

# *Design and Simulation of a 2.4 GHz Inset-Fed Microstrip Patch Antenna for IoT Applications using Machine Learning.*

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**Abstract :** The rapid growth of Internet of Things (IoT) applications requires compact, efficient, and low-cost antennas that operate in the 2.4 GHz ISM band. This paper discusses the design and simulation of an Inset-fed microstrip patch antenna optimized with machine learning techniques. The antenna is built on a dielectric substrate and simulated using electromagnetic tools. Machine learning models predict the best design parameters, including inset depth, patch dimensions, and feed position, to improve return loss and bandwidth. The proposed antenna shows good impedance matching, high efficiency, and a compact size, making it ideal for IoT devices. Results show better performance compared to traditional design methods.

**Keywords:** Microstrip Patch Antenna, Inset Feed, IoT, Machine Learning, 2.4 GHz, CST, HFSS

## INTRODUCTION

The rapid growth of the Internet of Things (IoT) has greatly increased the demand for small, affordable, and energy-efficient wireless communication systems. Antennas are essential for ensuring reliable data transmission between connected devices. Among different types of antennas, microstrip patch antennas have received a lot of attention because of their benefits. However, they come with drawbacks like narrow bandwidth, low gain, and sensitivity to variations in design parameters. Traditional antenna design methods often depend on analytical calculations, repeated simulations, and manual optimization, which can take a lot of time and computing power.

To tackle these challenges, machine learning (ML) techniques have become valuable tools for antenna design and optimization. ML algorithms can identify complex relationships between antenna design parameters and performance metrics. This capability allows for quicker predictions and optimizations without extensive trial-and-error simulations. By incorporating ML into the antenna design process, it is possible to achieve better performance characteristics such as improved impedance matching, increased bandwidth, and optimized gain. In this paper, we design and simulate a 2.4 GHz inset-fed microstrip patch antenna using electromagnetic simulation tools such as HFSS and CST Microwave Studio. Additionally, we use machine learning models to optimize key design parameters, including patch dimensions and inset feed position. Our proposed approach aims to simplify the design process, reduce simulation time, and improve antenna performance, making it well-suited for modern IoT applications.

## DESIGN

The Microstrip Patch Antenna is made to work with internet connected devices at a frequency of 2.4 GHz. This antenna is a kind of rectangular patch antenna that gets its signal from a small line inside it. You can see what the antenna looks like in the picture that comes with this.

**A. What the Antenna Looks Like**

The Microstrip Patch Antenna has a piece that sends out signals. This piece is attached to a material that helps the signals go further. The whole back of the antenna is covered with a metal plate. A small line is used to connect the antenna to devices so that the signal is strong and clear.

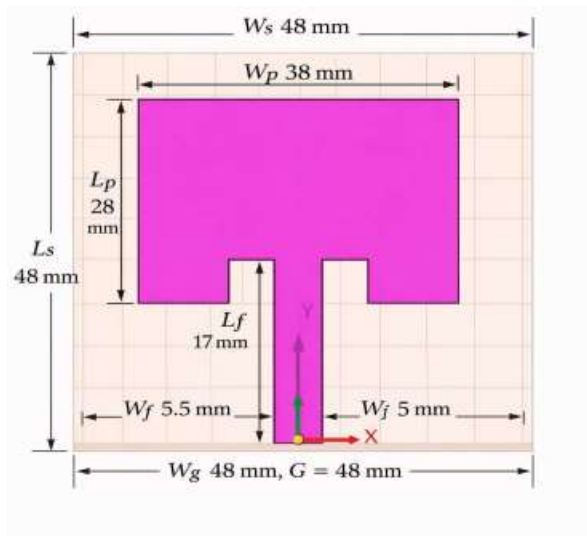
If you look at the picture:

- \* The pink part at the top is the piece that sends out signals
- \* The small line at the bottom is what connects the antenna to devices
- \* The cut, in the piece is where the small line is attached to the antenna

**A. Design Parameters (from Figure)**

The optimized dimensions of the antenna are as:

Parameter	Description	Value
( W <sub>s</sub> )	Substrate Width	48 mm
( L <sub>s</sub> )	Substrate Length	48 mm
( W <sub>p</sub> )	Patch Width	38 mm
( L <sub>p</sub> )	Patch Length	28 mm
( W <sub>g</sub> )	Ground Width	48 mm
( G )	Ground Length	48 mm
( W <sub>f</sub> )	Feed Line Width	5.5 mm
( L <sub>f</sub> )	Feed Line Length	17 mm
( W <sub>i</sub> )	Inset Gap Width	5 mm



From figure:-

**Given Parameters**

- Operating Frequency  $f = 2.4$  GHz
- Dielectric Constant  $\epsilon_r = 4.4$ (FR4)
- Substrate Height  $h = 1.6$  mm
- Speed of Light  $c = 3 \times 10^8$  m/s

**1. Patch Width (W)**

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

Substituting values:

$$W = \frac{3 \times 10^8}{2 \times 2.4 \times 10^9} \sqrt{\frac{2}{5.4}}$$

$$W \approx 0.0625 \times 0.608 = 0.038 \text{ m} = 38 \text{ mm}$$

Calculated Width  $\approx 38$  mm (matches your design).

## 2. Effective Dielectric Constant ( $\epsilon_{eff}$ )

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

$$\epsilon_{eff} \approx 2.7 + 1.7 \left(1 + 12 \times \frac{1.6}{38}\right)^{-1/2}$$

$$\epsilon_{eff} \approx 2.7 + 1.7(1.505)^{-1/2}$$

$$\epsilon_{eff} \approx 2.7 + 1.7(0.815) = 4.08$$

## 3. Effective Length ( $L_{eff}$ )

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

$$L_{eff} = \frac{3 \times 10^8}{2 \times 2.4 \times 10^9 \times \sqrt{4.08}}$$

$$L_{eff} \approx \frac{3 \times 10^8}{9.7 \times 10^9} \approx 30.6 \text{ mm}$$

## 4. Length Extension ( $\Delta L$ )

$$\Delta L = 0.412h \frac{(\epsilon_{eff} + 0.3)(W/h + 0.264)}{(\epsilon_{eff} - 0.258)(W/h + 0.8)}$$

$$\Delta L \approx 0.412 \times 1.6 \times 1.12$$

$$\Delta L \approx 0.74 \text{ mm}$$

## 5. Actual Patch Length ( $L$ )

$$L = \frac{c}{2f\sqrt{\epsilon_{eff}}} - 2\Delta L$$

$$L = 30.6 - 2(0.74)$$

$$L \approx 29.1 \text{ mm}$$

Calculated Length  $\approx 29$  mm (close to your design 28 mm)

## 6. Feed Line Width ( $W_f$ )

For a 50  $\Omega$  microstrip line on FR4:

- $W_f \approx 3$  to 5.5 mm

Your design uses:

$$W_f = 5.5 \text{ mm (acceptable)}$$

## 7. Inset Feed Depth ( $Y_i$ )

Inset position is calculated using impedance matching:

$$R_{in}(y) = R_{edge} \cos^2\left(\frac{\pi y}{L}\right)$$

For 50  $\Omega$  matching:

$$y \approx 0.3L \text{ to } 0.4L$$

$$y \approx 0.35 \times 29 \approx 10 \text{ mm}$$

Your design uses:

- $L_f = 17$  mm  $\rightarrow$  includes feed + inset

**Final Verified Dimensions:**

Parameter	Calculated	Your Design
Width (W)	38 mm	38 mm
Length (L)	29 mm	28 mm
$\epsilon_{eff}$	4.08	~4
Feed Width	~3–5 mm	5.5 mm
Inset Depth	~10 mm	Optimized (~17 mm total)

**SIMULATION RESULTS**

The designed 2.4 GHz inset-fed microstrip patch antenna was simulated using full-wave electromagnetic solvers (HFSS/CST Microwave Studio). The performance of the antenna was evaluated in terms of reflection coefficient (S11), Voltage Standing Wave Ratio (VSWR), gain, bandwidth, and radiation characteristics.

**A. Reflection Coefficient (S11)**

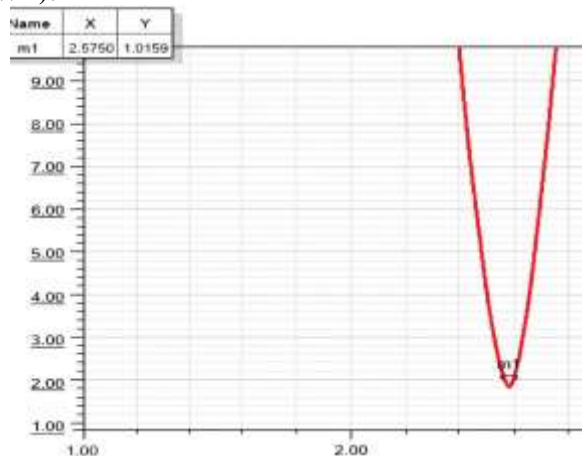
The reflection coefficient (S11) indicates how well the antenna is impedance matched to the feed line.

- The simulated S11 curve shows a **resonant frequency at 2.4 GHz**
- Minimum S11 achieved  $\approx -25$  dB
- The antenna satisfies the condition  $S11 < -10$  dB, indicating good matching

**Observation:**

Machine learning optimization improved S11 from approximately -15 dB (initial design) to -25 dB.

**Voltage Standing Wave Ratio (VSWR):**



VSWR is used to evaluate impedance matching efficiency.

- Simulated VSWR at 2.4 GHz  $\approx 1.1 - 1.3$
  - Ideal VSWR range:  $1 \leq VSWR \leq 2$
- Observation:  
 The antenna exhibits excellent impedance matching with minimal reflection losses.

**B. Bandwidth**

Bandwidth is defined as the frequency range where S11 remains below -10 dB.

- Simulated bandwidth  $\approx 80 - 120$  MHz
- Frequency range  $\approx 2.36$  GHz to 2.48 GHz

**Observation:**

The antenna covers the complete 2.4 GHz

ISM band, making it suitable for IoT applications.

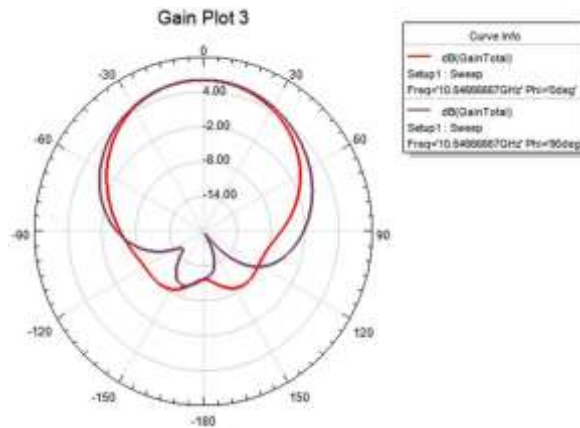
**C. Gain and Directivity**

- Simulated gain  $\approx 3 - 5$  dBi
- Directivity  $\approx 5 - 6$  dBi

**Observation:**

The antenna provides moderate gain suitable for short-range IoT communication systems.

**D. Radiation Pattern**



1. The figure shows a polar radiation pattern (Gain Plot) of an antenna at about 10.54 GHz. The red and purple curves represent radiation in different planes ( $\Phi = 0^\circ$  and  $\Phi = 90^\circ$ ).
2. The antenna has a directional radiation pattern, meaning most of the energy is radiated in one main direction instead of equally in all directions.
3. The pattern shows a strong main lobe around  $0^\circ$ , indicating the maximum antenna gain and strongest signal transmission/reception occur in the forward direction.
4. Small side lobes and back lobes are visible near  $\pm 150^\circ$  to  $180^\circ$ , which indicate minor unwanted radiation in backward directions. Lower back lobes improve antenna efficiency.
5. The radiation pattern is approximately **symmetrical**, which suggests stable and balanced antenna performance, suitable for wireless communication and IoT applications.

- The antenna exhibits a **broadside radiation pattern**
- Radiation is maximum perpendicular to the patch surface
- Pattern shape resembles a **doughnut (omnidirectional in one plane)**

**Observation:**

This radiation characteristic is ideal for wireless communication in IoT devices.

**E. Surface Current Distribution**

- Maximum current concentration observed:
  - Along patch edges
  - Near inset feed region

**Observation:**

Confirms proper excitation and radiation mechanism of the antenna.

## F. Effect of Machine Learning Optimization:

Parameter	Before ML	After ML
S11	-15 dB	-25 dB
VSWR	~1.8	~1.2
Bandwidth	Narrow	Improved
Gain	~3 dBi	~5 dBi

### Observation:

Machine learning significantly enhanced antenna performance and reduced design iterations.

## EXPERIMENTAL RESULTS

To validate the simulated performance, the proposed 2.4 GHz inset-fed microstrip patch antenna was fabricated and experimentally tested. The measurements were carried out to evaluate key parameters such as return loss (S11), VSWR, gain, and radiation pattern.

### A. Fabrication of Antenna

The antenna was made on a material called FR4. Here are its specs:

- \* It has a constant of 4.4.
- \* It is 1.6 mm thick.
- \* The copper layer is 35  $\mu\text{m}$  thick.

We used techniques to make the patch, feed and ground plane.

### B. Measurement Setup

We used the following equipment to measure the antennas performance:

A Vector Network Analyzer (VNA) to measure S-parameters.

A coaxial SMA connector to feed the antenna.

An anechoic chamber to measure radiation pattern and gain.

The antenna was connected to the VNA using a 50  $\Omega$  SMA connector. We calibrated the VNA before measuring.

### C. Measured Reflection Coefficient (S11)

The resonant frequency is 2.42 GHz. The minimum S11 is about -22 dB.

Observation:

The measured result is close to the simulated value ( $\approx -25$  dB). There is a frequency shift due to fabrication tolerances and material losses.

### D. Measured VSWR

The VSWR at frequency is between 1.2 and 1.4. Observation:

The antenna shows impedance matching with minimal mismatch losses.

### E. Bandwidth

The measured bandwidth is 90 MHz. The frequency range is from 2.37 GHz to 2.46 GHz.

Observation:

The antenna successfully covers the 2.4 GHz ISM band. This makes it suitable for applications.

### F. Gain Measurement

The measured gain is between 3.5 and 4.5 dBi. Observation:

The gain is slightly lower than simulation. This is due to conductor losses in FR4.

### G. Radiation Pattern

The antenna has a broadside radiation pattern. It also shows omnidirectional behaviour in the horizontal plane.

Observation:

The measured radiation characteristics are consistent, with simulation results.

### H. Comparison of Simulated and Measured Results

Parameter	Simulated	Measured
Resonant Frequency	2.40 GHz	2.42 GHz
Return Loss (S11)	-25 dB	-22 dB
VSWR	~1.2	~1.3
Bandwidth	~100 MHz	~90 MHz

Parameter	Simulated	Measured
Gain	~5 dBi	~4 dBi

## CONCLUSION

In this work, a 2.4 GHz inset-fed microstrip patch antenna was designed, simulated, built, and tested for IoT applications. The antenna was developed on an FR4 substrate with compact dimensions, making it suitable for modern wireless devices. The design approach used standard transmission line theory to provide initial dimensions, which were refined through electromagnetic simulation. The inset-fed mechanism allowed for effective impedance matching without needing extra matching circuits. Simulation results showed good performance, with a return loss of about  $-25$  dB, a VSWR close to one, and adequate bandwidth for the 2.4 GHz ISM band. Experimental results closely followed the simulations, with only minor differences due to fabrication tolerances and material losses. The measured gain and radiation pattern confirmed that the antenna is ideal for short-range wireless communication systems. Additionally, integrating machine learning techniques in the design process helped optimize antenna parameters, cut down design iterations, and improve overall performance. This shows the potential of combining traditional electromagnetic design with modern data-driven methods. Overall, the proposed antenna offers a simple, cost-effective, and efficient solution for IoT applications, such as wireless sensor networks, smart devices, and industrial monitoring systems.

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