehensive optimization that simultaneously considers bandwidth enhancement, gain improvement, and antenna miniaturization for S-band applications with low cost and easily available substrates like FR-4. Additionally, many existing studies lack a detailed comparative analysis between conventional and fuzzy-optimized designs under identical operating conditions. From a research motivation perspective, there exists a clear need for an intelligent, low-complexity, and physically interpretable optimization framework that can overcome the inherent trade-offs of conventional MSPA design while maintaining fabrication simplicity. Fuzzy Logic fulfils these requirements by providing a flexible decision making structure capable of mapping nonlinear relationships among antenna parameters without excessive computational burden. Motivated by these research gaps, the present work proposes a dedicated fuzzy logic based optimization framework for S-band Microstrip Patch Antennas, aiming to achieve wide bandwidth, enhanced gain, and compact geometry using a cost-effective substrate. This approach not only advances antenna performance but also contributes to the broader objective of integrating AI techniques into practical electromagnetic design workflows.

III. MSPA DESIGN METHODOLOGY (LINE FEED)

The suggested research approach starts with choosing the target resonant frequency in the S-band range and the ideal dielectric substrate. Because of its low cost and widespread availability, FR-4 epoxy material is chosen. Due to its structural simplicity and well-established analytical modeling methods, a rectangular microstrip patch geometry is selected. Using traditional transmission line model equations, the initial antenna parameters, such as the patch width,

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patch length, effective dielectric constant, and substrate dimensions, are determined. A microstrip line feeding method is used to obtain 50 Ω impedance matching. The conventional antenna performance parameters, such as return loss, voltage standing wave ratio (VSWR), gain, and bandwidth, are evaluated using MATLAB R2013a simulations.

To improve antenna performance, a Fuzzy Logic-based optimization technique is introduced. A Fuzzy Inference System (FIS) is created to dynamically adjust patch dimensions and feed position. Equations (1) through (7) have been used to derive the design parameters for the Microstrip Patch Antenna (MSPA), which is designed for the 2-4 GHz frequency range, which corresponds to the S-band spectrum that is frequently used in wireless or mobile communication applications. The fuzzy logic controller iteratively improves the antenna parameters in accordance with predetermined linguistic rules that are based on electromagnetic design knowledge.

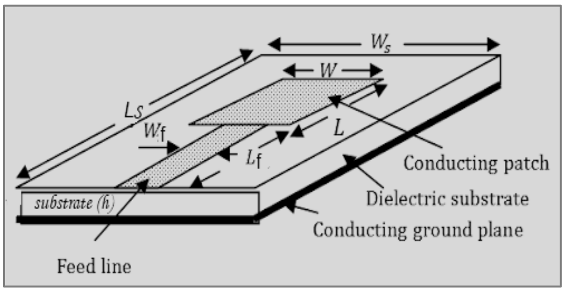

Fig.(1): Design structure of MSPA

1) MICROSTRIP PATCH CONVENTIONAL ANTENNA (MSPCA) DESIGN FRAMEWORK:

Achieving a return loss of less than −20 dB, a gain of more than 7 dBi, and a bandwidth of more than 100 MHz are among the optimization goals. MATLAB R2013a is used to carry out the antenna design and simulation. The created mathematical model has been tested for a resonant frequency (fr) of 2.6 GHz. In all calculations, the speed of light was assumed to be $c=3\times10^8$ m/s. All antenna prototypes have been made using flame retardant-4 (FR-4) substrate material with a uniform substrate height (h) of 1.60 mm and a relative dielectric constant (εr) of 4.4.

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

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

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

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

$$\text{Length of the patch (L)} = L_{eff} - 2\Delta L \quad \ldots\ldots\ldots\ldots\ldots\ldots \text{(5)}$$

$$\text{Length of the substrate } (L_g)= 6h+L \quad \ldots\ldots\ldots\ldots\ldots\ldots \text{(6)}$$

$$\text{Width of the substrate } (W_g) = 6h+W \quad \ldots\ldots\ldots\ldots\ldots\ldots \text{(7)}$$

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

Based on traditional Microstrip Patch Antenna (MSPA) theory, the current study employs a standard analytical approach that integrates transmission line and cavity model theory with expert knowledge based parametric tuning to optimize the Microstrip Patch Conventional Antenna (MSPCA). The patch width (W) and length (L) are initially calculated using standard equations that take into account the resultant dielectric constant and fringing total field effect. The analytically obtained dimensions are then empirically modified, such as by manually adjusting the line feed for impedance matching, carefully widening the patch width, slightly reducing the patch length, and appropriately choosing the ground plane size. These modifications are made using well-known design concepts and the designer's expertise, rather than using automated numerical optimization.

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The feed offset location is selected for optimal impedance matching without using iterative or adaptive optimization loops, and the feed line width is chosen for 50 Ω matching. In order to assess the efficiency of the selected design parameters, a single pass simulation is used to analyze antenna performance indicators such return loss, VSWR, gain, directivity, and bandwidth. As a result, the method used is a traditional optimization strategy that is experience driven, deterministic, and not AI-based. It serves as a trustworthy benchmark for evaluating intelligent optimization strategies, such as the fuzzy logic-based MSPCA design. The experimental findings from the optimization procedure, with an emphasis on the ideal design parameters of the suggested antenna, which runs in the S-band at a 2.6 GHz input frequency, are covered in the following section.

The Test Run: in this experiment the resonant frequency of 2.6 GHz produced the following optimized design parameters: patch size (PS) of **36.87 mm** (width) × **26.59 mm** (length), ground plane size (GPS) of 46.47 mm × 36.19 mm, feed line dimensions (FLD) of 3.06 mm (width, Wf) × 5.00 mm (length, Lf), and feed point offset (FPO) of 14.75 mm. Accordingly output designed MSPCA is as shown in the Fig. (2). And well tabulated in the Table-1

TABLE-I: RESULTS OF MSPCA

Sr. No.	MSPCA Design Parameters	Width (W) (mm)	Length (L) (mm)	Remark
1.	Patch Size (PS)	36.87	26.59	Radiating element
2.	Ground Plane Size (GPS)	46.47	36.19	Finite ground plane
3.	Feed Line Size (FLS)	3.06	5.00	Line feed for impedance matching
4.	Feed Point Offset (FPO)	–	14.75	Offset from patch edge

The optimized MSPCA design yields a patch size of 36.87 mm × 26.59 mm and a ground plane size of 46.47 mm × 36.19 mm. The feed line dimensions are 3.06 mm in width and 5.00 mm in length, with a feed point offset of 14.75 mm. The resulting antenna geometry is illustrated in Fig.(2), and the optimized design parameters are summarized in Table-1.

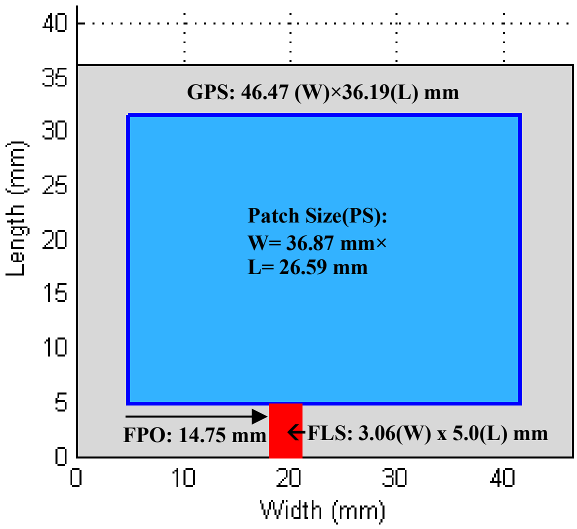

Fig. (2): Conventional Design of MSPCA (Top View)

Performance Analysis: The optimized line-fed microstrip patch conventional antenna (MSPCA) operating at 2.6 GHz is evaluated in terms of impedance matching, radiation behavior, and bandwidth. The normalized E-plane radiation pattern exhibits a symmetric broadside dumbbell-shaped profile, indicating stable and well directed radiation characteristics. At resonance, the antenna achieves an excellent minimum return loss of −116.58 dB with a corresponding VSWR of 1.00, confirming near ideal impedance matching between the feed and the radiating element. The estimated directivity and gain are −4.19 dBi and −6.41 dBi, respectively, while the impedance bandwidth is measured as 63.88 MHz around the operating frequency, demonstrating effective resonance and adequate bandwidth for S-band wireless applications.

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The antenna is designed using analytical transmission-line equations and refined through expert guided parametric optimization on an FR-4 substrate. Although the optimized design achieves precise resonance, excellent matching, and stable radiation behavior, the realized gain and directivity remain limited due to dielectric losses and surface-wave effects associated with FR-4 material. Moreover, the conventional optimization approach is largely designer dependent and lacks the flexibility to simultaneously optimize multiple performance metrics. Consequently, while the parametric optimization provides a reliable baseline design, its inherent limitations in radiation performance motivate the exploration of intelligent optimization techniques for further enhancement. **Therefore, the conventionally optimized MSPCA serves as a reference benchmark for evaluating the MSPFA presented in the subsequent section.**

2) MICROSTRIP PATCH FUZZY ANTENNA (MSPFA) DESIGN FRAMEWORK:

Fuzzy logic provides an effective framework for antenna design by managing uncertainty, imprecision, and nonlinear behavior while embedding expert knowledge into the optimization process, particularly when difficult analytical models are complex or inadequate. This research aims to develop a smart, semi-automated antenna design methodology that significantly reduces manual calculations without compromising accuracy or performance. The proposed approach is applied to S-band applications such as WLAN, radar, and satellite communications. A Mamdani-type Fuzzy Inference System (FIS) is employed to design and optimize a rectangular Microstrip Patch Fuzzy Antenna (MSPFA) with a microstrip line feed, enabling direct estimation of optimal patch width (W) and length (L) for a specified resonant frequency. By integrating expert defined fuzzy rules and triangular membership functions, the methodology effectively captures the nonlinear relationship between antenna geometry and electromagnetic characteristics, resulting in a systematic and adaptive design strategy.

A **Mamdani type Fuzzy Inference System (FIS)** is developed to estimate the resonant frequency based on the input patch dimensions. The system incorporates triangular membership functions for both input and output variables. Defuzzification is performed using the centroid method, which provides accurate and continuous frequency estimation. The next section presents the optimization of the MSPFA which uses the ***Fuzzy Logic Technique (FLT),*** which constitutes the core design innovation of the proposed approach.

- **MSPFA Optimization Using FLT**

The MSPA is widely used in modern wireless communication due to its compact size, low profile, and ease of integration. Optimizing its design parameters, such as patch width (W) and length (L), to achieve a desired resonant frequency (fr) is challenging due to the non-linear dependence of resonant frequency on geometrical and material parameters. Fuzzy logic provides an effective approach to model this non-linearity and achieve optimized MSPA design without relying solely on complex mathematical equations. The proposed methodology employs a Mamdani Fuzzy Inference System (FIS) to optimize the patch width (W) and patch length (L) of a rectangular microstrip patch antenna (MSPA) in order to achieve a desired resonant frequency (fr). Unlike conventional closed-form analytical equations, fuzzy logic incorporates expert knowledge, nonlinearity, and uncertainty, making it well suited for antenna optimization problems in which electromagnetic parameters are highly interdependent. The fuzzy system is integrated with an optimization framework to estimate antenna dimensions by minimizing the resonant frequency error. In this research, the fuzzy logic (FL)–based design methodology comprises four fundamental stages: (1) fuzzification, (2) fuzzy rule evaluation (inference), (3) aggregation, and (4) defuzzification. Based on this framework, a fuzzy optimization algorithm is developed in reference to the flowchart, as shown in Fig.(3.)

The obtained crisp resonant frequency is used to compute the frequency error and subsequently select the optimal antenna dimensions. This approach provides a smooth and physically meaningful estimation of the resonant frequency and is well suited for antenna optimization problems. The developed fuzzy logic based optimization algorithm employs a Mamdani fuzzy inference system (FIS) to estimate the microstrip patch antenna dimensions directly from the desired resonant frequency. The algorithmic steps are implemented as follows.

1. Specify the target resonant frequency fr and substrate parameters (εr,h).
2. Initialize the Mamdani FIS with patch width (W) and length (L) as inputs, define membership functions, and construct fuzzy rules.
3. Perform a parametric sweep of W and L, evaluate the FIS output using evalfis, and compute the frequency error $=\left|\mathbf{f}_{\mathbf{r}}^{\mathbf{estimated}} - \mathbf{f}_{\mathbf{r}}^{\mathbf{target}}\right|$.
4. Select the dimensions minimizing the error and validate antenna performance (S11, VSWR, bandwidth, gain, and radiation pattern).

This method enables direct dimension estimation, provides a reusable knowledge based FIS, and integrates AI with electromagnetic evaluation, improving design accuracy and efficiency.

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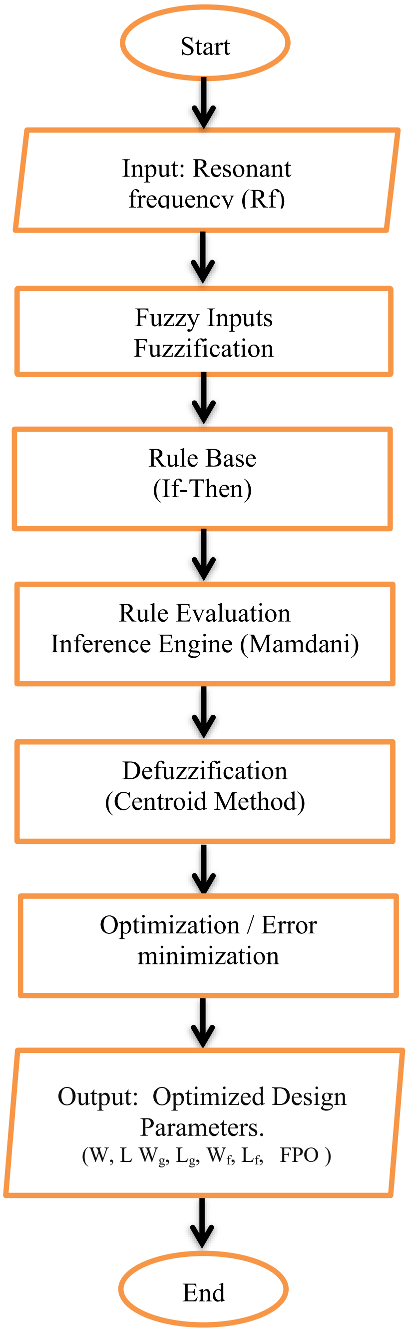

Fig.(3): Flow Chart-MSPFA Design Methodology

1) Fuzzification Process:

Fuzzification transforms crisp input and output values, such as patch width (W), patch length (L), and resonant frequency (fr), into fuzzy linguistic variables using membership functions. This enables the system to model uncertainty and nonlinear relationships in antenna parameters effectively.

- **Input Linguistic Variable**: There are two input Linguistic variables used,

(a) Patch Width (W)*:* The patch width (in mm) is defined within the universe of discourse $W \in [20,36]$ mm and is represented by the linguistic terms Small, Medium, and Large. Triangular membership functions (trimf) have been employed:

$$\mu_{\text{Small}}(W) = \text{trimf}(20, 24, 28)$$

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$\mu_{\text{Medium}}(W)$= trimf(26,28, 30)

$\mu_{\text{Large}}(W)$ = trimf(28, 32, 36)

(b) Patch Length (L): The patch length (in mm) is defined within the universe of discourse L∈ [16,25] mm and is represented by the linguistic terms Short, Medium, Long. Triangular Membership functions have been employed :

$\mu_{\text{Short}}(L)$ = trimf(16, 18, 20)

$\mu_{\text{Medium}}(L)$ = trimf(19, 20, 22)

$\mu_{\text{Long}}(L)$ = trimf(21,23,25)

- **Output Linguistic Variable**: The resonant frequency (fr), expressed in GHz, is defined over the universe of discourse $f_r \in [f_r - 0.2,\ f_r + 0.2]$ and is characterized by the linguistic terms ***Low, Mid, and High,*** with corresponding membership functions.

$\mu_{\text{Low}}(f)$= trimf(f_L, $f_L + \Delta f$, f_r)

$\mu_{\text{Mid}}(f)$ = trimf($f_r - 0.05$, f_r, $f_r + 0.05$)

$\mu_{\text{High}}(f)$= trimf(f_r, $f_r + \Delta f$, f_H)

The triangular input and output membership functions used in the fuzzy logic system are graphically illustrated in Figs. (4, 5, and 6.)

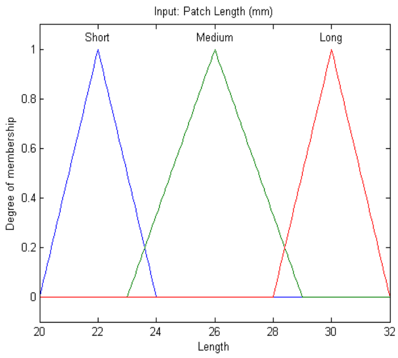

Fig.(4): Fuzzy Input Membership function-Patch Length (L)

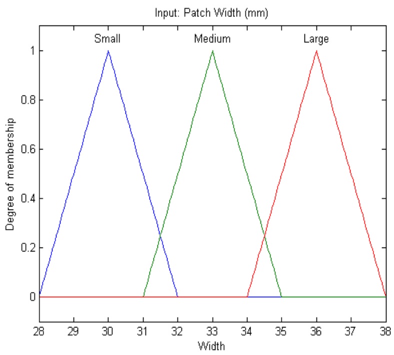

Fig.(5): Fuzzy Input Membership function-Patch Width (W)

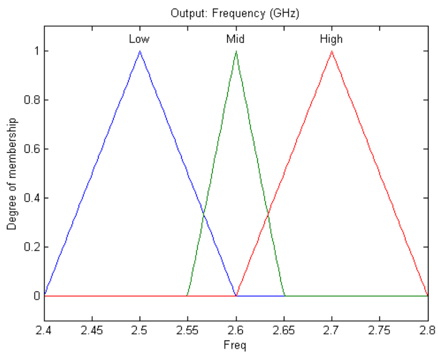

Fig.(6): Fuzzy Output Membership function – Frequency (fr)

(2) Fuzzy rule Evaluation (Inference):

Fuzzy Rule Base (IF–THEN Rules): Based on fundamental antenna theory, which indicates that an increase in patch dimensions leads to a reduction in resonant frequency, a fuzzy rule base consisting of nine IF–THEN rules is developed. The complete set of rules used in the proposed algorithm is given as follows.

1. IF Width is *Small* AND Length is *Short* THEN Frequency is *High*
2. IF Width is *Small* AND Length is *Medium* THEN Frequency is *High*
3. IF Width is *Small* AND Length is *Long* THEN Frequency is *Mid*
4. IF Width is *Medium* AND Length is *Short* THEN Frequency is *Hig*
5. IF Width is *Medium* AND Length is *Medium* THEN Frequency is *Mid*
6. IF Width is *Medium* AND Length is *Long* THEN Frequency is *Low*
7. IF Width is *Large* AND Length is *Short* THEN Frequency is *Mid*
8. IF Width is *Large* AND Length is *Medium* THEN Frequency is *Low*
9. IF Width is *Large* AND Length is *Long* THEN Frequency is *Low*

Inference Mechanism: A Mamdani Fuzzy Inference System is employed, where the logical AND and OR operations are implemented using the minimum and maximum operators, respectively. Rule implication uses the minimum operator, and aggregation is performed using the maximum operator. The firing strength of each rule is computed as $\alpha_i = \min\{\mu_W(W), \mu_L(L)\}$

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3) Aggregation:

Aggregation is the process of combining the outputs of all activated fuzzy rules into a single fuzzy output set. Since multiple rules may be triggered simultaneously, their individual output membership functions are merged using an aggregation operator, commonly the maximum operator. This step ensures that all relevant rule contributions are considered collectively, resulting in a unified fuzzy representation of the output variable (resonant frequency). In the proposed research, MSPFA model, aggregation combines the fuzzy output sets corresponding to the resonant frequency (fr) generated by all activated rules. For example, if multiple rules produce output linguistic terms such as Low, Mid and High resonant frequency with membership functions $\mu_{Low}(fr)$, $\mu_{Mid}(fr)$, and $\mu_{High}(fr)$, these outputs are aggregated using the maximum operator. The aggregated membership function is expressed as

$$\mu_{agg}(fr) = \max\{\mu_{Low}(fr), \mu_{Mid}(fr), \mu_{High}(fr)\} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (8)$$

This aggregated fuzzy set represents the combined influence of all fired rules and is subsequently used in the defuzzification stage to estimate the resonant frequency.

4) Defuzzification (Center Method):

Defuzzification converts the aggregated fuzzy output set into a single crisp value representing the estimated resonant frequency of the microstrip patch antenna. In this work, the centroid (center of gravity) method is employed due to its smooth and physically meaningful response. The defuzzified resonant frequency is computed as

$$f_r^* = \frac{\int_{all\ x} x \cdot \mu_{aggregated}(x)dx}{\int_{all\ x} \mu_{aggregated}(x)dx} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (9)$$

Where, x = possible frequency values, $\mu_{aggregated}(x)$=combined membership values from all rules and f_r^* = defuzzified resonant frequency. For instance, the aggregated fuzzy output (simplified for calculation) in the present case is as reported:

Aggregated μ ->	**0.5**	**1.0**	**1.0**	**0.5**
fr (GHz) >	2.50	2.55	2.60	2.65

Step-1: Numerator=$\sum x \cdot \mu(x)$ = 2.50*0.5+2.55*1.0+2.60*1.0+2.65*0.5 = 1.25 + 2.55 + 2.60 + 1.325 = 7.725

Step-2: Denominator =$\sum \mu(x)$ = 0.5 + 1.0 + 1.0 + 0.5 = 3.0

Step-3: Defuzzified frequency = $f_r^* = \frac{7.725}{3.0} \approx 2.575\ GHz$ = 2.6 GHz.

In the above test run, with finer sampling and full membership functions, the FIS yields a resonant frequency of 2.60 GHz for W= 28 mm and L=20 mm.

IV. MSPFA DESIGN: RESULTS, PERFORMANCE

In this research study, fuzzy logic is used to optimize the parameters of a Microstrip Patch Antenna (MSPA), with particular focus on patch dimensions to enhance antenna performance. A fuzzy logic based optimization technique designs a microstrip patch antenna operating at 2.60 GHz. The fuzzy inference system estimates the resonant frequency as 2.60 GHz, showing zero deviation from the target value and validating the prediction capability of the approach. The antenna uses an FR-4 substrate with a dielectric constant of 4.4 and thickness of 1.6 mm. The optimized ***patch dimensions*** obtained through fuzzy optimization are **28.0 (W) mm × 20.0 (L) mm,** with an effective dielectric constant of 4.0094 and a fringing field extension of 0.7351 mm. Proper optimization of ground plane and feed parameters ensures stable antenna operation. The optimized design parameters and their dimensions of the MSPA are shown in Fig. (7).

The simulated test run gives the return loss (S11) at resonance is −9.01 dB, corresponding to a VSWR of 2.10, indicating acceptable impedance matching for practical wireless applications. The antenna exhibits a wide impedance bandwidth of 1721.43 MHz, resulting in a fractional bandwidth of 66.21%, which is significantly higher than that of a conventional rectangular microstrip patch antenna. This improvement highlights the effectiveness of fuzzy optimization in enhancing bandwidth without introducing structural complexity. The estimated gain of 8.46 dBi

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demonstrates improved radiation performance and confirms that the fuzzy optimized geometry enhances directivity while maintaining efficiency.

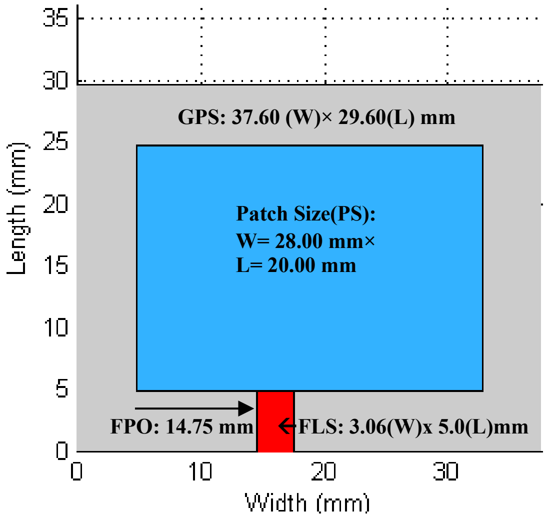

Fig.(7): MSPFA Design (Fuzzy Optimized)

Overall, the results indicate that fuzzy logic based optimization provides an effective and accurate approach for application specific microstrip antenna design, offering substantial bandwidth enhancement and reliable radiation performance with minimal design complexity.

V. COMPARATIVE STUDY OF MSPCA AND MSPFA (fr= 2.6 GHz)

A comparative study of the conventional microstrip patch antenna (MSPCA) and the proposed fuzzy logic based microstrip patch antenna (MSPFA), is carried out from various resulted parameters which are tabulated in the Table-2. Both the antennas designed to operate at 2.6 GHz on FR-4 substrate (εr=4.4, h=1.6 mm), shows that the key innovation of MSPFA lies in the intelligent optimization of the patch width (W) and length (L). In MSPCA, these parameters are obtained using fixed analytical equations and refined through repeated parametric tuning.

TABLE-2 Comparison of MSPCA AND MSPFA (fr = 2.6 GHz)

Sr. No.	Comparative Study of Optimized Design Parameters of MSPCA and MSPFA		
I)	**Optimized Design Parameter (Scale/ Unit)**	**MSPCA**	**MSPFA**
1	Optimized Patch Width, W (mm)	36.87	28.00
2	Optimized Patch Length, L (mm)	26.59	20.00
3	Ground Plane Width, Wg (mm)	46.47	37.60
4	Ground Plane Length, Lg (mm)	36.19	29.60
5	Feed Line Width, Wf (mm)	3.06	3.06
6	Feed Line Length, Lf (mm)	5.00	5.00
7	Feed Point Offset (FPO, x mm)	14.75	11.20
II)	**Performance Parameters (Scale/ Unit)**		
1	Return Loss, S11 (dB)	–116.58	–9.01
2	Voltage Standing Wave Ratio, VSWR (—)	1.00	2.10
3	Estimated Bandwidth (MHz / %)	63.88	1721.43 MHz (66.21%)
5	Estimated Gain (dBi)	–6.41	8.46

In contrast, MSPFA uses a Mamdani fuzzy inference system to estimate W and L by capturing nonlinear electromagnetic effects such as fringing fields and effective dielectric variations. As a result, the patch width is reduced from 36.87 mm to 28 mm and the patch length from 26.59 mm to 20 mm, achieving approximately 25% size reduction without shifting the resonant frequency. This optimized W–L relationship directly improves antenna performance, as the impedance bandwidth of a rectangular microstrip patch antenna is inversely related to its quality factor (FBW ∝ 1/Q). An increased effective W/L ratio enhances radiation conductance and reduces the radiation quality factor, leading

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to wider bandwidth while maintaining resonance through effective length compensation. Consequently, the MSPFA achieves a significantly larger impedance bandwidth of 1721.43 MHz (66.21%) compared to 63.88 MHz for MSPCA. Although the return loss and VSWR of MSPFA are moderate, they remain within acceptable operating limits, and the antenna exhibits a higher gain of 8.46 dBi, indicating improved radiation efficiency. This comparison clearly demonstrates that fuzzy-optimized W and L parameters result in a compact, wideband, and efficient antenna, making MSPFA a practical and effective alternative to conventional MSPCA for S-band wireless applications.

VI. CONCLUSION AND FUTURE RESEARCH

A fuzzy logic based microstrip patch antenna (MSPFA) for 2.6 GHz is designed and compared with a conventional MSPA (MSPCA) on FR-4 substrate (εr=4.4, h=1.6 mm). The MSPFA employs a Mamdani fuzzy inference system to optimize patch width (W) and length (L), capturing nonlinear effects such as fringing fields, achieving ~25% size reduction without altering resonance. Performance evaluation shows that MSPFA offers significantly enhanced bandwidth (66.21%), improved gain (8.46 dBi), and stable radiation patterns, compared to the conventional design with narrow bandwidth and poor radiation efficiency. The proposed fuzzy logic based framework directly optimizes antenna dimensions, achieving compact size, wideband performance, and reduced computational difficulty compared to regular conventional methods.

In future work, the antenna **will be fabricated and tested** experimentally, and a detailed comparison **will be carried out** between conventional MSPCA (Microstrip Patch Conventional Antenna) and fuzzy logic based MSPFA (Microstrip Patch Fuzzy Antenna) in terms of VSWR, bandwidth, return loss and gain. Future work also includes experimental validation, refinement of fuzzy rules and membership functions, and extension to hybrid optimization techniques, multiband, reconfigurable, and defected-ground microstrip antennas for broader wireless communication applications.

REFERENCES

[1]. D. M. Pozar and D. H. Schaubert, *Microstrip Antennas: The Analysis and Design of Microstrip Antennas and Arrays*. New York, NY, USA: IEEE Press, 1995.
[2]. R. Garg, P. Bhartia, I. Bahl, and A. Ittipiboon, *Microstrip Antenna Design Handbook*. Norwood, MA, USA: Artech House, 2001.
[3]. J. R. James and P. S. Hall, *Handbook of Microstrip Antennas*. London, U.K.: IET, 1989.
[4]. A. Mishra, R. Singh, and P. Kumar, “Design and optimization of microstrip patch antenna using fuzzy logic controller,” *International Journal of Computer Applications*, vol. 144, no. 3, pp. 1–5, Jun. 2016.
[5]. R. K. Mishra and M. Gupta, “ANN and fuzzy logic-based optimization of microstrip patch antenna for wireless communication,” *Journal of Electromagnetic Waves and Applications*, vol. 32, no. 18, pp. 2406–2418, 2018.
[6]. K. Patel and V. Kumar, “Optimization of microstrip patch antenna parameters using fuzzy logic controller for high-frequency applications,” in *Proc. IEEE Int. Conf. on Recent Innovations in Signal Processing and Embedded Systems (RISE)*, Bhopal, India, 2019, pp. 105–110.
[7]. S. Deb, A. Basak, and M. K. Ghosh, “Artificial intelligence-based optimization techniques in antenna design: A review,” *Progress In Electromagnetics Research B*, vol. 88, pp. 63–84, 2020.
[8]. MathWorks, *Fuzzy Logic Toolbox User’s Guide*. Natick, MA, USA: The MathWorks, Inc., 2023.