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A RECTANGULAR PATCH ANTENNA FOR INTERNET OF THINGS APPLICATIONS IN SUB-6 GHZ BAND

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Abstract. *In the rapidly expanding domain of the Internet of Things (IoT), there is a burgeoning requirement for compact and efficient antennas operating within the Sub-6 GHz frequency range (2.3–4.2 GHz). This research focuses on the design and optimization of a rectangular patch antenna, specifically intended for use in Internet of Things (IoT) applications within this frequency spectrum. The proposed antenna features a rectangular slot in the ground plane and employs substrate removal methodologies to enhance its performance. It is made on an FR-4 substrate, characterized by a loss tangent of 0.025, a dielectric constant of 4.3, and a thickness of 1.6 mm. The antenna is fed through a 50-Ohm inset feedline to ensure effective signal transmission. Simulations are conducted using CST Studio Suite to evaluate the antenna's design and performance metrics. The results indicate an impressive reflection coefficient (S11) of −35.39057 dB, a 209.273 MHz bandwidth (2.525316 GHz–2.734589 GHz), and a VSWR of 1.03908. Furthermore, the antenna exhibits a gain of 0.623 dBi, a directivity of 3.71 dBi, and a radiation efficiency of 49.12%. These findings strongly suggest the antenna's excellent potential for diverse IoT services, promising reliable and robust wireless communication. Future research will focus on physical prototyping, further parametric optimization, and integration into practical IoT devices. This study significantly contributes to the progression of high-performance antenna design for next-generation IoT systems, consequently aiding in the creation of more compact and efficient wireless communication technologies.*

Key words: *IoT, Rectangular patch antenna, Ground Slot, Substrate removal, Sub-6 GHz, Bandwidth.*

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1. INTRODUCTION

The rapid proliferation of the Internet of Things (IoT) has driven a growing demand for efficient communication systems capable of supporting numerous connected devices, particularly in the Sub-6 GHz frequency band. As IoT applications continue to expand into diverse fields such as smart homes, healthcare, automotive, and industrial automation, the need for compact, lightweight, and cost-effective antenna solutions has become increasingly critical [1]. Apart from the several kinds of antennas that are accessible, patch antennas are preferred owing to their diminutive size, simplicity of manufacturing, and capacity to perform multiple tasks within a particular spectrum [2–3]. The Sub-6 GHz spectrum, especially within the 2.3–4.2 GHz range, offers a balanced compromise between coverage and data rate, making it ideal for IoT devices [4]. This frequency range not only supports short-range communication but also ensures effective penetration through obstacles, a critical feature for indoor applications. However, designing antennas for this spectrum presents challenges such as maintaining a compact form factor while achieving desirable gain, bandwidth, and efficiency [5]. In order to confront these difficulties, several novel designs have been put forward and meticulously examined. For example, a compact rectangular microstrip patch antenna featuring corner truncation, built on an FR4 substrate, demonstrated impressive compactness with dimensions of 23 × 23 × 1.6 mm^3 [6]. This design achieved a 5.33 dBi gain, and a bandwidth of 0.06 GHz (2.41–2.47 GHz), making it particularly suitable for small wearable IoT devices. Another variant, also measuring 23 × 23 × 1.6 mm^3, boasts an expanded 1.42 GHz bandwidth (3.68–5.1 GHz) and a higher 8.1 dBi gain, positioning it as an excellent option for wideband IoT systems [7]. Moreover, MIMO antenna configurations proved effective in improving system capacity and reliability. A MIMO antenna featuring a ground rectangular slot with dimensions of 40 × 40 × 1.6 mm^3 revealed an impressive impedance bandwidth of 2.4 GHz (3.2–5.6 GHz) alongside strong port isolation, making it an attractive choice for high-performance IoT networks [8]. Additionally, an inset-fed wideband rectangular microstrip patch antenna realized a remarkable return loss of –33.235 dB and a bandwidth of 3.198 GHz (3.6959–6.8939 GHz), underscoring its potential for Sub-6 GHz 5G IoT operations [9].

A modified microstrip patch antenna, characterized by a meander shape with a footprint of 40 × 10 × 1.6 mm^3, successfully achieved a gain of 1.347 dBi, a bandwidth of 146 MHz, and an efficiency level of 79% [10]. Furthermore, a dual-band patch antenna, exhibiting a gain of 2.77 dBi and a 0.3 GHz bandwidth, was developed specifically for Sub-6 GHz operational frequencies [11]. Continued advancements in antenna design were illustrated by a refined meander-form microstrip patch antenna, which achieved an impressive gain of 4.01 dBi alongside an efficiency of 90% [12]. Additionally, compact dual-band antennas featuring slotted patches gained significant traction, providing a 0.76 GHz bandwidth and a 5.01 dBi gain [13]. A 20 × 30 × 1.5 mm^3 multi-grooved antenna for LTE/5G fields featured a 2.4 GHz bandwidth and a 2.69 dBi maximum gain [14]. Another proposed planar antenna, intended for Sub-6 GHz 5G operations, measured 135 × 80 × 0.8 mm^3, achieving a −6 dB impedance bandwidth of 0.26 GHz and a peak gain of 4.7 dBi [15]. Lastly, a cross-dipole antenna designed for 4G and Sub-6 GHz 5G base stations, measuring 76 × 42 × 1.6 mm^3, delivered a −6 dB impedance bandwidth of 2.493 GHz along with an optimal gain of 3.2 dBi [16].

A wideband microstrip patch antenna employing defected ground structures (DGS) attained a bandwidth of 4.2 GHz, encompassing frequencies from 1.8 to 6 GHz, and was characterized by dimensions of 30 × 26.5 × 1.42 mm^3 [17]. Additionally, an inverted C-configuration dual-band monopole antenna for IoT and 5G offered 0.9 GHz and 0.3 GHz bandwidths with maximal gains of 2.7 dBi and 1.8 dBi [18], while a T-slot patch antenna for 5G provided 0.44 GHz bandwidth and 7.6 dB highest gain [19]. Moreover, a multiband patch antenna with SINC-shaped edges, alongside a Y-shaped tri-band DGS patch antenna for 5G communication, presented commendable bandwidths and gains [20–21]. Finally, a broadband, high-efficiency 2×1 monopole antenna array purposed for WiMAX and Sub-7 GHz applications underscored significant progress in antenna technology, providing a robust solution for contemporary communication systems [22].

A compact L-shaped microstrip patch antenna, measuring 28 × 21 × 1.6 mm^3, operated at 2.4 GHz with a 140 MHz bandwidth, a 1.96 dBi gain, and an impressive 98% efficiency [23]. A circularly polarized patch antenna with a faulty ground structure, inspired by a metasurface, was designed to enhance functionality in Sub-6 GHz scenarios [24]. Additionally, another design featured a meandered monopole and dipole configuration, targeting long-range sub-GHz communications with a 10 MHz bandwidth and a 0.5 dB gain [25]. Furthermore, a microstrip patch antenna characterized by slot configurations operated across multiple frequency bands, successfully attaining bandwidths of 160 MHz at 3.45 GHz and 220 MHz at 5.9 GHz [26]. A semicircular dual-band multiple input multiple output (MIMO) patch antenna facilitated broadband services, exhibiting a 20 dB largest gain across a 6 GHz bandwidth [27]. A microstrip antenna specifically engineered for Internet of Things (IoT) sectors was developed, providing a bandwidth of 20 MHz [28]. A compact four-element MIMO antenna system designed for Sub-6 GHz scenarios incorporated an altered M-carved segment, with physical dimensions measuring 100 × 60 mm^2 [29]. Additionally, a dual-band microstrip patch antenna intended for Long Range (LoRa) functions was fabricated on an FR-4 substrate, with dimensions of 60 mm by 65 mm by 1.6 mm, achieving gains of 1.7 dBi at 433 MHz and 2.56 dBi at 868 MHz [30]. A miniscule antenna designed for 2.4 GHz IoT purposes demonstrated gain values of 1.2 dBi and 1.142 dBi [31]. Lastly, a wideband microstrip patch antenna employing a malfunctioning ground construction accomplished a bandwidth of 0.835 GHz [32].

A 2 × 2 MIMO antenna developed for Sub-6 GHz 5G IoT services exhibited a notable gain of 7.05 dBi [33]. An innovative flat antenna with flipped stub, E-shaped, and rectangular slots as well as a circular erroneous segment was also created for Sub-6 GHz 5G usage [34]. It achieved a 19 MHz bandwidth, an 82% efficiency, and an approximate gain of 4.2 dB. A microstrip antenna operating at 3.8 GHz, with a 7.77 dBi gain and a 350 MHz bandwidth, was also demonstrated for Sub-6 GHz purposes [35]. A patch antenna for Sub-6 GHz services was introduced [36], in conjunction with a multiband MIMO antenna layout meticulously tailored for Sub-6 GHz 5G IoT usages [37]. For impending Internet of Things purposes, an enormous rectangular patch antenna (30 × 20 × 0.8 mm^3) based on a mixed approach was created [38]. Simulations demonstrated an extended bandwidth (19.9 GHz), a 96.51% efficiency rate, and a gain of 7.97 dB. A tri-band multiple input multiple output (MIMO) antenna with a 3D construction, six ports, and 360° range was unveiled for 5G IoT devices [39]. Verified by machine learning with 89% precision, the antenna incorporated apertures and complex segments. It achieved high isolation, strong diversity, and peak gains of 4.3 dBi (Sub-6 GHz), 5.5 dBi (Kuband), and 9.9 dBi (mm-wave), making it suitable for smart cities, V2X communication, and satellite services.

A 5G Sub-6 GHz vehicle antenna (58 × 30 × 1 mm^3) was designed using Characteristic Mode Analysis (CMA) to maintain a stable monopole radiation pattern across 0.617–5 GHz while suppressing higher-order modes [40]. The FR-4 PCB-based antenna was simulated, fabricated, and tested on a 1-m ground plane, achieving 80% efficiency, stable gain (0.5–2.5 dBi), and omnidirectionality. The VSWR remained below 2.7:1, with a gain deviation under 1 dB near the horizon, ensuring optimal automotive performance. A 5G Sub-6 GHz antenna (160 mm × 70 mm) with MIMO and array configurations was demonstrated for 5.57 GHz applications [41]. Its circular radiator, featuring inner and rectangular slots, is built on an RT5880 substrate, achieving 12.4 dB gain, 30 dB isolation, 80% efficiency, and SAR compliance (<2 W/kg per 10 g tissue). A high-gain wideband microstrip patch antenna (28.03 × 23.45 × 1.6 mm^3) for Sub-6 GHz 5G was created using a defected ground structure and a reflective plate to enhance bandwidth and gain [42]. It operates from 4.921–5.784 GHz with 6.21 dB gain, 7.56 dB directivity, and 80% efficiency. A defected ground-based slotted patch antenna (38 × 38 × 1.575 mm^3) for Sub-6 GHz 5G applications was proposed [43]. It achieved a 69.2 MHz bandwidth, -54.028 dB reflection coefficient, 6.463 dB gain, and 93.475% efficiency.

This study introduces the creation and optimization of a compact rectangular patch antenna specifically tailored for Sub-6 GHz Internet of Things (IoT) applications, focusing on the frequency range of 2.3–4.2 GHz. The innovative design incorporates techniques such as ground plane slotting and substrate removal, resulting in significant enhancements in reflection coefficient, bandwidth, gain, directivity, and efficiency. Built on an FR-4 substrate, the antenna features a 50-Ohm inset feedline for effective impedance matching, ensuring reliable performance while being cost-efficient to manufacture. Simulation results substantiate the antenna's capabilities, emphasizing its appropriateness for a multitude of IoT applications.

The originality of this study is attributed to the distinctive amalgamation of ground plane slotting techniques and substrate removal strategies, which elevate the antenna's effectiveness while preserving a diminutive size. The design achieves an impressive reflection coefficient (S_{11}) of −35.39057 dB, a bandwidth of 209.273 MHz, and a Voltage Standing Wave Ratio (VSWR) of 1.03908, reflecting exceptional impedance matching. Furthermore, the antenna boasts a radiation efficiency of 49.12% and a gain of 0.623 dBi. While the gain is relatively modest, the design's compact nature and straightforward manufacturing process effectively compensate for this shortcoming. In summary, this research advances the field of IoT communication systems by presenting a compact and cost-efficient antenna design specifically for the Sub-6 GHz frequency spectrum. The outcomes of this investigation lay the groundwork for future endeavors, including experimental validation and further refinement of the antenna's performance metrics. With its small footprint, efficient design, and strong performance characteristics, the proposed antenna fulfills the diverse requirements of a wide array of IoT applications.

The remainder of this paper is organized as follows: Section 2 delineates the IoT system architecture, Section 3 elaborates on the microstrip antenna design with parametric optimizations, Section 4 explores proposed methodology, Section 5 presents the simulation results, Section 6 provides a discussion, Section 7 offers a comparative analysis, and Section 8 concludes the study.

2. Structure of the System

This study presents a comprehensive overview of an Internet of Things (IoT) system that incorporates a microstrip patch antenna. Figure 1 delineates the block diagram of the system, elucidating the several attributes and their interconnections. Each segment is explicated to facilitate a clear understanding of the system's functionality and design.

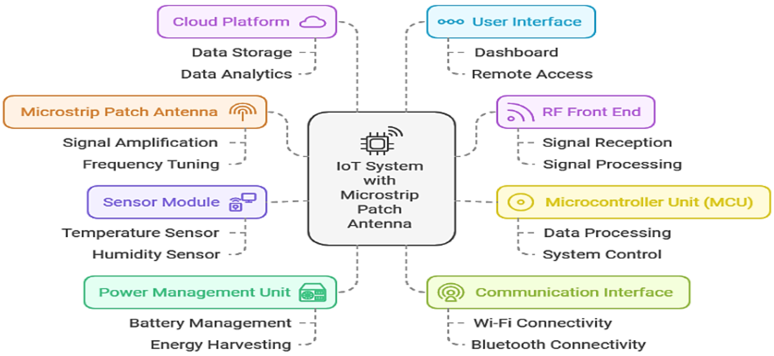

Fig. 1 Block diagram of IoT system with microstrip patch antenna

- **Microstrip Patch Antenna:** This antenna facilitates signal amplification and permits frequency tuning, thereby enabling the efficient transmission and reception of electromagnetic signals within the system [44].
- **RF Front End:** This essential component manages signal reception and processing by amplifying weak signals and filtering out unwanted noise, ensuring efficient communication [28].
- **Microcontroller Unit (MCU):** Acting as the brain of the system, the MCU is responsible for data processing and overall system control, facilitating seamless coordination among the various components [28].
- **Sensor Module:** Featuring sensors such as temperature and humidity detectors, this module gathers environmental data and transmits it to the microcontroller for further analysis [28].
- **Power Management Unit:** It optimizes energy consumption through effective battery management and energy harvesting, thereby improving the system's reliability and sustainability [44].
- **Communication Interface:** This module enables Wi-Fi and Bluetooth connectivity, promoting effortless wireless communication between devices and the IoT network [28].
- **Cloud Platform:** The data amassed by the system is relayed to the cloud for storage and analytical purposes, facilitating remote monitoring and informed decision-making [28].
- **User Interface:** End-users can interact with the system through a dashboard, providing them with the capability to monitor and control the system from a distance [28].

Together, these components function harmoniously to ensure reliable Internet of Things (IoT) operations, characterized by efficient data collection, transmission, and analysis.

3. MICROSTRIP ANTENNA DESIGN

This study elucidates a pioneering microstrip antenna specifically engineered for Internet of Things (IoT) applications, functioning at a frequency of 2.68 GHz within the Sub-6 GHz spectrum (2.3 to 4.2 GHz). The design incorporates a ground rectangular slot and a substrate removal technique to enhance performance while maintaining a compact size. Built on an FR-4 dielectric substrate with a relative permittivity of 4.3, a thickness of 1.6 mm, and a tangent loss of 0.025, these properties are crucial for achieving optimal resonant frequency and efficiency. Utilizing CST Studio Suite for modeling, the design includes a rectangular patch with dimensions derived from established antenna theory equations [40]. A 50-Ohm inset feedline ensures effective power transfer. Simulations assess performance indicators like reflection coefficient and bandwidth, confirming the antenna's suitability for IoT applications. Future research will concentrate on fabrication and hands-on verification to further explore its potential in communication technologies.

Patch Width (W) [45]: The patch width is ascertained utilizing a specific formula to augment the antenna's impedance characteristics and radiation pattern:

$$W = \frac{c}{2f_{\mathrm{r}}\sqrt{\frac{(\varepsilon_{\mathrm{r}}-1)}{2}}} \tag{1}$$

Where, c represents the speed of light in a vacuum (approximately 3×10^8 m/s),
f_{r} is the resonant frequency,
ε_{r} denotes the dielectric constant of the substrate.

Patch Length (L) [45]: The patch length is carefully adjusted to match the targeted resonant frequency, typically being less than half the wavelength due to the effects of fringing fields. This length can be expressed as:

$$L = \frac{c}{2f_{\mathrm{r}}\sqrt{\varepsilon_{\mathrm{r\,eff}}}} - 2\Delta L \tag{2}$$

Where, ΔL represents the length extension caused by fringing effects, which is calculated using the following method:

$$\Delta L = 0.412h\frac{(\varepsilon_{\mathrm{r\,eff}}+0.3)\left(\frac{W}{h}+0.264\right)}{(\varepsilon_{\mathrm{r\,eff}}-0.258)\left(\frac{W}{h}+0.8\right)} \tag{3}$$

Where, $\varepsilon_{\mathrm{r\,eff}}$, the effective dielectric constant, is crucial for integrating the fringing effects that manifest at the peripheries of the patch. It is computed using the formula:

$$\varepsilon_{\mathrm{r\,eff}} = \frac{\varepsilon_{\mathrm{r}}+1}{2} + \frac{\varepsilon_{\mathrm{r}}-1}{2}\left[1+12\frac{h}{W}\right]^{-\frac{1}{2}} \tag{4}$$

These formulas are essential principles for designing a rectangular patch antenna. They assure that the antenna operates effectively at the designated frequency while maintaining proper impedance matching for maximum radiation efficiency. This design utilizes an inset feeding technique and is tailored for a 50-Ohm impedance. The geometric configuration of the antenna is illustrated in Fig. 2, and Table 1 provides a detailed list of its dimensions.

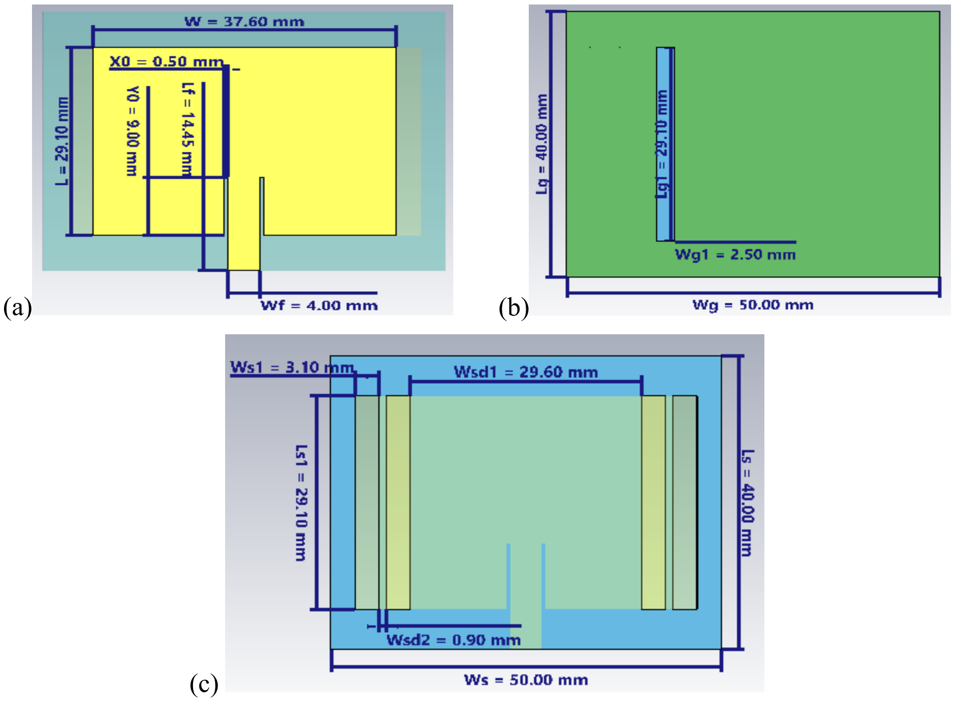

Fig. 2 Geometry of the proposed antenna (a) Front view, (b) Back view and (c) Substrate view

Table 1 Specifications of Antenna Size

Parameters	Value
Frequency band used	Sub-6 GHz band (2.3 - 4.2 GHz)
Operating frequency, f_r (GHz)	2.68
Dielectric constant of the substrate, ε_r	4.3
Thickness of the substrate, h	1.6 mm
Length of the substrate, L_s	40 mm
Width of the substrate, W_s	50 mm
Substrate Slot Distance, Wsd_1	29.60 mm
Gap between substrate slot, Wsd_2	0.9 mm
Substrate Rectangular Slot Width, Ws_1	3.10 mm
Substrate Rectangular Slot Length, Ls_1	29.10 mm
Width of the ground plane, W_g	50 mm
Length of the ground plane, L_g	40 mm
Ground Rectangular Slot Length, Lg1	29.10 mm
Ground Rectangular Slot Width, Wg1	2.50 mm
Length of the patch, L	29.1 mm
Width of the patch, W	37.6 mm
Thickness of the copper, t	0.035 mm
Width of the feed, W_f	4 mm
Feed length, L_f	14.45 mm
Inset distance, Y_0	9 mm
Inset gap, X_0	0.5 mm
Characteristics impedance of Inset-feedline (Z_0)	50 Ω

The influence of ground slot length (Lg1) variation on antenna performance is depicted in Fig. 3. An increase in Lg1 leads to an initial peak in bandwidth at 28.5 mm, followed by a subsequent decline, while the resonant frequency experiences only minor variations. Notably, reflection coefficient (S_{11}) significantly improves at Lg1 = 29.1 mm, achieving a value of −35.39 dB, which signifies optimal impedance matching. Conversely, both gain and efficiency exhibit a downward trend. The selection of Lg1 = 29.1 mm is justified as it provides the best impedance matching (S_{11} = −35.39 dB), facilitating efficient power transmission with minimal reflections—an essential requirement for reliable IoT applications operating in the Sub-6 GHz range.

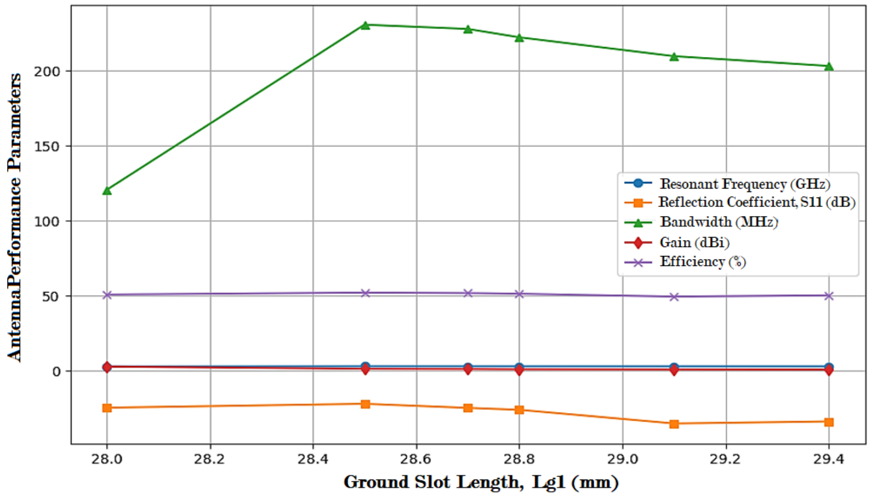

Fig. 3 Effect of ground slot length variation on antenna performance

The impact of ground slot width (Wg1) variation on antenna performance is shown in Fig. 4. The bandwidth exhibits peaks at both extremes of the range, with a notable dip occurring between 2.5 and 3.5 mm, while the resonant frequency remains largely unchanged. The reflection coefficient (S_{11}) reaches its lessened value of −35.39 dB at a width of Wg1 = 2.5 mm, signifying optimal impedance matching. Both gain and efficiency show moderate variations. The choice of Wg1 = 2.5 mm is justified as it provides the best impedance matching (S_{11} = −35.39 dB), thereby reducing signal reflections and enhancing power transfer, which is essential for effective IoT applications within the Sub-6 GHz frequency range.

Figure 5 demonstrates the influence of substrate slot length (Ls1) on antenna performance. As Ls1 increases, the bandwidth remains relatively constant with minor fluctuations. The resonant frequency shows slight variations, while reflection coefficient (S_{11}) improves (becomes more negative), indicating enhanced impedance matching. Although gain and efficiency experience slight changes, they largely remain stable. Ls1 = 29.1 mm is selected for its optimal impedance matching (S_{11} = −35.39 dB), which reduces signal reflections and maximizes power transfer—vital for effective antenna operation in IoT applications.

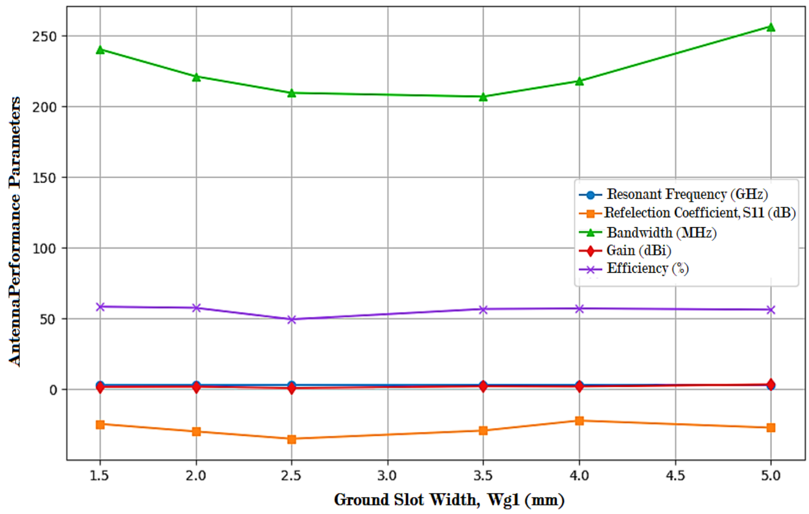

Fig. 4 Effect of ground slot width variation on antenna performance

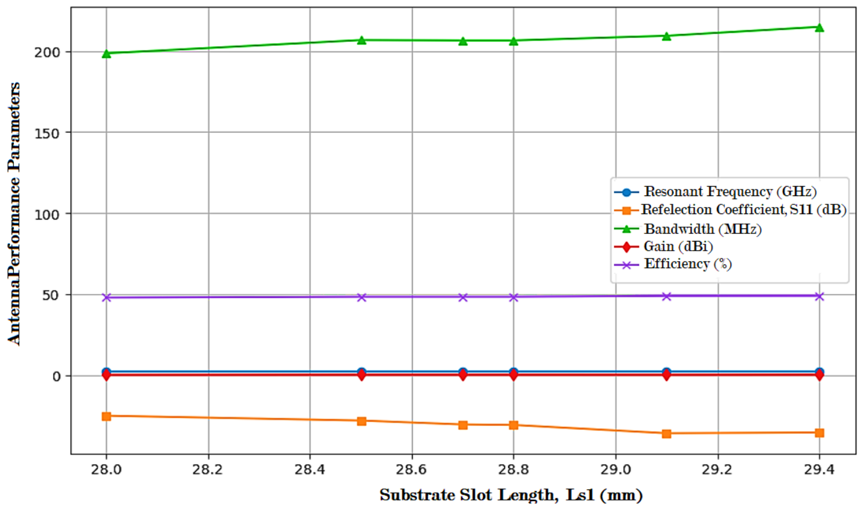

Fig. 5 Effect of substrate slot length variation on antenna performance

Figure 6 presents the effect of substrate slot width (Ws1) on antenna performance. With an increase in Ws1, the bandwidth shows a consistent upward trend. The resonant frequency remains stable with minimal fluctuations. Reflection coefficient (S_{11}) improves (becomes more negative) as Ws1 increases, indicating better impedance matching. Gain and efficiency display minor variations but are predominantly stable. The choice of Ws1 = 3.1 mm is based on the reflection coefficient (S_{11}) reaching −35.39 dB at this value, signifying optimal impedance matching. This condition mitigates signal reflections and enhances power transfer, which is paramount for the effective operation of antennas in applications encompassing IoT and wireless communications.

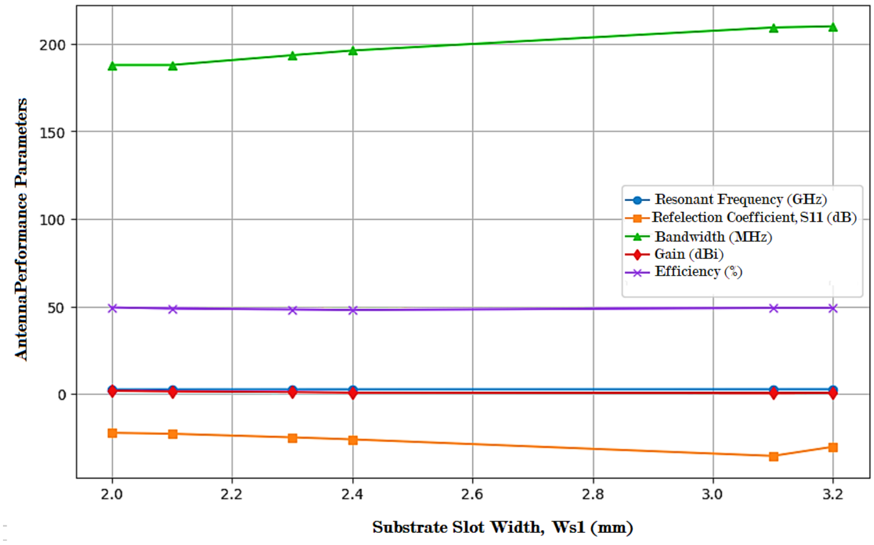

Fig. 6 Effect of substrate slot width variation on antenna performance

4. Approaches for the Proposed Work

Figure 7 portrays the suggested antenna design methodology with a block diagram that outlines the sequential steps in the simulation process. This diagram provides an organized overview, emphasizing the inclusion of a ground plane rectangular slot and a substrate removal strategy, both crucial for enhancing performance, particularly bandwidth. By simplifying a potentially complex workflow, the diagram clarifies the simulation and evaluation phases while ensuring clarity, repeatability, and reliable results, which are essential for future modifications and optimizations.

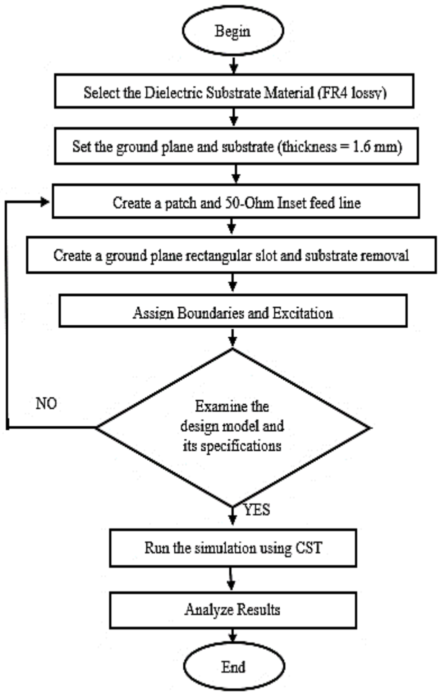

Fig. 7 Illustrative depictions of the proposed methodology

5. Simulated Results

5.1 Reflection coefficient (S_{11})

Reflection coefficient (S_{11}) is a vital metric in antenna design, representing the power reflected due to impedance mismatches, measured in decibels (dB). A lower (more negative) S_{11} implies better impedance matching, ensuring efficient power transfer between the antenna and its feedline. Generally, an S_{11} of −10 dB or lower is considered acceptable, meaning at least 90% of the input power is transmitted. The proposed antenna boasts an outstanding S_{11} of −35.39057 dB at 2.68 GHz (Fig. 8), signifying that only 0.028% of the input power is reflected, while approximately 99.97% is successfully transmitted. This remarkable value is particularly advantageous for IoT applications, where efficient energy transfer is crucial for devices with limited power sources. Additionally, the antenna's performance ensures compatibility with various IoT communication protocols such as Zigbee, LoRaWAN, and NB-IoT, enhancing connectivity and data transmission in smart environments.

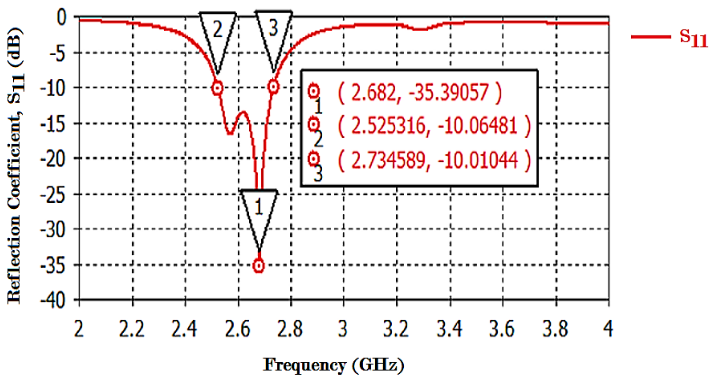

Fig. 8 Reflection coefficient (S_{11}) characteristics of the proposed antenna

5.2. Bandwidth

Bandwidth signifies the spectrum of frequencies within which an antenna operates optimally, characterized by a reflection coefficient (S_{11}) that does not exceed −10 dB. This level ensures that at least 90% of the input energy is successfully transmitted. A broader bandwidth enhances an antenna's capability to support multiple frequencies, making it compatible with various IoT devices and protocols. This is vital for ensuring stable communication in IoT applications. Antennas with sufficient bandwidth can adapt to diverse operational scenarios, which is valuable in various IoT ecosystems. By analyzing the reflection coefficient graph, one can determine the bandwidth; for instance, the proposed rectangular patch antenna achieves a bandwidth of 209.273 MHz (2.525316 GHz–2.734589 GHz) (Fig. 8), making it suitable for multiple IoT use cases such as Smart Homes, Healthcare IoT, Industrial IoT, Agricultural IoT, and Transportation IoT. It is a great option for a variety of IoT applications that need consistent and effective connectivity because of its Sub-6 GHz performance, which guarantees dependable communication.

5.3. Voltage Standing Wave Ratio (VSWR)

The VSWR, a metric that assesses how well power is transferred from a transmission line to an antenna, has a significant influence on antenna design. This ratio, which is determined by dividing the greatest voltage along the transmission line by the lowest voltage, indicates the quality of impedance matching. An ideal VSWR is 1:1, indicating perfect matching and minimal signal reflection, while a VSWR up to 2:1 is generally considered acceptable, equating to less than 11% signal loss. The recommended antenna achieves an impressive VSWR of 1.03908 at 2.68 GHz (Fig. 9), demonstrating excellent impedance matching and effective power transmission. This low VSWR is particularly beneficial for Internet of Things (IoT) devices, ensuring improved signal quality, reduced power loss, and extended range, which are essential for reliable communication in smart home systems, wearable technology, and industrial applications.

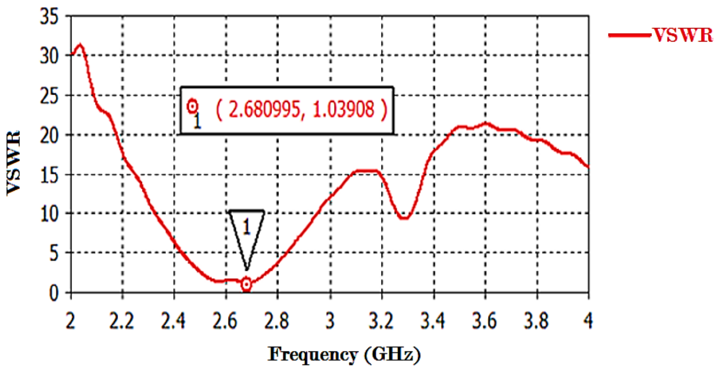

Fig. 9 VSWR characteristics of the proposed antenna

5.4. Gain

Antenna design is essential for effective wireless communication, especially in the realm of Internet of Things applications, as it significantly affects the transmission and reception of signals. One important metric is gain, which assesses an antenna's proficiency in concentrating radio frequency energy in a designated direction relative to an isotropic radiator, measured in decibels (dBi). High-gain antennas are optimal for long-distance communication, augmenting range and signal integrity, whereas low-gain antennas provide extensive coverage, making them suitable for environments with physical obstructions. The suggested antenna attains a gain of 0.623 dBi at 2.68 GHz (Fig. 10), reflecting moderate directivity, thereby rendering it suitable for short to medium-range communication in smart homes, wearable devices, and industrial networks. Refining this design can markedly enhance IoT system efficiency and connectivity.

5.5. Directivity

Directivity measures how focused an antenna's radiation pattern is compared to an isotropic radiator, which emits energy equally in all directions. High directivity means the antenna effectively concentrates energy in a specific direction, boosting signal strength and minimizing interference. Conversely, low directivity offers a more omnidirectional pattern, useful for broader coverage but may result in signal loss for targeted applications. The recommended antenna exhibits a directivity of 3.71 dBi at 2.68 GHz (Fig. 11), demonstrating its ability to direct signals efficiently while reducing power loss. This feature is crucial for IoT devices operating within the 2.53 GHz to 2.734 GHz spectrum, where reliable communication is vital in crowded frequency bands for applications like smart homes, industrial automation, and healthcare monitoring.

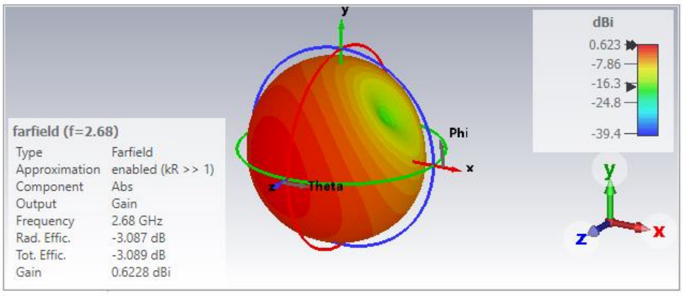

Fig. 10 3D gain of the proposed antenna

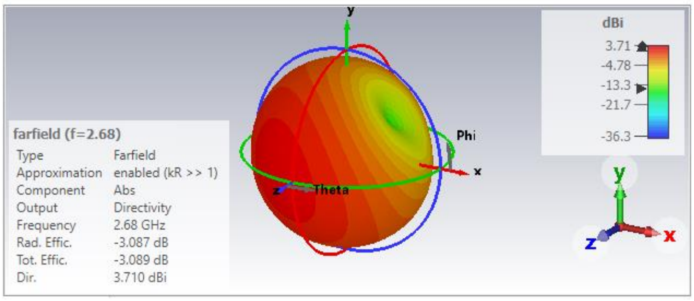

Fig. 11 3D directivity of the proposed antenna

5.6. Efficiency

Antenna performance is greatly influenced by efficiency, which is the ratio of energy radiated to total energy input. A high-efficiency antenna enhances communication system performance and signal quality by converting more input energy into radiated energy. This study presents an antenna with a moderate efficiency of 49.12% (Figs. 10 and 11), underscoring the need for optimization, particularly for Internet of Things (IoT) applications where energy conservation is crucial. Low efficiency can lead to increased battery drain, limited range, and compromised data transmission, affecting IoT network reliability. While the current efficiency is acceptable for the 2.3 GHz to 4.2 GHz frequency range, enhancements in design and materials could bolster performance, benefiting smart cities, industrial automation, and connected devices. Prioritizing efficiency improvements will ensure more robust and reliable communication as technology evolves.

5.7. Radiation Pattern

A radiation pattern graphically represents an antenna's emission characteristics based on spatial coordinates, detailing how it transmits or receives energy. Typically assessed in the far-field region, these patterns can be depicted in polar or Cartesian coordinates and are characterized for both electric field (E-field) and magnetic field (H-field). The main lobe indicates peak radiation direction, crucial for antenna focus. The proposed antenna operates at a frequency of 2.68 GHz (Fig. 12), demonstrating an E-field main lobe magnitude of 15.4 dB(V/m) at an angle of 161.0° and a beamwidth of 79.2°. In comparison, the H-field pattern shows a magnitude of –36.7 dB(A/m) at 170.0° with a width of 113.4° (Fig. 13). The antenna is designed for Internet of Things (IoT) applications within the Sub-6 GHz frequency range, promoting effective communication in crowded environments. With high radiation efficiency and optimized beamwidth, it facilitates reliable sensor-to-sensor and sensor-to-gateway links, meeting the needs of factory automation and control systems while minimizing interference.

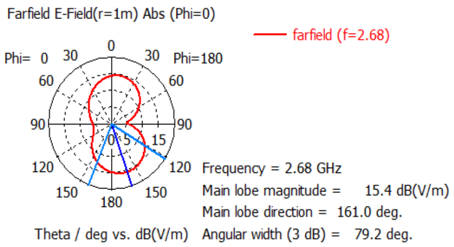

Fig. 12 E-field radiation pattern

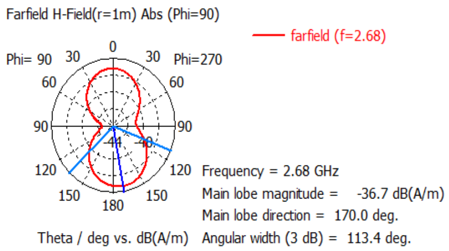

Fig. 13 H-field radiation pattern

6. Discussion

The results of the simulation affirm the appropriateness of the suggested rectangular patch antenna for IoT purposes functioning in the Sub-6 GHz spectrum (2.3–4.2 GHz). This antenna showcases outstanding performance metrics, including a reflection coefficient (S_{11}) of –35.39057 at 2.68 GHz, ensuring minimal signal reflection—ideal for low-power IoT devices. It provides a bandwidth of 209.273 MHz (2.525316 GHz–2.734589 GHz), supporting various IoT communication protocols and ensuring stable connectivity. With a VSWR of 1.03908, the antenna minimizes power loss and reflection. Its directivity of 3.71 dBi and gain of 0.623 dBi make it suitable for short- to medium-range applications, such as wearables and smart home devices. The antenna's efficiency of 49.12% is moderate, primarily due to the FR-4 substrate, which introduces significant dielectric losses. Additionally, the ground plane's rectangular slot alters the current distribution, increasing surface wave losses. The substrate removal process, while enhancing performance, may introduce discontinuities that lead to signal degradation. Furthermore, the compact size limits optimal current distribution, and the inset feedline, although effective for impedance matching, may introduce resistive losses if not precisely optimized. Future improvements should focus on enhancing efficiency through better materials, such as low-loss substrates or metasurfaces. Gain can be improved by incorporating parasitic elements or advanced feeding techniques, while bandwidth can be expanded using optimized slot geometries or defected ground structures (DGS). These optimizations will enhance the antenna's efficacy to meet the increasing demands of IoT connectivity.

7. COMPARATIVE ANALYSIS

Table 2 provides a detailed comparison of the key performance metrics and design characteristics of previously developed antenna models with the newly designed antenna for IoT applications. The proposed antenna, measuring 40 × 50 × 1.6 mm³, is compact, smaller than models [15] (135 × 80 × 0.8 mm³) and [30] (60 × 65 × 1.6 mm³), but larger than models [6] (23 × 23 × 1.6 mm³) and [23] (28 × 21 × 1.6 mm³). The proposed antenna achieves a bandwidth of 209.273 MHz (from 2.525316 GHz to 2.734589 GHz), outperforming models [6] (60 MHz) and [23] (140 MHz), though it has a narrower range compared to models [15] (260 MHz) and [22] (1.71 GHz). Its gain of 2.563 dBi is moderate, falling short of models [6] (5.33 dBi), [15] (4.7 dBi), and [22] (6.47 dBi), but exceeding models [23] (1.96 dBi) and [30] (1.7 dBi). With an efficiency of 49.12%, the proposed antenna lags behind models [15] (88%), [22] (99%), and [23] (98%). The design incorporates a ground slot with substrate removal, setting it apart from techniques like corner truncation [6], parasitic ground strips [15], array configurations [22], and L-shaped designs [23]. In summary, the proposed antenna offers a favorable balance of size, bandwidth, and gain, though its efficiency presents an area for improvement to enhance its competitiveness in IoT applications. The proposed antenna offers several advantages over existing designs (Table 2):

- **Bandwidth vs. Compactness:** The suggested antenna outperforms [6] (60 MHz) and [23] (140 MHz) with a bandwidth of 209.273 MHz, despite being smaller than [15] and [30]. This keeps its small size while supporting multi-frequency IoT protocols like Zigbee and LoRa.
- **Simplified Design:** Unlike [15] (parasitic ground strips) and [22] (array configurations), the proposed ground slot with substrate removal technique is simpler, cost-effective, and facilitates mass production.
- **IoT Suitability:** Despite its low gain (0.623 dBi), the antenna's compact size, sufficient bandwidth, and excellent impedance matching (VSWR = 1.03908) make it ideal for short-range IoT applications such as smart homes, healthcare sensors, and industrial monitoring, where energy efficiency and integration ease are more critical than high gain.

Table 2 An Analytical Comparison of Earlier Antenna Designs and the Recently Developed Antenna Specifically Designed for IoT Applications.

Refs.	Year	Antenna Size (mm³)	Bandwidth (GHz)	Gain (dBi)	Efficiency (%)	Methods
[6]	2023	23 × 23 × 1.6	60 MHz (2.41–2.47 GHz)	5.33	Not Mentioned	Corner Truncation
[15]	2020	135 × 80 × 0.8	260 MHz (0.7–0.9 GHz)	4.7	88	Parasitic Ground Strips
[22]	2024	50.5 × 41.12 × 1.5	1.71 GHz (2–3.71 GHz)	6.47	99	Array
[23]	2023	28 × 21 × 1.6	140 MHz (2.36–2.5 GHz)	1.96	98	L-Shaped
[30]	2022	60 × 65 × 1.6	Not Mentioned	1.7	Not Mentioned	Not Mentioned
Proposed Antenna		40 × 50 × 1.6	209.273 MHz (2.525316–2.734589 GHz)	0.623	49.12	Ground slot with Substrate Removal

8. CONCLUSION

This study successfully designs and optimizes a rectangular patch antenna for IoT applications within the Sub-6 GHz frequency range (2.3–4.2 GHz). The antenna is built on an FR4 substrate, measuring 1.6 mm in thickness and possessing a dielectric constant of 4.3. It employs substrate removal techniques and incorporates rectangular slots in the ground plane to enhance its performance. Simulations conducted using CST Studio reveal excellent results, including a remarkable reflection coefficient (S_{11}) of −35.39057 at 2.68 GHz, a bandwidth of 209.273 MHz (2.525316 - 2.734589 GHz), and a low VSWR of 1.03908. Additional parameters, such as a gain of 0.623 dBi, a radiation efficiency of 49.12%, and a directivity of 3.71 dBi, validate the antenna's effectiveness for IoT communication. This compact antenna is ideal for small devices, wearables, and industrial automation. Operating in the Sub-6 GHz range, it supports IoT standards like Zigbee, LoRaWAN, and NB-IoT. The adequate bandwidth, good reflection coefficient, and low VSWR ensure stable communication and efficient power transfer. Its moderate gain and directivity ensure reliable short- to medium-range coverage, making it suitable for battery-powered IoT devices. Future work will focus on prototyping, efficiency optimization (e.g., using low-loss substrates), and integration into IoT devices, contributing to cost-effective and high-performance antenna solutions in next-generation wireless systems. This research bridges the gap between compact design and functional reliability, addressing critical needs for scalable IoT connectivity.

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