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Performance Analysis of Patch Modification Techniques for Microstrip Antennas in 5.8 GHz IoT Applications

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Abstract
This paper presents the design and simulation of a microstrip patch antenna for Internet of Things (IoT) applications in the 5.8 GHz ISM band, using an FR4 substrate to ensure cost-effective prototyping. A baseline inset-fed rectangular patch is compared with three optimized geometries: an inset-modified patch, a notched patch, and a U-shaped slotted patch. Simulations were conducted in CST Studio Suite using the frequency domain solver. Important performance metrics that were evaluated include return loss (S_{11}), gain, bandwidth, directivity, and radiation efficiency. This inset-optimized design yielded the best results with a radiation efficiency above 57%, a return loss of –49.8 dB, a bandwidth of 250 MHz, and a gain of 3.97 dB. The notched design also showed good performance, offering bandwidth (237 MHz) and strong impedance matching (–44.8 dB) with only minor gain trade-offs. Despite having the highest directivity, the slotted patch's lower efficiency (54%) and gain (3.55 dB) limited its applicability for low-power IoT nodes. All of the designs outperformed the 150 MHz target bandwidth, confirming that FR4-based antennas are feasible for small IoT systems. The study demonstrates how simple geometric changes can improve performance while maintaining low cost and ease of fabrication.

Keywords: Microstrip antenna, IoT, patch modification, notches, slots, inset feed, FR4, 5.8 GHz.

1. Introduction

As the Internet of Things (IoT) has grown, there has been an increasing demand for wireless communication systems that are small, inexpensive, and reliable at higher frequencies. Microstrip patch antennas (MPAs) are particularly attractive for these types of applications due to their planar profile, ease of fabrication, and printed circuit board compatibility [1]. However, it can be challenging to design MPAs that meet the strict performance requirements of the 5.8 GHz band. The challenge increases when naturally lossy, inexpensive materials like FR4 are used as they can lower radiation efficiency [2], [3].

The 2.4 GHz and 5 GHz ISM bands have historically supported a large number of IoT applications. However, increasing interference, spectrum congestion, and regulatory pressure necessitate research into alternative bands. [4]. In contrast to the overused 2.4 GHz range, the 5.8 GHz sub-band of the 5 GHz ISM spectrum is showing promise as a substitute because of its better data throughput potential, lower interference, and comparatively cleaner spectrum [5], [6]. However, tradeoffs of attenuation and increased path loss at higher frequencies [7], necessitate carefully considered antenna designs.

It can be difficult to get the ideal balance between bandwidth, gain, and return loss in the 5.8 GHz band, particularly when keeping the small form factor needed for small Internet of Things devices. Many existing designs prioritize one selected performance metric over another or use complex geometries and specialized substrates, raising the complexity and cost of fabrication [8], [9]. Furthermore, although FR4 is inexpensive and widely available, its high loss tangent impacts antenna efficiency significantly. As a result, geometry-level adjustments are often required to make up for material losses [10].

By examining three geometry-based optimization strategies on a rectangular inset-fed FR4 microstrip patch antenna that was initially intended for the 5.8 GHz band, this study tackles these issues. The performance of three modified versions—an optimized inset-fed version, a patch with square edge notches, and a patch with a vertical U-shaped slot—is compared to that of an unmodified patch (baseline) in this study. In order to make the antenna practical for actual IoT deployments at 5.8 GHz, the objective is to increase return loss and bandwidth while preserving acceptable gain and radiation efficiency [11].

The frequency domain solver was used to extract important parameters from simulations carried out in CST Microwave Studio, including radiation efficiency, gain, directivity, bandwidth, far-field stability, and return loss (S11). The performance trade-offs of each modification are examined and evaluated critically, with special attention paid to the effects of design geometry and the constraints imposed by the FR4 substrate.

The results show that while changes to geometry can enhance bandwidth and impedance matching, they may also have an impact on gain and radiation efficiency because of changes in substrate interaction and current distribution. The optimized inset-fed patch outperformed the other modified designs in terms of trade-off between performance metrics.

The use of low-loss (high efficiency) substrates and integration with filtering structures that enhance spectral efficiency and out-of-band suppression are two possible areas for future development that are identified in this work. The results are intended to guide future antenna designs for realistic Internet of Things systems that aim to strike a balance between cost, performance, and ease of fabrication.

2. Related works

Microstrip patch antennas are widely regarded as strong candidates for Internet of Things (IoT) applications. Numerous studies have explored design strategies to meet the stringent performance requirements of IoT nodes, particularly under constraints such as miniaturization, low power, and cost-effective substrates.

Khan et al. [1] provided a broad review of antenna systems tailored for IoT and highlighted the growing trend of using modified microstrip geometries to support frequency, bandwidth, and size requirements. Similarly, Anchidin et al. [10] designed a compact rectangular patch for IoT systems and verified its viability using FR4 substrate. Although their results were promising, gain remained relatively low due to the high dielectric loss.

To address impedance matching challenges, Mbinack et al. [5] carried out a detailed experimental study on inset-fed rectangular patches, emphasizing the importance of precise feed positioning and substrate characterization. Behera and Panda [12] extended this by optimizing the inset parameters, significantly reducing return loss while keeping structural simplicity—an approach that directly inspired the inset optimization in our study.

Design efforts focusing on bandwidth enhancement have included techniques like edge notching and reactive loading. Islam et al. [13] introduced grounded stubs to extend resonance and bandwidth.

However, the added fabrication complexity may not be ideal for scalable IoT deployment. Notch-based and slot-loaded antennas have also been explored extensively. Deshmukh and Ray [14] reviewed various slot-loading strategies and demonstrated how these can create multi-resonant behavior and improve return loss and bandwidth simultaneously. However, these designs can introduce radiation pattern distortion if not carefully tuned.

Efficiency is another critical parameter, especially when low-cost materials like FR4 are used. Zaini and Rani [7] showed that, despite FR4's high loss tangent, acceptable performance is possible through careful geometric tuning. Their wearable antenna prototype balanced efficiency and size effectively for short-range applications. Elijah and Mokayef [8] proposed a miniature patch for IoT nodes, demonstrating strong integration potential but highlighting the inevitable trade-offs in gain and beamwidth when using compact designs.

More recently, Guneser et al. [6] focused specifically on 5.8 GHz designs for transportation-related IoT systems. Their work demonstrated that this band offers improved throughput with lower interference, but emphasized the need for impedance and bandwidth tuning due to higher attenuation. Naqvi and Lim [15] reviewed recent slot-loaded patch designs and concluded that while slots can enhance performance metrics, they often introduce geometry sensitivity that demands precise tuning to avoid performance degradation.

Motivated by the above review, in this work we carry out research on a 5.8 GHz microstrip antenna using FR4, examining how simple geometry modifications—specifically optimized inset feed, notching, and slotting—can be used to enhance bandwidth, return loss, and radiation performance, while maintaining cost-efficiency and fabrication simplicity.

3. Antenna Design and Methodology

This study used a method based on simulations to design, improve, and compare a number of microstrip patch antenna configurations centered on 5.8 GHz. CST Microwave Studio 2019 was used to run the simulations and we chose the frequency domain solver because it is very good at analyzing S-parameters, gain, and radiation characteristics [16]. The antenna substrate was FR4, which had a dielectric constant $\varepsilon_R = 4.3$, a thickness of 1.6 mm, and a loss tangent of 0.025. The patch and ground plane were both made of copper of 0.035 mm thickness. A waveguide port was used to excite the antenna and simulate it over a frequency range of 1 GHz to 7 GHz. Key performance monitors were focused between 5.0 and 6.5 GHz, which covered the target 5.8 GHz ISM band and also allowed for observation of out of band behavior.

Baseline Design

The baseline antenna was a standard rectangular inset-fed microstrip patch, shown in Figure 1 below.

Figure. 1. Geometry and dimensions of the baseline inset-fed rectangular microstrip patch antenna on FR4 substrate

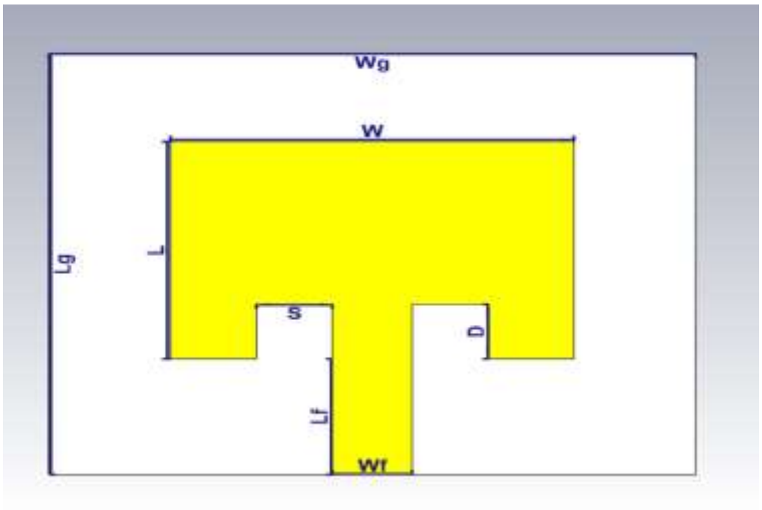


Table 1 Baseline patch dimensions in mm

Wg	Lg	W	L	Wf	Lf	S	D
25.5	23	15.9	11.9	3.14	6.3	3	3

The initial dimensions were determined using standard transmission line equations to put the fundamental resonance close to 5.8 GHz [17]. The Width of patch (W), Length of patch (L), Width of feedline (W_f), length of feedline (L_f), inset depth (D), Inset gap (s), width of ground (W_g), and length of ground were determined using the equations shown.

$$W = \frac{c}{2f_o\sqrt{\frac{\varepsilon_R+1}{2}}} \quad (1)$$

$$\varepsilon_{eff} = \frac{\varepsilon_R+1}{2} + \frac{\varepsilon_R-1}{2}\left[\frac{1}{\sqrt{1+12\left(\frac{h}{W}\right)}}\right] \quad (2)$$

$$L = \frac{c}{2f_o\sqrt{\varepsilon_{eff}}} - 0.824h\left(\frac{(\varepsilon_{eff}+0.3)\left(\frac{W}{h}+0.264\right)}{(\varepsilon_{eff}+0.258)\left(\frac{W}{h}+0.8\right)}\right) \quad (3)$$

$$Z_o = \frac{120\pi}{\sqrt{\varepsilon_{eff}}\left[\frac{W}{h}+1.393+\frac{2}{3}\ln\left(\frac{W}{h}+1.444\right)\right]} \quad (4)$$

$$W_f = \frac{7.48\times h}{e^{\left(Z_o\frac{\sqrt{\varepsilon_R+1.41}}{87}\right)}} - 1.25t \quad (5)$$

$$L_f = \frac{\lambda}{4} \quad (6)$$

$$D = \frac{L}{\pi}\cos^{-1}\left(\sqrt[4]{\frac{Z_{feedline}}{Z_{antenna}}}\right) \quad (7)$$

$$s \approx W_o \quad (8)$$

$$W_g \approx W + 6h \quad (9)$$

$$L_g \approx L + 3h + L_f \quad (10)$$

To make sure that energy was transferred efficiently, the feedline length was kept at about one-quarter of the guided wavelength (λg/4) for all designs.

Geometry Modification Techniques

The baseline served as a starting point for investigating geometry-based adjustments that would enhance the antenna's performance metrics, particularly bandwidth and return loss, while maintaining acceptable levels of gain and radiation efficiency. The baseline's overall patch and ground dimensions (Wg, Lg, W, L, Wf and Lf) are maintained in all modified designs, with only specific changes made to the same baseline in each modification.

1. Optimized Inset Feed: Only the inset depth (D)—the distance the feedline enters the patch from its radiating edge—and the gap (S) between the feedline edge and the inset edge were manually adjusted to improve the impedance matching close to 50 ohms. Several S and D dimensions were simulated during this trial-and-error process, and the combination with the best return loss characteristics at 5.8 GHz was selected. In contrast to a full parametric sweep, this manual optimization maintained the original quarter-wavelength feedline length (Lf) across all designs [12].

Table 2 Optimized Inset-feed Dimensions in mm

D (inset depth)	S (inset gap)
3.15	2.2

2. Notched Patch: Two symmetrical squares (1mm*1mm) were used to notch the patch's non-radiating edges, as shown in the Figure 2 below. By changing the surface current distribution and extending the effective path, this modification enhances impedance bandwidth and matching without significantly increasing the antenna's size or complexity [13].

Figure 2. Notched Patch

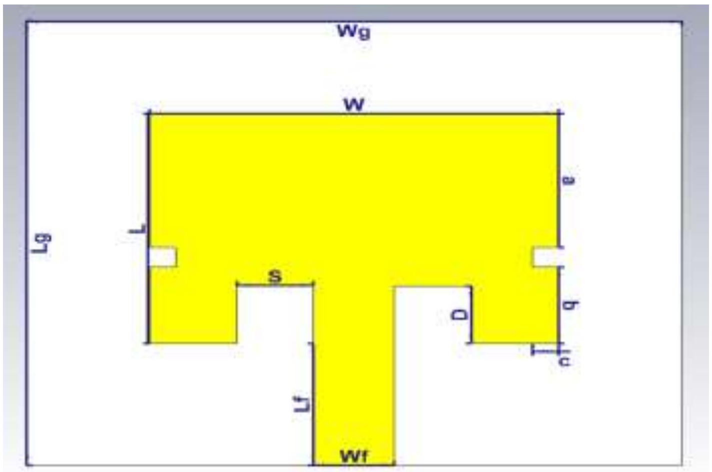


Table 3 Notched Patch Dimensions in mm

L	a	b	c (notch)
11.9	6.93	3.97	1 × 1

Table 3 shows the position of notch from the top radiating edge – distance (a), position of the notch from the bottom radiating edge (b) and the dimension of notch (c) which makes the notch a 1mm × 1mm square.

3. Slotted Patch: Near the left edge of the patch, a thin, vertical U-shaped slot shown in Figure 3 was inserted. This asymmetrically positioned slot was designed to add more resonant behavior and disturb surface currents to increase bandwidth and change impedance behavior [14].

Figure 3. Slotted Patch

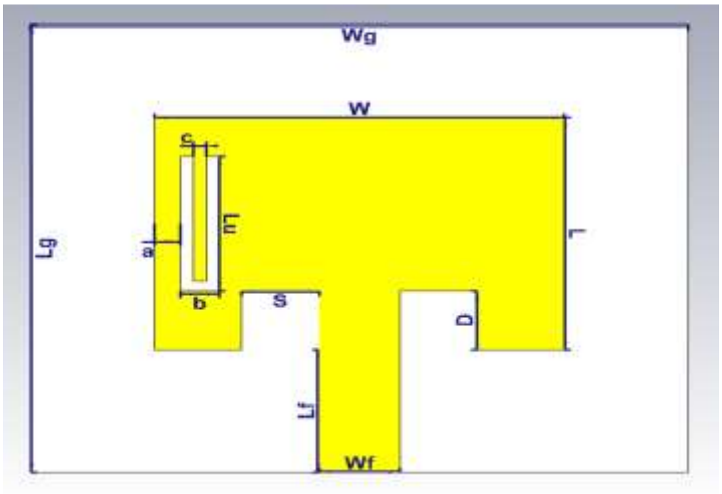


Table 4 U-Slot Dimensions in mm

a (distance from edge)	b (U slot base)	c (island width)	Lu (slot length)
1	1.5	0.5	6.9

Table 4 shows the slot placed 1mm from the patch edge, with its base aligned with the inset feed depth – 3mm from the bottom radiating edge. The slot has a base of 1.5mm and a central island of 0.5mm, making the slot itself of 0.5mm width on either side of the island and a slot length of 6.9mm obtained by manual tuning and simulation.

With the exception of the local geometric adjustments, all designs were built on the same FR4 substrate and shared the same patch area as the baseline patch. Because of this uniformity, any performance variations that were noticed could be directly linked to the geometric optimizations. Directivity, radiation efficiency, gain, bandwidth, and return loss (S11) were measured for every design and are shown in the Results section for a thorough comparison in order to determine trade-offs and determine which method best handles the inherent difficulties of utilizing FR4 in high-frequency Internet of Things applications.

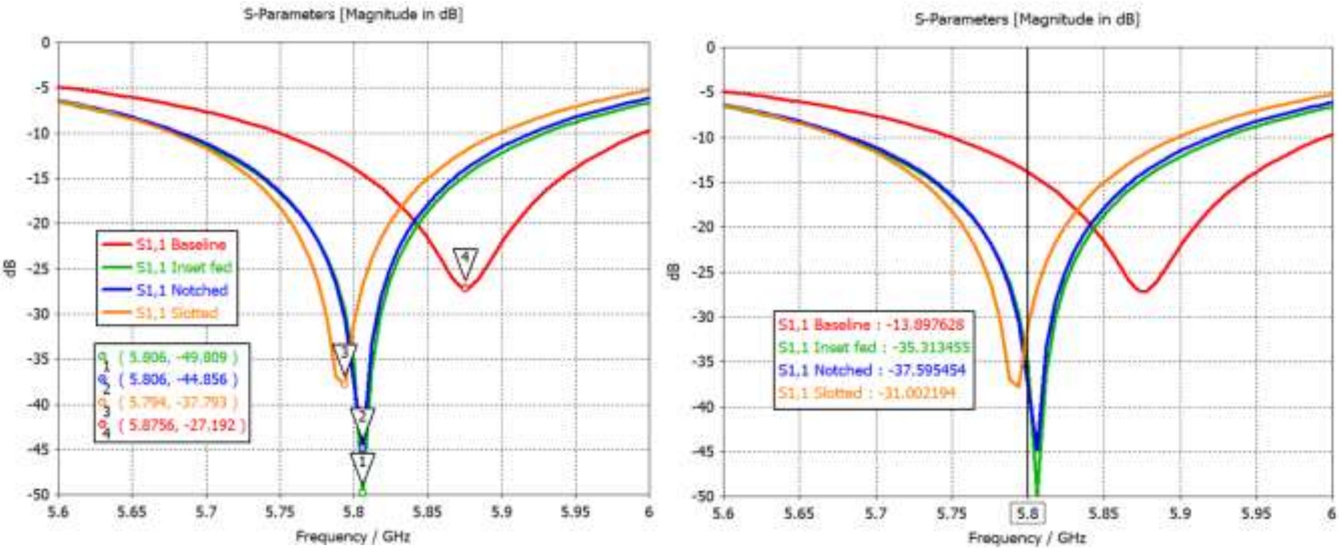
4. Results

The simulated performance outcomes of the four antenna configurations—baseline, optimized inset-fed, notched, and slotted—that are intended to function in the 5.8 GHz ISM band are shown in this section. All of the simulations were carried out with the frequency domain solver with waveguided ports and open boundary conditions in CST Microwave Studio 2019. Performance metrics considered include return loss (S11), impedance bandwidth, gain, radiation efficiency, and radiation pattern characteristics at θ = 90°, including main lobe magnitude, 3 dB beamwidth, and side lobe level [18].

Return Loss and Impedance Bandwidth

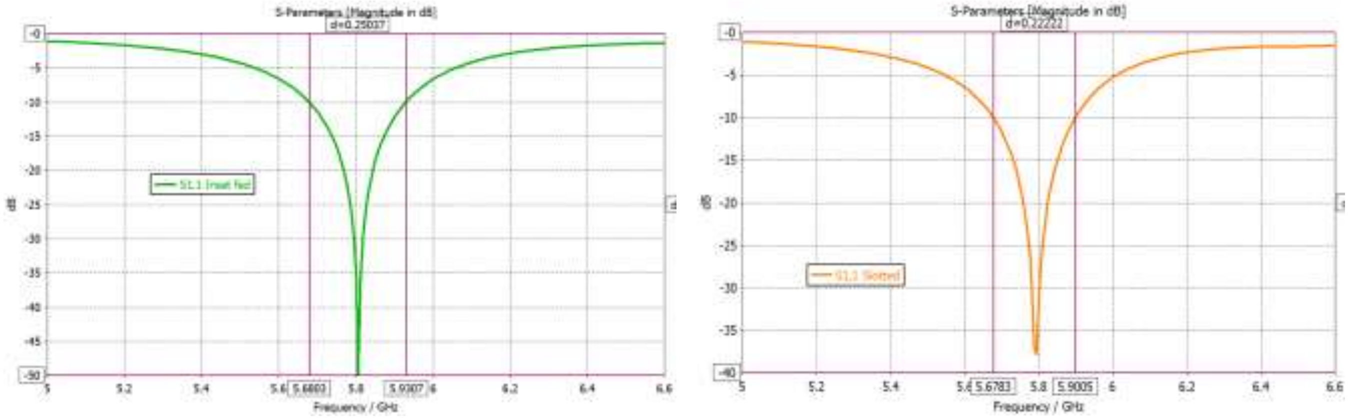
The baseline antenna resonated at 5.875 GHz with a return loss of –27.2 dB, and a –10 dB bandwidth of 246 MHz (5.749–5.996 GHz). This served as the reference for comparison. The inset-fed design exhibited the best impedance matching, with a deep return loss of –49.8 dB at 5.806 GHz and the widest bandwidth of 250 MHz. This improvement is attributed to the careful adjustment of inset depth and gap, which helped align the input impedance closer to 50 ohms [19]. The notched patch showed stable matching and modest bandwidth retention, resonating at 5.806 GHz with a bandwidth of 237 MHz and exhibiting a return loss of –44.8 dB, despite increased complexity. With a return loss of -37.8 dB, the slotted patch had the narrowest bandwidth of all the variations (222 MHz), despite resonating slightly lower at 5.794 GHz. The impedance bandwidth was slightly constrained by the additional reactive behavior introduced by the U-slot [5], [9].

Figure 4. Comparison of Return Loss Across Antenna Designs. (a) S11 Measured at Each Antenna's Resonant Frequency, Illustrating Resonance Alignment. (b) S11 Measured at the Fixed Target Frequency of 5.800 GHz for All Designs, Highlighting Behavior Under Uniform Uperating Conditions



The return loss (S_{11}) for each of the four antenna configurations is contrasted in Figure 4. In comparison to the baseline design, all three geometry modifications result in appreciable improvements in return loss. Because of its slightly offset resonant frequency at 5.875 GHz, the baseline antenna shows a higher (worse) return loss at the target frequency of 5.800 GHz. Better impedance matching at the intended operating frequency is shown by the optimized inset-fed and notched designs, which have closely matched and noticeably deeper nulls [20]. Although it is marginally less effective than the other two modified versions, the slotted patch also improves return loss over the baseline.

Figure 5. Impedance Bandwidth of the Optimized Inset-fed Antenna (a) with 250MHz and the Slotted Antenna (b) with 222MHz



The impedance bandwidth for two of the modified antennas is shown in Figure 5. The slotted design shows a slightly narrower span of 222 MHz, whereas the optimized inset-fed design attains the widest bandwidth at 250 MHz. Crucially, with comfortable margins between 72 and 100 MHz above 150MHZ, all four antenna configurations surpassed the target bandwidth. This demonstrates that all designs comfortably meet the bandwidth requirements for 5.8 GHz Internet of Things applications [18], [19].

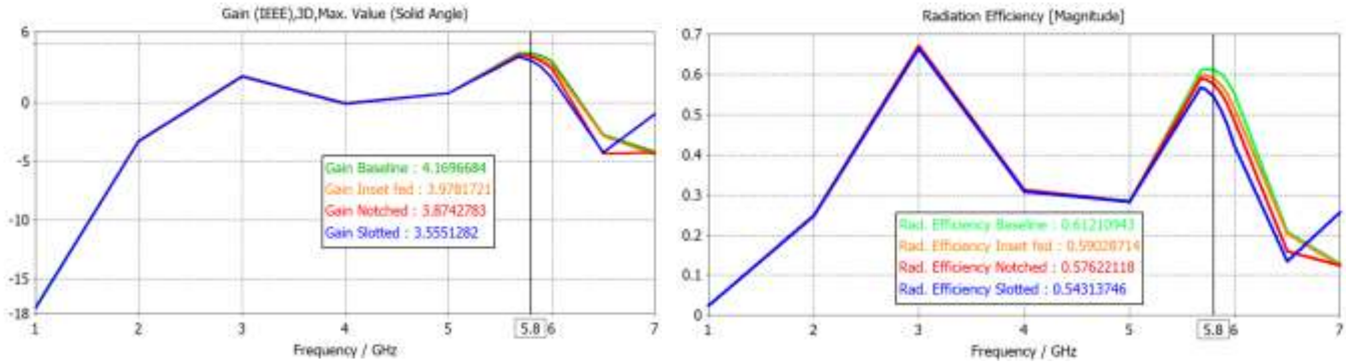
Gain and Radiation Efficiency

The antenna designs showed different gain and radiation efficiency values at their respective resonant frequencies. As expected for FR4-based microstrip designs [6], [9], the baseline patch had a radiation efficiency of 61% and the highest gain at 4.03. The optimized inset-fed variant demonstrated a 59% efficiency and a somewhat lower gain of 3.96 dB. This suggests that feed tuning improved impedance matching while compromising radiating performance as little as possible [8]. The notched patch came next with an efficiency of 57% and a gain of 3.85 dB, which was marginally lower but still within reasonable performance limits. The slotted design had the lowest gain of 3.57 dB and radiation efficiency of 54%, most likely as a result of the U-shaped slot's increased dielectric losses and disruption of surface current [21].

It is crucial to remember that these gains indicate the best operating performance of each design by representing peak values at each design's unique resonant frequencies. However, Figure 6 below shows the gain (a) and efficiency (b) values at the fixed target frequency of 5.800 GHz for a more consistent and meaningful comparison.

With gains ranging from 3.55 dBi to 4.16 dBi, or gain factors between 2.26× and 2.60×, all designs maintained comparatively strong performance at the precise target frequency (typically 2.5 to 4.5 dBi for FR4 based antennas), as seen in Figure 6.(a) [6], [8]. At 5.8 GHz, radiation efficiencies stayed between 54% and 61%, which is on the higher end of the usual performance range for FR4-based antennas (usually 40–65%) [5], [6], [10]. This confirms that the material is suitable for low-cost IoT designs.

Figure 6. Comparison of Gain and Radiation Efficiencies Across Antenna Designs. (a) Gain at Target Frequency 5.800 GHz. (b) Radiation Efficiency at Target Frequency 5.800 GHz.

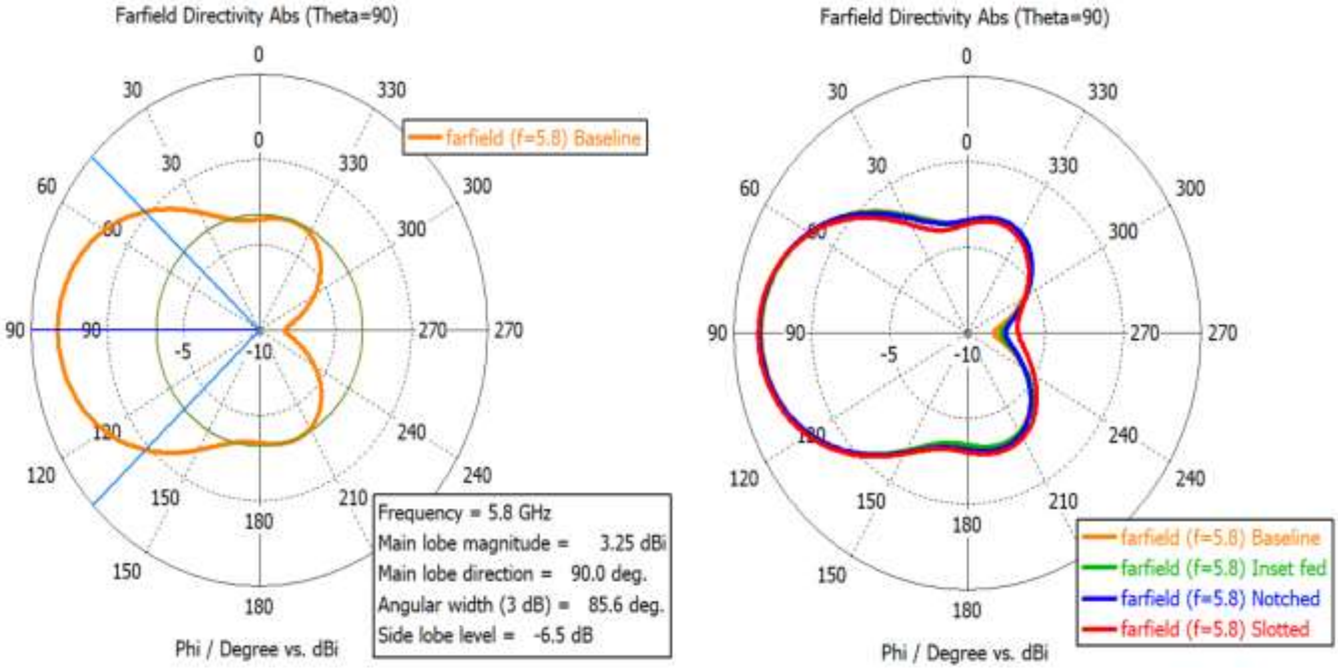


Broadside Radiation Characteristics (θ = 90°)

The baseline antenna demonstrated a main lobe directivity of 3.25 at broadside (θ = 90°), a side lobe level of –6.5 dB, and a 3 dB beam-width of 85.6° as shown in Figure 7(a) . While keeping the same side lobe level, the inset-fed design achieved a narrower 3 dB beam-width of 84.1° and a slightly higher directivity of 3.28. This trend was maintained by the notched patch, which achieved a directivity of 3.32 and further reduced the beam-width to 83.1°. In addition to having the narrowest beam-width (81.3°) and the slightly higher side lobe level (–6.2 dB), the slotted antenna had the highest directivity (3.41).

All of the antennas have similar directivity values, as seen in Figure 7 (b), with slight increases from 3.25 to 3.41 for the three modified designs. The 3 dB beam-width narrows gradually from 85.6° to 81.3°, indicating increasingly more focused radiation in the broadside direction. The side lobe levels were barely impacted across all the designs as they stayed near -6.5 dB. This indicates that the pattern sharpening introduced very little to no undesired radiation [2], [5].

Figure 7. 2D Radiation Patterns at 5.800 GHz, θ = 90° Cut, for (a) the Baseline Patch and (b) All Designs Compared



Summary of Performance Metrics

With the inset-fed patch reaching highest bandwidth of 250 MHz, all four designs achieved the desired bandwidth of 150 MHz. Due to offset from its resonant peak, the baseline patch displayed a much weaker match at 5.8 GHz, whereas the inset-fed and notched patches demonstrated outstanding performance at both the resonant and target frequencies in terms of return loss. Radiation efficiency and gain showed the expected pattern, with the slotted patch displaying the lowest values and the baseline patch leading in peak gain beam-width and directivity data show minimal side lobe degradation, a gradual narrowing of the beam, and a slightly higher directionality across modified patches [19], [21]. Table 5 is a summary of the key performance metrics for the four antennas.

Table 5. Summary of Key Performance Metrics for the Four Antenna Designs at Both Resonant and Target Frequencies.

Patch Design	Resonant Freq (GHz)	Bandwidth (MHz)	S11 @ Res Freq (dB)	S11 @ 5.8GHz (dB)	Gain @ Res Freq	Gain @ 5.8GHz (dB)	Efficiency (%)	Theta = 90 Directivity		
								Main lobe	3dB width	Side lobe level
Baseline	5.875	246	-27.2	-13.9	4.03	4.16	61	3.25	85.6	-6.5
Inset fed	5.806	250	-49.8	-36.6	3.96	3.97	59	3.28	84.1	-6.5
Notched	5.806	237	-44.8	-38.2	3.85	3.87	57	3.32	83.1	-6.3
Slotted	5.794	222	-37.8	-30.6	3.57	3.55	54	3.41	81.3	-6.2

Observations and Design Trade-offs

Together, these findings imply that small geometrical adjustments, especially to the inset feed, can greatly increase return loss while maintaining acceptable gain, bandwidth, and radiation efficiency. The inset-fed and notched versions both showed better impedance matching at the target frequency and accomplished balanced trade-offs, but no single design outperformed the baseline in every performance metric. These designs are particularly well-suited for Internet of Things applications that value portability, affordability, and dependable performance at 5.8 GHz [6], [9], [10], [18].

5. Discussion

According to the simulation results shown in Section III, all four antenna configurations satisfy the minimal performance requirements for Internet of Things applications operating in the 5.8 GHz ISM band. Nonetheless, the disparities in relative performance draw attention to significant design compromises influenced by substrate constraints, geometry, and impedance matching strategies. This section looks at the underlying reasons for these differences in order to identify the design that best strikes a balance between performance, complexity, and practical deployment in IoT environments.

Return Loss and Impedance Matching

Improved input impedance matching and control over current distribution are responsible for the significant improvement in return loss seen in the optimized inset-fed and notched designs. By allowing for precise adjustment of the feed position and gap, the inset feed geometry successfully reduces the mismatch at the feed point [12]. The -49.8 dB return loss indicates that this leads to an input impedance of about 50 ohms, which is close to ideal. In similar manner, the notched patch improved impedance matching without adding undue complexity. The notches introduce discontinuities that aid in surface current localization and resonance expansion [14].

On the other hand, the slotted patch adds more reactive components and resonant paths, which results in slightly less ideal matching even though return loss is still improved over the baseline. The importance of targeted tuning is further supported by the baseline's higher return loss at 5.800 GHz, which verifies that it is out of alignment with the intended operating frequency [5].

Bandwidth and Frequency Stability

All four designs easily surpassed the target bandwidth of 150 MHz. This margin is necessary to cater for frequency shifts brought on by environmental influences or fabrication tolerances, ensuring reliable communication [19]. The optimized inset-fed patch is once again in the lead with a span of 250 MHz. This enhancement results from the inset geometry's ability to more precisely adjust the coupling [12]. Although the slotted design has a slightly shifted resonant frequency (5.794 GHz), which suggests sensitivity to the slot geometry and dielectric interaction, it has acceptable margin of 72 MHz despite having a narrower bandwidth [14].aa

Gain and Radiation Efficiency Trade-offs

The absolute radiation efficiencies were below 65% for all designs, which is to be expected given that FR4 substrates are known to have higher dielectric and conductive losses [7]. The baseline patch outperformed the inset-fed and notched patches with small margins. This implies that inset and notch modifications mainly alter impedance without significantly disrupting surface current [17].

However, the slotted design had the lowest gain (3.55 dB) and efficiency (54%).This can be traced to the slot's influence on current paths—while it supports multi-resonance behavior, it can scatter or localize currents in a way that reduces radiating area effectiveness [14], [15]. This makes the design less desirable when power efficiency is critical.

Directionality and Beam Shape

All modified designs showed modest improvements in beam shaping and directivity, indicating improved forward radiation [10]. Interestingly, the slotted patch had the highest directivity and the narrowest beam-width, which could be advantageous for applications that need concentrated transmission (like directional sensing or point-to-point links). However, there is a slight increase in side lobe level as well, which may cause slight interference sensitivity in densely populated regions [22].

Preferred Design Recommendation

The optimized inset-fed patch is the best-balanced choice for general-purpose 5.8 GHz IoT applications, particularly those that value ease of fabrication, and reliable performance. It offers the widest bandwidth, deepest return loss, and competitive gain and efficiency compared to the baseline, with the least amount of extra complexity [6], [12].

A close second is the notched patch, which has a little lower gain and beam precision but offers great matching and bandwidth. Notching may be the better choice in cases where it is easier to carry out than precise feed placement [14].

Although still feasible, the slotted patch is less effective and more sensitive to geometry, so it may only appropriate in specific situations where directionality is more crucial than overall radiating efficiency [15].

6. Conclusion

This study presented the design and optimization of a microstrip patch antenna operating at 5.8 GHz for IoT applications, using an FR4 substrate to ensure cost efficiency and ease of prototyping [7], [17]. A baseline rectangular inset-fed patch was used as a reference, against which three modified designs—optimized inset depth, length-edge notching, and U-shaped slotting—were evaluated through CST frequency domain simulations [6], [14].

With a gain of 3.97 dB, a wide bandwidth of 250 MHz, and a return loss of –49.8 dB, the optimized inset-fed patch outperformed the other configurations tested while preserving a respectable radiation efficiency on the lossy FR4 substrate [6], [15]. With only slight gain trade-offs, the notched patch also showed excellent bandwidth and impedance matching performance, confirming that structural perturbations such as edge notching can significantly enhance return loss and bandwidth without excessive complexity [10].

The slotted patch was less appropriate for low-power IoT environments that prioritize effective, omnidirectional coverage because it had lower radiation efficiency and gain despite having better directivity and beam shaping [22]. However, such characteristics may benefit directional sensing or point-to-point IoT links where beam control is prioritized.

These findings demonstrate how geometric tuning can enhance antenna performance without raising the cost or complexity of the design. Additionally, they confirm that, with careful impedance matching optimization, FR4 is viable for 5.8 GHz IoT antennas [7], [10].

Future research could involve creating reconfigurable or multi-band designs that are in line with changing IoT standards [1], [16], evaluating low-loss substrate substitutes [23], integrating filtering elements for out-of-band suppression [24], and fabricating and validating prototypes of the simulated designs.

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