Design of Patch antenna with Various shapes and various feeding techniques for IoT in the 2.45 GHz ISM Band

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Abstract. This paper introduces the design and feeding techniques of microstrip patch antennas with triangular, circular, and rectangular shapes, optimized for operation within the 2.45 GHz ISM band and tailored for IoT applications. The 2.45 GHz ISM band supports a variety of IoT protocols, including Bluetooth, Wi-Fi, Zigbee, Thread, and RFID, each offering distinct functionalities for applications ranging from smart home automation to advanced connected health systems. The study focuses on the pivotal role of feeding techniques in antenna performance, categorizing them into contact methods (such as coaxial feed and microstrip line) and non-contact methods (such as aperture coupling and proximity coupling). Utilizing the transmission line method for initial design and the method of moments for parameter optimization, the performance of each antenna shape is rigorously compared in terms of reflection coefficient, gain, and bandwidth. This comprehensive analysis provides valuable insights into the efficacy of different geometrical shapes and feeding mechanisms, empowering designers to select suitable configurations for specific IoT requirements, thus enhancing the development of efficient and reliable wireless communication solutions in the 2.45 GHz ISM band.

Keywords—IoT applications, 2.45 GHz, Feeding Mechanisms, Microstrip Antenna, ISM band, patch antennas, Wi-Fi, Zigbee.

1 Introduction

Among the spectrum of frequencies favored for IoT applications, the 2.45 GHz Industrial, Scientific, and Medical (ISM) band stands out prominently. This band serves as a cornerstone in various IoT communication protocols such as RFID, WiFi, Bluetooth, and ZigBee [3-4], owing to its widespread compatibility with multiple wireless standards, ensuring seamless connectivity across IoT networks.

Recent studies have highlighted significant constraints in the design of patch antennas tailored for IoT applications within the 2.45 GHz ISM band, predominantly centered on rectangular patch geometries [1-2]. This limited focus overlooks the potential advantages offered by alternative shapes such as circular and triangular patches, which emerging research suggests could enhance critical performance metrics including gain, bandwidth, and radiation efficiency [3-4].

Moreover, there is extensive documentation on the predominant use of conventional feeding techniques like microstrip line or coaxial probe feeding [5-6], coupled with a restricted exploration of more sophisticated methods such as aperture or proximity coupling, which hold promise for optimizing antenna performance [7-8].

Additionally, the larger physical footprint of rectangular patches poses challenges in integrating these antennas into compact IoT devices, which are increasingly crucial in the field [9]. To address these challenges, there is a growing consensus in the literature advocating for the exploration of innovative and compact antenna designs that leverage alternative geometries and advanced feeding techniques [10-11].

By diversifying antenna shapes and exploring novel feeding mechanisms, researchers aim not only to enhance performance metrics but also to meet the evolving demands of IoT applications for smaller, more efficient antennas [12].

This paper aims to present a comprehensive comparative analysis of contacting feed and non-contacting feed techniques for rectangular, circular, and triangular microstrip patch antennas. The first section provides an overview of various feeding techniques, followed by detailed microstrip antenna designs for the three shapes. The final section offers an in-depth description of the triangular patch antenna and concludes with a thorough comparative study among the different shapes. The designed antennas were rigorously

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simulated using CST, a renowned solver based on the FIT method.

2 FEEDING MECHANISMS

When discussing feeding mechanisms in the context of patch antennas, we're referring to how the electromagnetic energy is delivered to the antenna element. Here are some typical feeding mechanisms for patch antennas:

2.1 Microstrip Line Feed

In this technique, a microstrip transmission line is directly attached to the radiating patch of the microstrip antenna to constitute a planar structure. The microstrip line is narrower, compared to the radiating patch. The substrate of the bottom side is attached to the ground plane.

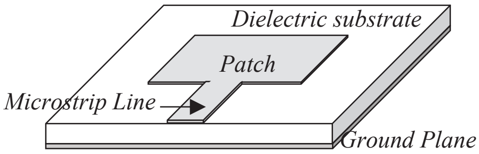


Fig. 1. Microstrip Line Feed.

2.2 Coaxial Probe Feed

In a coaxial probe feed, a coaxial cable is used to feed energy directly to the antenna. The inner conductor of the coaxial cable extends through the ground plane and is connected to the radiating patch, while the outer conductor is connected to the ground plane.

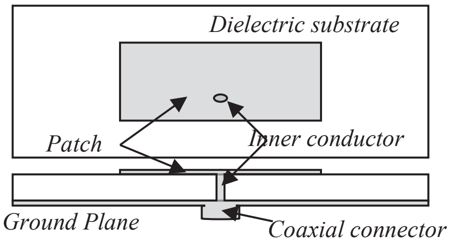


Fig. 2. Coaxial probe feed.

2.3 CPW Feed

A CPW feed involves a coplanar waveguide transmission line where the signal conductor and the ground planes are on the same side of the substrate. It offers flexibility in design and can be used for a variety of antenna configurations.

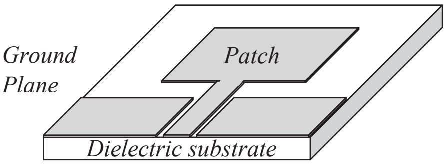


Fig. 3. CPW Feed.

2.4 Aperture Coupled Feed

In an aperture coupled feed, the ground plane with a slot or aperture, usually rectangular, is placed between two substrates of different permittivities. This aperture couples the energy from the feed line to the radiating patch, with the latter positioned on the upper substrate, while the feed line, which is a microstrip, is located below the lower substrate.

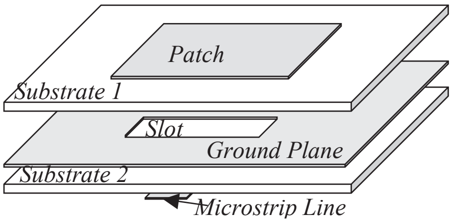


Fig. 4. Aperture-Coupled Feed.

2.5 Proximity Coupled Feed

In a proximity coupled feed, the radiating patch is positioned on the top layer of the upper substrate, while the feed line, typically a microstrip, is placed between the two substrates of different permittivities, with the ground plane located beneath the lower substrate. are essential for optimizing antenna performance.

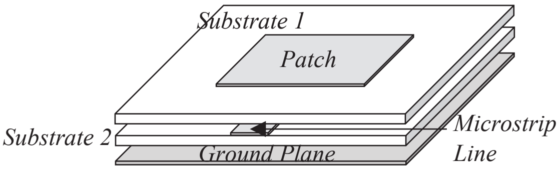


Fig. 5. Proximity-Coupled Feed.

3 MICROSTRIP ANTENNA DESIGN

The transmission line method is a commonly used approach to designing microstrip antennas. Here is a detailed explanation of this method with each form of patch:

3.1 Rectangular Patch

A practical width (W) leading to good radiation efficiency is given by the formula:

$$W = \frac{c}{2f}\sqrt{\frac{2}{\varepsilon_r+1}} \qquad (1)$$

The effective dielectric constant (εeff) is defined by the equation:

$$\varepsilon_{eff} = \frac{\varepsilon_r+1}{2}+\frac{\varepsilon_r-1}{2}\left(1+12\frac{h}{w}\right)^{-\frac{1}{2}} \qquad (2)$$

The length of the patch antenna is extended on each side by a quantity ΔL given by the equation:

$$\Delta L = 0.412h\frac{(\varepsilon_{eff}+0.3)\left(\frac{w}{h}+0.264\right)}{(\varepsilon_{eff}-0.258)\left(\frac{w}{h}+0.8\right)} \qquad (3)$$

The effective length of the patch antenna (L) is then given by the equation:

$$L=\frac{c}{2f\sqrt{\varepsilon_{eff}}}-2\Delta L \qquad (4)$$

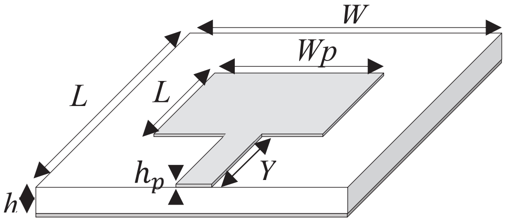


Fig. 6. Rectangular Patch Antenna.

3.2 Triangular Patch

The side length of the triangular patch antenna (a) is calculated as:

$$a=\frac{2c}{3f\sqrt{\varepsilon_r}}-\frac{h}{\sqrt{\varepsilon_r}} \qquad (5)$$

The effective side length of the triangular patch antenna (a_e) is calculated as:

$$a_e=a+\frac{h}{\sqrt{\varepsilon_r}} \qquad (6)$$

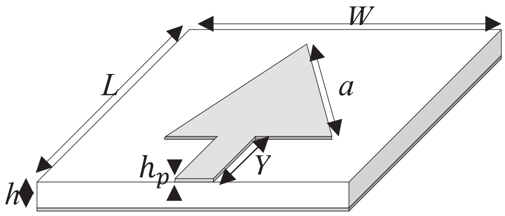


Fig. 7. Triangular Patch Antenna.

3.3 Circular Patch

The form factor (F) is calculated as:

$$F=\frac{8.791\times10^{9}}{f\sqrt{\varepsilon_r}} \qquad (7)$$

The radius of the circle (r) is calculated as:

$$r=\frac{F}{\sqrt{1+\frac{2h}{F\pi\varepsilon_r}\times\left(ln\left(\frac{\pi F}{2h}\right)+1.7726\right)}} \qquad (8)$$

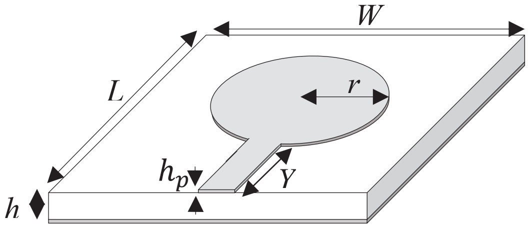
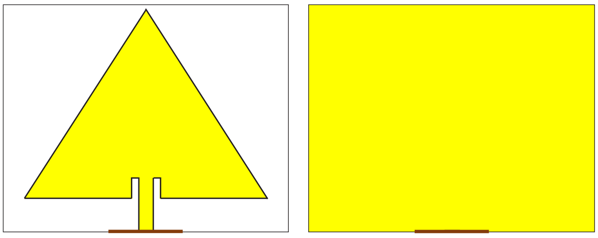


Fig. 8. Circular Patch Antenna.

4 SIMULATION AND RESULTS

The antennas designed were made with CST using two different substrates for a patch antenna: the FR4 (εr= 4.3) and the Rogers RT/Duroid 5880 (εr = 2.2). Both substrates are 1.6 mm thick, and the patch and ground plane are made of copper with a thickness of 0.035 mm. The simulation shows that the choice of substrate strongly influences the resonance frequency, bandwidth, efficiency and gain of the antenna. We will explore the case of the triangle patch only.

4.1 Design of Microstrip Line Feed



(a) (b)

Fig. 9. (a) The front plane, and (b) the ground plane of Antenna with Microstrip line feed.

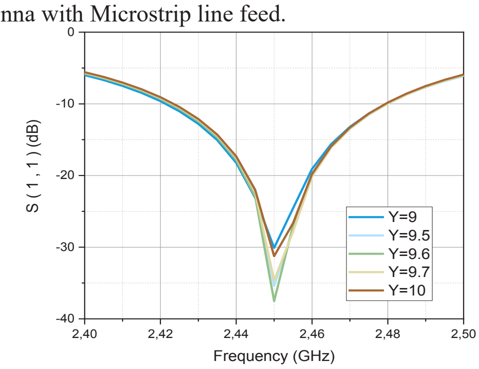


Fig. 10. Evolution of parameter ($S11$) as a function of frequency.

The graph shows the evolution of the S_{11} parameter as a function of frequency for different values of the feed length Y. Each curve represents a different Y value, ranging from 9 to 10 units.

In summary, adjusting the feed length Y affects the resonant frequency and impedance matching of the antenna, which is reflected in the S_{11} curves.

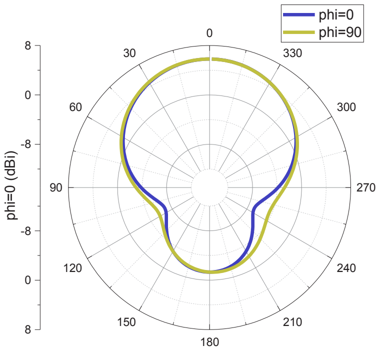


Fig. 11. E-plane (phi = 90º), and H-plane (phi = 0º) of Antenna with Microstrip line feed at 2.45 GHz

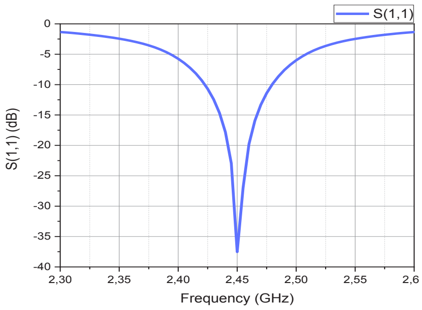
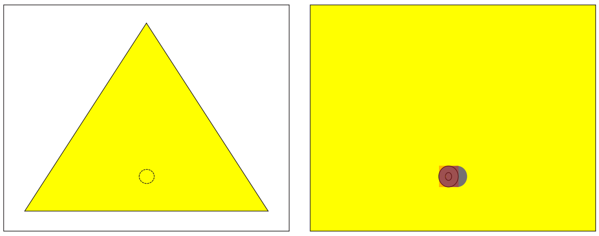


Fig. 12. Reflection coefficient ($S11$).

It's observed that the antenna resonance at frequency 2.45 GHz with reflection coefficient of $-37.53dB$ and the simulated gain in the 2.45 GHz band is 5.8 dBi.

4.2 Design of Coaxial Probe Feed



(a) (b)

Fig. 13. (a) The front plane, and (b) the ground plane of Antenna with Coaxial Probe Feed.

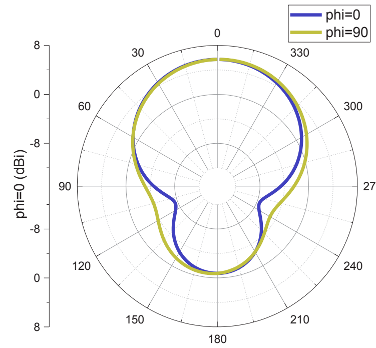


Fig. 14. E-plane (phi = 90º), and H-plane (phi = 0º) of Antenna with Coaxial Probe Feed at 2.45 GHz

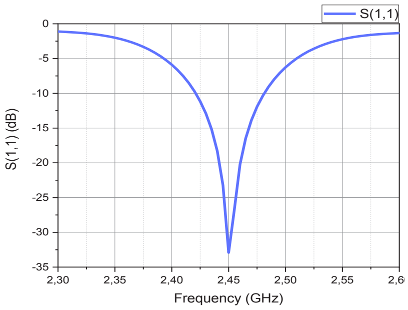
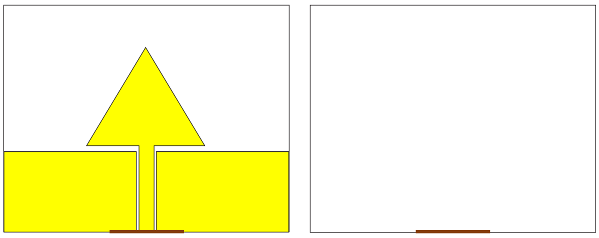


Fig. 15. Reflection coefficient ($S11$).

It's observed that the antenna resonance at frequency 2.45 GHz with reflection coefficient of $-32.92dB$ and the simulated gain in the 2.45 GHz band is 5.72 dBi.

4.3 Design of CPW Feed



(a) (b)

Fig. 16. (a) The front plane, and (b) the ground plane of Antenna with CPW feed.

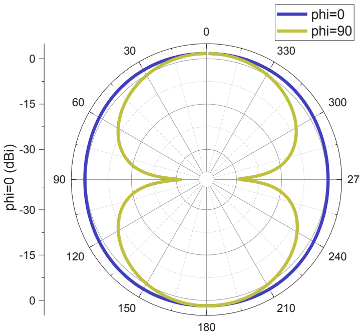


Fig. 17. E-plane (phi = 90º), and H-plane (phi = 0º) of Antenna with CPW feed at 2.45 GHz

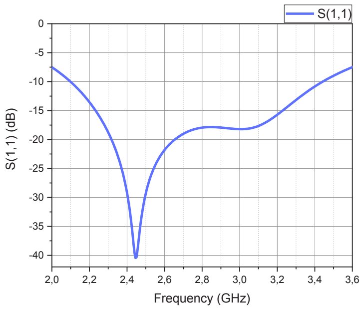
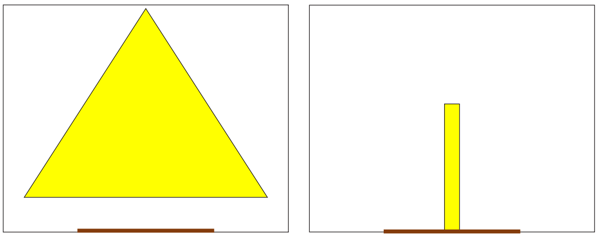


Fig. 18. Reflection coefficient ($S11$).

It's observed that the antenna resonance at frequency 2.45 GHz with reflection coefficient of $-40.36dB$ and the simulated gain in the 2.45 GHz band is 1.83 dBi.

4.4 Design of Aperture Coupled Feed



(a) (b)

Fig. 19. (a) The front plane, and (b) the ground plane of Antenna with Aperture Coupled Feed.

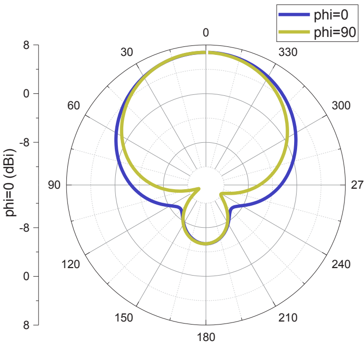


Fig. 20. E-plane (phi = 90º), and H-plane (phi = 0º) of Antenna with Aperture Coupled Feed at 2.45 GHz

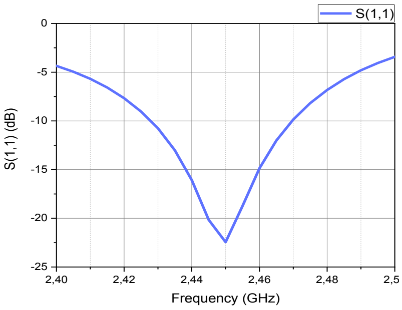
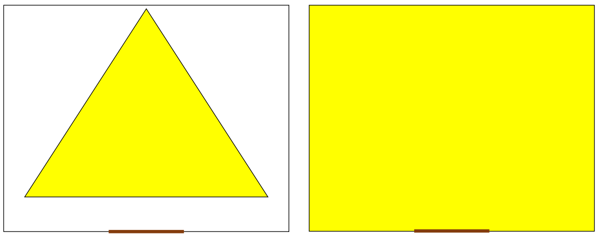


Fig. 21. Reflection coefficient ($S11$).

It's observed that the antenna resonance at frequency 2.45 GHz with reflection coefficient of $-22.44dB$ and the simulated gain in the 2.45 GHz band is 6.77 dBi.

4.5 Design of Proximity Coupled Feed



(a) (b)

Fig. 22. (a) The front plane, and (b) the ground plane of Antenna with Proximity Coupled Feed.

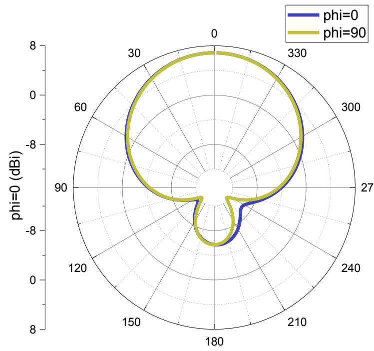


Fig. 23. E-plane (phi = 90º), and H-plane (phi = 0º) of Antenna with Aperture Coupled Feed at 2.45 GHz

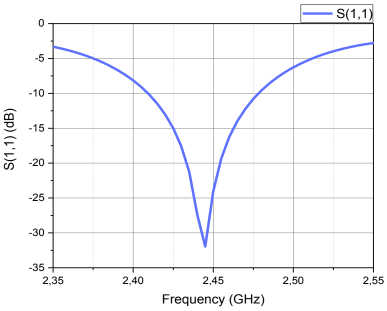


Fig. 24. Reflection coefficient ($S11$).

It's observed that the antenna resonance at frequency 2.445 GHz with reflection coefficient of $-31.96dB$ and the simulated gain in the 2.445 GHz band is 6.85 dBi.

5 Comparative Study

The table compares the performance of microstrip patch antennas based on feeding techniques and patch shapes (rectangular, circular, and triangular). The CPW (Coplanar Waveguide) feeding method provides exceptionally wide bandwidths, especially for triangular (1350 MHz) and circular (1040 MHz) patches, significantly outperforming other techniques. In terms of frequency range, CPW also stands out, covering up to 3.44 GHz for triangular patches. However, CPW feeding shows relatively low gains, ranging from 1.91 to 2.88 dB, making it less efficient in terms of radiation. Other methods, such as microstrip line and proximity coupling, offer higher gains exceeding 6 dB, with better impedance matching (S11) in some configurations. Nevertheless, CPW antennas often require larger sizes, which may limit their integration in compact applications.

Table 1. Comparison of Feeding Techniques for Microstrip Patch Antennas

		Microstrip Line feed	**Coaxial probe feed**	**CPW feed**	**Aperture coupled feed**	**Proximity coupled feed**
Bandwidth (MHz)	**Rectangular**	80	80	1194	110	110
	Circular	80	41	1040	70	100
	Triangular	57	60	1350	40	70
Frequency band (GHz)	**Rectangular**	2.41 - 2.49	2.41 - 2.49	1.78 - 2.98	2.39 - 2.5	2.4 - 2.51
	Circular	2.41 - 2.49	2.428 - 2.469	2.08 - 3.12	2.41 - 2.48	2.4 - 2.5
	Triangular	2.42 - 2.47	2.42 - 2.48	2.09 - 3.44	2.42 - 2.46	2.40 - 2.47
f_r (GHz)	**Rectangular**	2.452	2.453	2.445	2.45	2.46
	Circular	2.455	2.45	2.45	2.45	2.455
	Triangular	2.45	2.45	2.45	2.45	2.445
S11 (dB)	**Rectangular**	- 37.1	-24.96	-37.42	-25.5	-20.28
	Circular	-45.85	-30.53	-33.2	-32.29	-36.08
	Triangular	-37.53	-32.92	-40.36	-22.44	-31.96
Gain (dB_i)	**Rectangular**	7.01	7.03	2.88	6.8	6.92
	Circular	5.77	6.99	2.29	6.76	6.05
	Triangular	5.8	5.71	1.91	6.77	6.85
Size (mm^3)	**Rectangular**	74.3 x 57.6 x 1.67	74.3 x 57.6 x 1.67	77 x 80 x 1.635	74.3 x 57.6 x 3.3	74.3 x 57.6 x 3.3
	Circular	40 x 55 x 1.67	50 x 50 x 1.67	60 x 55 x 1.635	55 x 55 x 3.3	42 x 42 x 3.3
	Triangular	45 x 50 x 1.67	45 x 40 x 1.67	75 x 65 x 1.635	55 x 55 x 3.3	63 x 52 x 3.3

Conclusion

In conclusion, the choice of feeding technique for microstrip patch antennas plays a crucial role in determining their suitability for IoT devices. CPW feeding stands out with its exceptionally wide bandwidth and frequency range, making it a strong candidate for IoT applications that require broad spectral coverage and versatility, such as multi-band sensors and wireless communication systems. However, its lower gain and larger size may limit its practicality in compact IoT devices, where size and efficiency are critical. Microstrip line and proximity-coupled feeding, with their higher gains and better impedance matching, are more suitable for IoT applications focused on energy efficiency and space-saving, like wearable devices or compact sensors. Ultimately, the selection of the feeding method should align with the specific requirements of the IoT device, balancing the trade-offs between bandwidth, gain, and size for optimal performance.

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