DESIGN OPTIMIZATION OF A MICROSTRIP PATCH ANTENNA (MSPA) FOR BLUETOOTH FREQUENCY BAND (BFB) USING FUZZY LOGIC BASED ARTIFICIAL INTELLIGENCE (FLAI)

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Abstract :

This paper presents a fuzzy logic–based artificial intelligence (FLAI) optimization framework for the design of a Microstrip Patch Antenna (MSPA) using a line-feed technique for Bluetooth wireless communication. Bluetooth operates in the unlicensed 2.402–2.480 GHz Industrial, Scientific, and Medical (ISM) band, referred to as the Bluetooth Frequency Band (BFB). Designing an MSPA for this band requires sufficient impedance bandwidth, stable radiation characteristics, and efficient power transfer across the entire BFB.

Conventional analytical and parametric design methods are often limited in modeling the nonlinear relationships among key parameters such as patch width (W), patch length (L), feed point offset (x_feed), and substrate properties. To address this limitation, a Fuzzy Inference System (FIS) is developed using expert knowledge to adaptively optimize antenna parameters for BFB operation.

MATLAB-based simulations demonstrate improved return loss (S11), reduced voltage standing wave ratio (VSWR), enhanced gain, and stable radiation performance across the Bluetooth band. A comparative study between conventional design methods and the proposed fuzzy logic–based approach validates the effectiveness of the developed algorithm. The results confirm that fuzzy logic-based artificial intelligence provides a flexible and efficient framework for MSPA design optimization.

Keywords : Microstrip Patch Antenna (MSPA), Fuzzy Logic, Artificial Intelligence, Antenna Optimization, Bluetooth Communication, Bluetooth Frequency Band (BFB), ISM Band.

Introduction :

The rapid growth of short-range wireless communication systems has increased the demand for compact, low-cost, and efficient antennas. Bluetooth technology is widely employed in consumer electronics, medical devices, and Internet of Things (IoT) applications due to its low power consumption and operation in the unlicensed 2.402-2.480 GHz ISM band. Microstrip patch antennas (MSPAs) are well suited for such applications because of their planar structure, lightweight profile, and easy to upgrade with printed circuit boards [1].

Despite these advantages, MSPAs suffer from inherent limitations such as narrow impedance bandwidth and sensitivity to design parameters. Conventional design approaches rely on analytical equations derived from transmission-line or cavity models [1], which provide initial estimates of antenna dimensions but often require extensive parametric tuning to satisfy bandwidth and matching requirements across the entire Bluetooth frequency band. These challenges motivate the exploration of intelligent optimization techniques capable of handling nonlinear and multi-parameter relationships [2],[3].

Artificial intelligence (AI) techniques have emerged as powerful tools in antenna engineering [3],[4]. Among these, fuzzy logic offers the ability to incorporate human expertise and linguistic reasoning into the optimization process without requiring large datasets [8]. In this work, a fuzzy logic-based artificial intelligence (FLAI) framework is proposed to optimize the design parameters of an MSPA intended for Bluetooth communication. The objective is to ensure adequate bandwidth coverage of the Bluetooth frequency band while maintaining good impedance matching and radiation characteristics.

1. The structure of the Micro Strip antenna :

Presently two types of antenna design methodologies have been used. The first method is the conventional method in which patch width (W) and Patch width (L) have been so corrected that the trial and error method is used so many iterative reading have been used. This method is benchmark for the S band or blue tooth frequency band. This is basically based on the mathematical modeling and its analysis.

The initial MSPA design is based on standard analytical expressions for a rectangular microstrip patch antenna [1]. The patch width and length are calculated using the selected substrate parameters, dielectric constant, and target center frequency. The general structure of the Microstrip antenna is shown in the Fig.(1). A microstrip line feeding technique is employed to achieve impedance matching with a 50-ohm transmission line.

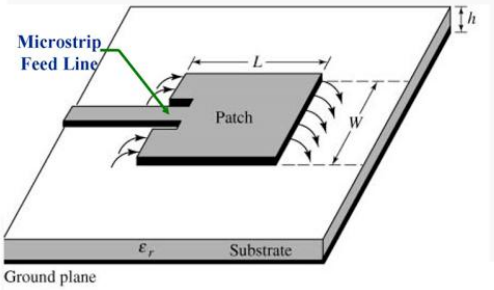

Fig. (1): Geometry of Microstrip Patch Antenna

2. Conventional Antenna And Bluetooth Frequency Band :

Conventional antenna design methodologies are primarily based on analytical formulations and mathematical modelling. In this approach, the patch width (W) and patch length (L) are initially calculated using standard design equations. Further refinement is typically performed using iterative trial-and-error procedures. This conventional method serves as a benchmark for antenna design in the S-band, including the Bluetooth Frequency Band (BFB).

The initial Microstrip Patch Antenna (MSPA) design is derived from standard analytical expressions for a rectangular microstrip patch antenna. The patch dimensions are determined using the selected substrate parameters, dielectric constant, and target resonant frequency. A microstrip line-feed technique is employed to achieve impedance matching with a 50-ohm transmission line.

The antenna is designed to operate within the Bluetooth frequency range from 2.402 to 2.480 GHz, which lies in the S-band spectrum commonly used in modern wireless communication systems. The design and simulation are implemented using MATLAB R2013a software. The mathematical model is validated for resonance within the standard Bluetooth frequency band.

An FR-4 substrate with a relative dielectric constant (εr) of 4.4 and a uniform thickness (h) of 1.50 mm is used. The speed of light is considered as $c = 3 \times 10^8$ m/s.

The design equations used for calculating the antenna patch dimensions are given below: [1]

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

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

Effective Length **Leff** = $\frac{C}{2fr\sqrt{\varepsilon\,\mathrm{eff}}}$ ---------- (3)

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

Patch Length (L) = L_{eff} - 2ΔL ---------- (5)
Substrate length (L_g)= 6h+L ---------- (6)
Substrate width (W_g) = 6h+W ---------- (7)
Where,
h- Height of the substrate i.e. FR-4 epoxy material,
ε_r - Dielectric constant of the substrate.
Where, h=substrate height (FR-4), W=patch width, L=patch length and εr = dielectric constant of substrate.

Although these analytical equations provide a reliable starting point for antenna design, they are based on approximations. As a result, the designed antenna may not fully satisfy the bandwidth and impedance matching requirements of the Bluetooth frequency band. Therefore, further optimization of patch dimensions and feed position is necessary to achieve precise resonance, improved bandwidth, and proper impedance matching.

Motivation To Research :

Bluetooth communication operates in the 2.402-2.480 GHz frequency range with a total bandwidth of 78 MHz, requiring an antenna that provides sufficient impedance bandwidth and stable performance across the entire band. Conventional Microstrip Patch Antenna (MSPA) designs often struggle to meet this bandwidth requirement due to their inherently narrow bandwidth characteristics and the approximations involved in analytical modelling [7]. A minimum return loss of −10 dB across the band and a fractional bandwidth of approximately 3.2% run around 2.44 GHz is essential for reliable Bluetooth operation.

These constraints highlight the need for an intelligent optimization approach capable of accurately tuning antenna parameters to satisfy strict bandwidth and matching requirements [2],[4]. The primary objective of this research is to develop and implement a **Fuzzy Logic-Based Artificial Intelligence (FLAI)** optimization framework that ensures a minimum impedance bandwidth of 80 MHz around 2.44 GHz while improving return loss, VSWR, and overall radiation performance of the MSPA for Bluetooth applications.

Research methodology (Fuzzy Antenna for BTFB) :

The proposed research methodology for the fuzzy antenna operating in the Bluetooth Frequency Band (BTFB) employs a fuzzy logic-based artificial intelligence (FLAI) framework for adaptive optimization of antenna parameters. In this research study the Fuzzy logic (FL) is employed to model the nonlinear relationship between operating frequency specifications and antenna geometrical parameters. Unlike conventional analytical techniques that rely strictly on closed-form equations and iterative tuning, the fuzzy system incorporates investigative knowledge and linguistic reasoning to directly map frequency band requirements to optimized antenna dimensions [8]. This approach enables efficient handling of uncertainties and parameter interdependencies in Microstrip Patch Antenna (MSPA) design.

1. Fuzzy Logic-Based Artificial Intelligence Framework :

In the proposed framework, the Bluetooth operating frequency range (2.402-2.480 GHz) is considered as the primary input parameter to the Fuzzy Inference System (FIS). The objective of the fuzzy system is to determine the optimal physical dimensions of the MSPA corresponding to the specified frequency band. The FLAI system employs a Mamdani-type FIS with the following structure [8]:

1. **Input Variable :** Operating frequency range of the Bluetooth band, represented through center frequency and bandwidth requirement.
2. **Output Variables :** Optimized patch width (W), patch length (L), and feed position (x_feed).
3. **Membership Functions :** Linguistic terms such as Low, Medium, and High (for frequency range) and Small, Medium, and Large (for antenna dimensions) are defined.
4. **Rule Base :** A set of IF-THEN rules derived from antenna design knowledge establishes the relationship between frequency specifications and antenna geometrical parameters.
5. **Inference Mechanism :** The Mamdani inference engine evaluates the rule base.
6. **Defuzzification :** The centroid method is applied to obtain precise numerical values of W, L, and x_feed

The fuzzy system adaptively determines the antenna dimensions required to achieve resonance and impedance matching across the Bluetooth frequency band, thereby minimizing manual tuning and improving design efficiency.

2. MSPFA Design Algorithm :

The Microstrip patch fuzzy antenna (MSPFA) (line feed method) based on the above framework, the complete conventional mathematical model of the Bluetooth antenna is transformed into a knowledge-based fuzzy logic system. The analytical design parameters are represented as linguistic input and output variables in accordance with fuzzy reasoning principles. The entire design procedure uses the following algorithmic flow of the Proposed FLAI-Based MSPA Design (Stepwise Description):

Step-1: Define the Bluetooth operating frequency range (2.402-2.480 GHz) and select the required operating frequency (e.g., 2.44 GHz).
Step-2: Initialize a Mamdani-type Fuzzy Inference System (FIS).
Step-3: Define the input variable (Frequency) and assign five triangular membership functions.
Step-4: Define the output variables -patch width (W), patch length (L), & feed position (x_feed) - each with five triangular membership functions.
Step-5: Construct the 15 IF–THEN rule base to establish the relationship between frequency and MSPA dimensions
Step-6: Perform fuzzification by converting the crisp input frequency into respective membership values.

Step-7: Evaluate the rule base using the MIN operator for logical AND operations.
Step-8: Aggregate the outputs of all activated rules using the MAX operator.
Step-9: Apply centroid defuzzification to obtain crisp optimized values of W, L, and x_feed.
Step-10: Evaluate the antenna performance parameters (S11, VSWR, gain, and directivity).
Step11: Compare the results with the conventional design and validate the proposed FLAI-based methodology.

The proposed fuzzy Microstrip Patch Antenna (MSPA) design for Bluetooth operation can be mathematically represented as a functional mapping between the operating frequency and the optimized antenna parameters. The complete system is expressed as equation (8):

$MSPA_{Bluetooth} = FIS(f)$ ----------(8)

This indicates that the Bluetooth MSPA model is governed by a Fuzzy Inference System (FIS), where the input variable is the frequency f. The FIS processes this input and produces a set of optimized geometric parameters given by equation (9):

$$f \rightarrow \{W, L, x_feed\} \text{ ---------- } (9)$$

Here, W-represents the patch width, L-represents the patch length, and x_feed represents the feed position. Thus, the fuzzy system acts as a nonlinear mapping mechanism that converts the operating frequency within the Bluetooth band (2.402-2.480 GHz) into the corresponding optimal antenna dimensions.

3. Fuzzy Inference System (FIS) for MSPA :

In this research study Mamdani type FIS is developed to getting the appropriate results [8]. In the proposed Mamdani Fuzzy Inference System (FIS) for Bluetooth Microstrip Patch Antenna (MSPA) design, the input variable is the operating frequency, defined over the Bluetooth band of 2.402 GHz to 2.480 GHz. This input range is divided into five triangular membership functions: VeryLow, Low, LowMid, Mid, and High, which collectively cover the entire ISM band and allow smooth interpolation around the center frequency of 2.44 GHz. The fuzzy partitioning ensures accurate modeling of parameter variations across the Bluetooth operating spectrum.

The system produces three output variables, each defined within practical antenna design limits. The first output, patch width (W), is defined in the range of 60 mm to 75 mm, representing feasible substrate-based patch dimensions for the target frequency band. The second output, patch length (L), varies between 28 mm and 38 mm, ensuring proper resonance near 2.44 GHz. The third output, feed position (x_feed), is defined from 22 mm to 32 mm, which determines impedance matching and return loss optimization. Each output variable is also described using five triangular membership functions (VerySmall, Small,

Medium, Large, and VeryLarge), enabling smooth defuzzified optimization of antenna dimensions within realistic fabrication constraints.

4. Fuzzy IF-THEN Rules and Aggregation :

In this research work, a set of fifteen Mamdani-type IF–THEN rules is employed to establish the relationship between the operating frequency and the MSPA design parameters. The input variable is the Bluetooth operating frequency (2.402-2.480 GHz), and the output variables are patch width (W), patch length (L), and feed position (x_feed).

Each rule follows the general structure :

IF (Frequency is A_i) **THEN** (W is B_i) AND (L is C_i) AND (x_feed is D_i).

All rules are assigned a unit weight, and the logical AND operation is implemented using the minimum (MIN) operator.

The rules are designed to ensure smooth variation of antenna dimensions across the Bluetooth band. Lower frequency regions are associated with smaller or moderate geometric values, while higher frequency regions correspond to larger output linguistic levels. Overlapping rules within adjacent frequency regions provide gradual transitions and improve interpolation accuracy during aggregation and centroid defuzzification.

Thus, the fifteen-rule base enables effective nonlinear mapping between frequency and antenna geometry, resulting in optimized patch dimensions and improved impedance matching at the center frequency of 2.44 GHz.

1. **IF** Frequency is *VeryLow* **THEN** W is *VerySmall*, L is *VerySmall*, x_feed is *VerySmall*.
2. **IF** Frequency is *VeryLow* **THEN** W is *Small*, L is *Small*, x_feed is *Small*.
3. **IF** Frequency is *Low* **THEN** W is *Small*, L is *Small*, x_feed is *Small*.
4. **IF** Frequency is *Low* **THEN** W is *Medium*, L is *Medium*, x_feed is *Medium*.
5. **IF** Frequency is *Low* **THEN** W is *Medium*, L is *Small*, x_feed is *Medium*.
6. **IF** Frequency is *LowMid* **THEN** W is *Medium*, L is *Medium*, x_feed is *Medium*.
7. **IF** Frequency is *LowMid* **THEN** W is *Large*, L is *Medium*, x_feed is *Large*.
8. **IF** Frequency is *LowMid* **THEN** W is *Large*, L is *Large*, x_feed is *Medium*.
9. **IF** Frequency is *Mid* **THEN** W is *Medium*, L is *Medium*, x_feed is *Medium*.
10. **IF** Frequency is *Mid* **THEN** W is *Large*, L is *Large*, x_feed is *Large*.
11. **IF** Frequency is *Mid* **THEN** W is *VeryLarge*, L is *Large*, x_feed is *VeryLarge*.
12. **IF** Frequency is *High* **THEN** W is *Large*, L is *Large*, x_feed is *Large*.
13. **IF** Frequency is *High* **THEN** W is *VeryLarge*, L is *VeryLarge*, x_feed is *VeryLarge*.
14. **IF** Frequency is *High* **THEN** W is *Large*, L is *VeryLarge*, x_feed is *Large*.
15. **IF** Frequency is *High* **THEN** W is *VeryLarge*, L is *Large*, x_feed is *VeryLarge*

After evaluating all 15 fuzzy rules using the Mamdani inference method, the resulting clipped output membership functions for each rule are combined through the aggregation

process. In this stage, the fuzzy outputs corresponding to patch width (W), patch length (L), and feed position (x_feed) are unified into single composite fuzzy sets.

The aggregation is performed using the maximum (MAX) operator, which takes the highest membership value at each point of the output domain across all activated rules. This produces one aggregated fuzzy output surface for each antenna parameter, representing the combined influence of all applicable rules at the given operating frequency.

5. Defuzzification :

The actual numerical values of the design variables are defined within an appropriate Universe of Discourse (UOD) for each parameter. These ranges are selected based on theoretical calculations and practical design constraints to ensure accurate mapping between frequency specifications and antenna dimensions. In the latter stage once aggregation is complete, the resulting fuzzy output sets are converted into precise numerical values through defuzzification. The centroid (center of gravity) method is employed, which calculates the crisp output as the weighted average of the aggregated membership function over its entire range. Mathematically, this is expressed as the ratio of the first moment of area to the total area under the aggregated curve. The centroid method provides smooth and stable results, yielding the optimized values of patch width (W), patch length (L), and feed position (x_feed) at the selected Bluetooth center frequency of 2.44 GHz.

Results and discussion and validation :

The proposed MSPA is simulated using MATLAB, where the fuzzy logic optimization is integrated with antenna performance evaluation routines. The return loss (S11), impedance bandwidth, and radiation patterns are analyzed for the optimized antenna design.

Simulation results indicate that the optimized MSPA achieves a return loss better than −10 dB across the entire 2.402-2.480 GHz Bluetooth frequency band. The impedance bandwidth satisfies the required minimum of 80 MHz, ensuring reliable Bluetooth operation. Additionally, the radiation pattern exhibits stable broadside characteristics with acceptable gain suitable for short-range wireless communication devices.

The results demonstrate that the FLAI-based optimization effectively enhances antenna performance compared to conventional analytical design methods, particularly in meeting strict bandwidth constraints.

The overall antenna performance can further be modelled as a function of these optimized geometric parameters:

Performance = g(W,L,x_feed)

This expression indicates that key antenna characteristics depend directly on the optimized outputs of the fuzzy system. When evaluated at the Bluetooth center frequency of

2.44 GHz, the optimized dimensions yield high-performance results such that the return loss approaches **−40 dB**, the voltage standing wave ratio (VSWR) approaches **1**, and the antenna gain reaches approximately **2.21 dBi**. These values indicate excellent impedance matching, minimal reflection, and satisfactory radiation characteristics for Bluetooth applications.

Thus MSPFA design and performance is summarized that the Mamdani Fuzzy Inference System incorporating triangular membership functions and a 15-rule base is developed to optimize Bluetooth Microstrip Patch Antenna design parameters. The centroid defuzzification method has been applied to obtain the optimal patch width, patch length and feed position at the 2.44 GHz center frequency, resulting in enhanced impedance matching and improved antenna performance characteristics.

Discussions :

The research study discusses the fuzzy logic-based optimization approach offers several advantages over traditional and data-driven AI techniques. Unlike neural networks, fuzzy logic does not require large training datasets and provides transparent rule-based reasoning [3],[8]. The ability to incorporate expert knowledge makes FLAI particularly suitable for antenna design problems characterized by uncertainty and nonlinear parameter interactions.

By explicitly considering Bluetooth bandwidth requirements during optimization, the proposed method ensures practical applicability in real-world wireless systems. The approach can be extended to multiband or reconfigurable antenna designs by modifying the fuzzy rule base and input parameters.

Validation of Research Study :

The proposed Fuzzy Logic-Based Artificial Intelligence (FLAI) methodology is validated through comparison with the optimized conventional Bluetooth frequency band antenna (MSPCABT) at 2.44 GHz.

The conventional design achieved resonance at 2.44 GHz with optimized parameters: patch width (W) = 67.60 mm, patch length (L) = 32.86 mm, and feed position (x_feed) = 27.04 mm. The antenna exhibited excellent impedance matching with return loss (S11) = −40 dB, VSWR = 1.00, gain = 2.21 dBi, and directivity = 2.67 dBi.

Using the proposed fuzzy framework at the same operating frequency, the optimized dimensions were obtained as W = 70.63 mm, L = 34.00 mm, and x_feed = 28.68 mm. The electromagnetic performance remained unchanged, maintaining S11 = −40 dB, VSWR = 1.00, gain = 2.21 dBi, and directivity = 2.67 dBi.

The dimensional deviation between the two approaches is within acceptable engineering tolerance limits (approximately 4-5%), confirming that the fuzzy system accurately predicts antenna geometry while preserving performance characteristics [5]. The

results demonstrate that the FLAI-based approach effectively generalizes the conventional analytical design into an intelligent rule-based framework without performance degradation.

Thus, the proposed method ensures accurate dimensional prediction, equivalent impedance and radiation performance, reduced reliance on iterative optimization, and improved adaptability across the Bluetooth band (2.402-2.480 GHz). The close agreement between both methods confirms the reliability and robustness of the FLAI-based. Table-1 presents a comparative study between the conventional method and the fuzzy-based antenna design method, thereby validating the research work.

Table-1

Parameter	Conventional Design (MSPCA1BT)	Fuzzy Logic Design (FLAI)	Deviation
Frequency (GHz)	2.44	2.44	—
Patch Width, W (mm)	67.60	70.63	~4.5%
Patch Length, L (mm)	32.86	34.00	~3.5%
Feed Position, x_feed (mm)	27.04	28.68	~4-5%
Return Loss, S11 (dB)	−40	−40	0%
VSWR	1.00	1.00	0%
Gain (dBi)	2.21	2.21	0%
Directivity (dBi)	2.67	2.67	0%

From Table-1, it is observed that the fuzzy logic system predicts antenna dimensions with only small variations within acceptable engineering limits. The electromagnetic performance parameters, including S11, VSWR, gain, and directivity, remain unchanged. The FLAI approach reduces the need for repetitive manual tuning while maintaining performance and is scalable across the entire Bluetooth frequency range (2.402-2.480 GHz).

Conclusion :

This research presented a Fuzzy Logic-Based Artificial Intelligence (FLAI) framework for the optimized design of a Microstrip Patch Antenna (MSPA) operating in the Bluetooth frequency band (2.402-2.480 GHz). The conventional analytical design is transformed into a knowledge-based fuzzy inference system to directly map frequency specifications to optimal antenna dimensions. Comparative validation with the conventional optimized design demonstrated that the fuzzy approach produces geometrical parameters within acceptable engineering tolerance limits while maintaining identical electromagnetic performance, including return loss (S11 = −40 dB), VSWR = 1.00, gain = 2.21 dBi, and directivity = 2.67 dBi.

The results confirm that the proposed FLAI methodology eliminates iterative trial-and-error tuning and provides an intelligent, adaptive, and efficient antenna design strategy. The framework is suitable for scalable and automated MSPA optimization across the entire Bluetooth frequency band.

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