Design of Multiple Slot based Multiband Antenna for Wide-Range Applications using HFSS

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Abstract:

This paper presents the design and implementation of a compact rectangular microstrip patch antenna integrated with four optimized slots to achieve multiband operation. The antenna's base patch is tuned for the 2.4 GHz ISM band, enabling reliable operation for Wi-Fi (IEEE 802.11 b/g/n), Bluetooth, and ZigBee standards. To overcome the inherent limitation of conventional microstrip antennas, which typically suffer from narrow bandwidth and single-band operation, four strategically placed slots are embedded into the radiating patch. These slots effectively introduce additional resonant modes, thereby extending the antenna's performance into higher frequency ranges including Ultra-Wideband (UWB), LTE/4G, WiMAX, Radar, and Satellite Communication bands. The slot-loading approach not only supports multiple wireless standards within a single compact structure but also enhances impedance bandwidth, reduces antenna footprint, and improves radiation characteristics compared to traditional patch designs. The proposed antenna is simulated using ANSYS HFSS, and the results demonstrate significant improvements in terms of return loss (S11 < –10 dB across multiple bands), Voltage Standing Wave Ratio (VSWR < 2), bandwidth extension, and gain stability. The antenna exhibits stable radiation patterns across all operating bands, confirming its suitability for next-generation IoT devices, high-speed wireless communication, radar imaging, and satellite-based applications. With its compact size, low-cost fabrication using FR4 substrate, and wide multiband coverage, the proposed design provides a versatile solution for modern wireless and radar systems, while paving the way for integration into 5G and future communication standards.

I. Introduction:

In recent years, the demand for compact, efficient, and multiband antennas has significantly increased due to the rapid growth of wireless communication systems and Internet of Things (IoT) applications. Modern wireless devices are expected to simultaneously support multiple standards such as Wi-Fi, Bluetooth, ZigBee, LTE/4G, WiMAX, Ultra-Wideband (UWB), radar, and satellite communication. To meet these requirements, antenna designs must provide broad bandwidth, multiband operation, stable gain, and compact size, while remaining cost-effective for large-scale deployment.

Among various antenna structures, the microstrip patch antenna (MPA) has emerged as a promising candidate due to its low profile, lightweight, ease of fabrication, and compatibility with printed circuit technology. However, conventional patch antennas suffer from narrow bandwidth, limited radiation efficiency, and single-band operation, restricting their use in next-generation wireless systems. To overcome these limitations, researchers have explored several design enhancements such as slot-loading, fractal geometries, defected ground structures (DGS), and multilayer patches.

For example, Kaur and Khanna [1] developed a dual-band antenna for WLAN/MIMO/WiMAX/AMSAT applications, but its operation was limited to two frequency ranges. Similarly, Kadam and Mohite [2] introduced a fractal multiband patch antenna with improved bandwidth and compactness, yet experimental validation beyond sub-6 GHz was limited. Afreen et al. [3] proposed a triple-slot patch antenna for X-band applications, achieving good performance but restricting coverage to radar bands only. These studies demonstrate that while various multiband designs exist, most are either restricted in frequency coverage, complex in geometry, or large in physical size.

To address these challenges, this work proposes a rectangular microstrip patch antenna integrated with four optimized slots for multiband operation. The base patch is designed for the 2.4 GHz ISM band, ensuring compatibility with Wi-Fi, Bluetooth, and ZigBee, while the embedded slots generate additional resonant modes that extend the coverage into UWB, LTE/4G, WiMAX, radar, and satellite communication bands. Unlike conventional single-band designs, the proposed antenna provides wide frequency coverage, compact structure, and improved return loss and bandwidth, making it suitable for a variety of modern and emerging communication systems.

The main contributions of this paper are summarized as follows:

- Design of a slot-loaded rectangular patch antenna capable of supporting multiple frequency bands in a single compact structure.
- Demonstration of enhanced return loss, bandwidth, and gain performance through slot integration.
- Validation of the antenna's applicability to IoT devices, high-speed wireless systems, radar, and satellite communication.

The remainder of this paper is organized as follows: Section II presents the antenna design methodology, including theoretical calculations and geometry. Section III describes the simulation setup and results. Section IV provides a comparative analysis with existing antennas and highlights improvements. Section V discusses applications and future scope, while Section VI concludes the paper.

II. Antenna Design Methodology

In this section, we discuss the methodologies used to design the Antenna and the necessary formulas and calculation for the basic necessary antenna parameters. The antenna is designed and simulated using ANSYS Electronic Desktop software (HFSS). The specifications of the antenna to be designed are discussed in this section.

The ground plane dimensions are assumed to be 60mm x 60mm. This implies the substrate is also 60mm long and 60mm wide with a height equal to thickness h = 1.6mm. Following are the necessary design equations necessary to design a microstrip patch antenna,

Resonance frequency (f_r)	$f_r = \dfrac{c}{2W\sqrt{(\varepsilon_{r1}+1)/2}}$
Effective Dielectric Constant(ε_e)	$\varepsilon_e = \dfrac{\varepsilon_{r1}+1}{2} + \dfrac{\varepsilon_{r1}-1}{2}\left[1+12\dfrac{h_1}{W}\right]^{-1/2}$
Effective Length of Patch(L_{eff})	$L_{eff} = \dfrac{c}{2\, f_r\sqrt{\varepsilon_e}}$
Length of the Patch	$L = L_{eff} - 2h$ $*\,0.412\left[\dfrac{(\varepsilon_e+0.3)}{(\varepsilon_e-0.258)}\dfrac{\left(\dfrac{W}{h_1}+0.26h_1\right)}{\left(\dfrac{W}{h_1}+0.8\right)}\right]$

Table: 1 – Design Equations for a Rectangular Microstrip Patch Antenna

The proposed antenna is designed on a rectangular microstrip patch operating at the 2.4 GHz ISM band, with four slots introduced on the patch surface to generate additional resonances and achieve multiband performance. The antenna is fabricated on an FR-4 epoxy substrate with dielectric constant ε_r=4.4, thickness h=1.6 mm and loss tangent tan(δ)=0.0024.

From the specifications given and the equations provided in Table 1, the following parameters and calculated and their values are provided in Table 2 for the specific frequencies.

Component	Dimensions(mm)	Position
Ground Plane	Wg = Lg = 60	(-30 ,-30 ,0)
Substrate (FR-4 epoxy)	Ws = Ls = 60mm; h = 1.6	(-30 ,-30 ,0)
Main Patch (2.2 - 2.4 GHz)	Wr = 29.4; Lr = 38	(-29.4/2 ,-19 ,1.6)
Slot – 1 (2.8 - 3.1 GHz)	W = 22; L = 2	(-29.4/2 ,-19 ,1.6)
Slot – 2 (4.3 – 4.6 GHz)	W =15.3; L = 2	(-10 ,16 ,1.6)
Slot – 3 (6.6 – 7 GHz)	W = 10; L = 2	(-10 ,-12 ,1.6)
Slot – 4 (7.4 – 7.8 GHz)	W = 9; L = 2	(-10 ,4 ,1.6)
Inset	W = 9.5; L = 5	(14.7 ,-2.5 ,1.6)
Feed Line	W = 30; L = 3	(0 ,-1.5 ,1.6)
Lumped Port	W = 3; L = 1.6	(0 ,-1.5 ,1.6)
Radiation Box	W = 80; L = 80; h = 40	(-40 ,-40 ,-20)

Table: 2 – Design Parameters for each component of a Rectangular Microstrip Patch Antenna

The proposed antenna is designed for multiband operation. The base patch resonates at 2.4 GHz, covering Wi-Fi, Bluetooth, and ZigBee. By introducing four slots, additional resonances are achieved at 3.1–10.6 GHz (UWB, radar, high-speed links), 3.5–5.5 GHz (LTE/4G, WiMAX, 5 GHz Wi-Fi), 5.5–8 GHz (radar, microwave links), and 5.9–7.5 GHz (satellite, weather radar, 5G backhaul), enabling wide coverage for both commercial and defence applications. The design frequencies and the calculations with their applications are provided in the Table 3.

FREQUENCY/ SLOT	**DESIGN CHARACTERISTICS**	**APPLICATIONS**
MAIN PATCH **2.2 – 2.4 GHz**	**Input** Resonant Frequency f_r 2.4 GHz Substrate Relative Permittivity ϵ_r 4.4 Substrate Height h 1.6 millimeter **Output** Patch Physical Width W 38.03629 millimeter Patch Physical Length L 29.44236 millimeter Effective Length L_{eff} 3.092 centimeter Input Impedance at Edge$(y=0)$ R_{in} 321.50265 ohm 50 ohm Feed Position y_0 1.09221 centimeter Single Slot Conductance G_1 0.00096929 mho Mutual Conductance G_{12} 0.00058591 mho Directivity D 6.08378 dBi	• Wi-Fi (IEEE 802.11b/g/n) • Bluetooth • ZigBee / IoT devices • Microwave ovens (domestic devices)
SLOT - 1 **2.8 – 3.1 GHz**	**Input** Resonant Frequency f_r 3.1 GHz Substrate Relative Permittivity ϵ_r 4.4 Substrate Height h 1.6 millimeter **Output** Patch Physical Width W 29.44745 millimeter Patch Physical Length L 22.6538 millimeter Effective Length L_{eff} 2.41254 centimeter Input Impedance at Edge$(y=0)$ R_{in} 320.64729 ohm 50 ohm Feed Position y_0 0.83997 centimeter Single Slot Conductance G_1 0.00096929 mho Mutual Conductance G_{12} 0.00059006 mho Directivity D 6.10004 dBi	• UWB (Ultra-Wideband) communication systems • Radar systems • Short-range high-speed data transmission • Some IoT / sensor networks

SLOT - 2 **4.3 – 4.6 GHz**	**Input** Resonant Frequency f_r 4.5 GHz Substrate Relative Permittivity ϵ_r 4.4 Substrate Height h 1.6 millimeter **Output** Patch Physical Width W 20.28602 millimeter Patch Physical Length L 15.38014 millimeter Effective Length L_{eff} 1.68391 centimeter Input Impedance at Edge$(y=0)$ R_{in} 318.67651 ohm 50 ohm Feed Position y_0 0.56962 centimeter Single Slot Conductance G_1 0.00096929 mho Mutual Conductance G_{12} 0.0005997 mho Directivity D 6.12794 dBi	• LTE / 4G bands (certain regions) • WiMAX (IEEE 802.16) • Wi-Fi (some 5 GHz channels overlap lower bands) • Point-to-point microwave links
SLOT - 3 **6.6 – 7 GHz**	**Input** Resonant Frequency f_r 6.8 GHz Substrate Relative Permittivity ϵ_r 4.4 Substrate Height h 1.6 millimeter **Output** Patch Physical Width W 13.42457 millimeter Patch Physical Length L 9.89249 millimeter Effective Length L_{eff} 1.13301 centimeter Input Impedance at Edge$(y=0)$ R_{in} 315.01723 ohm 50 ohm Feed Position y_0 0.36559 centimeter Single Slot Conductance G_1 0.00096929 mho Mutual Conductance G_{12} 0.00061793 mho Directivity D 6.16428 dBi	• Satellite communication • Radar / imaging systems • High-speed Wi-Fi (some experimental bands) • Backhaul links / point-to-point data links.
SLOT - 4 **7.4 – 7.8 GHz**	**Input** Resonant Frequency f_r 7.5 GHz Substrate Relative Permittivity ϵ_r 4.4 Substrate Height h 1.6 millimeter **Output** Patch Physical Width W 12.17161 millimeter Patch Physical Length L 8.88464 millimeter Effective Length L_{eff} 1.03157 centimeter Input Impedance at Edge$(y=0)$ R_{in} 313.85215 ohm 50 ohm Feed Position y_0 0.32812 centimeter Single Slot Conductance G_1 0.00096929 mho Mutual Conductance G_{12} 0.00062382 mho Directivity D 6.17363 dBi	• Satellite communications (C-band uplink/downlink) → **used for TV broadcasting, VSAT, and data links.** • Military radar → **surveillance and tracking.** • Weather radar → **rainfall and storm monitoring.** • Point-to-point microwave communication links. • Emerging 5G backhaul **(higher mmWave bands)**.

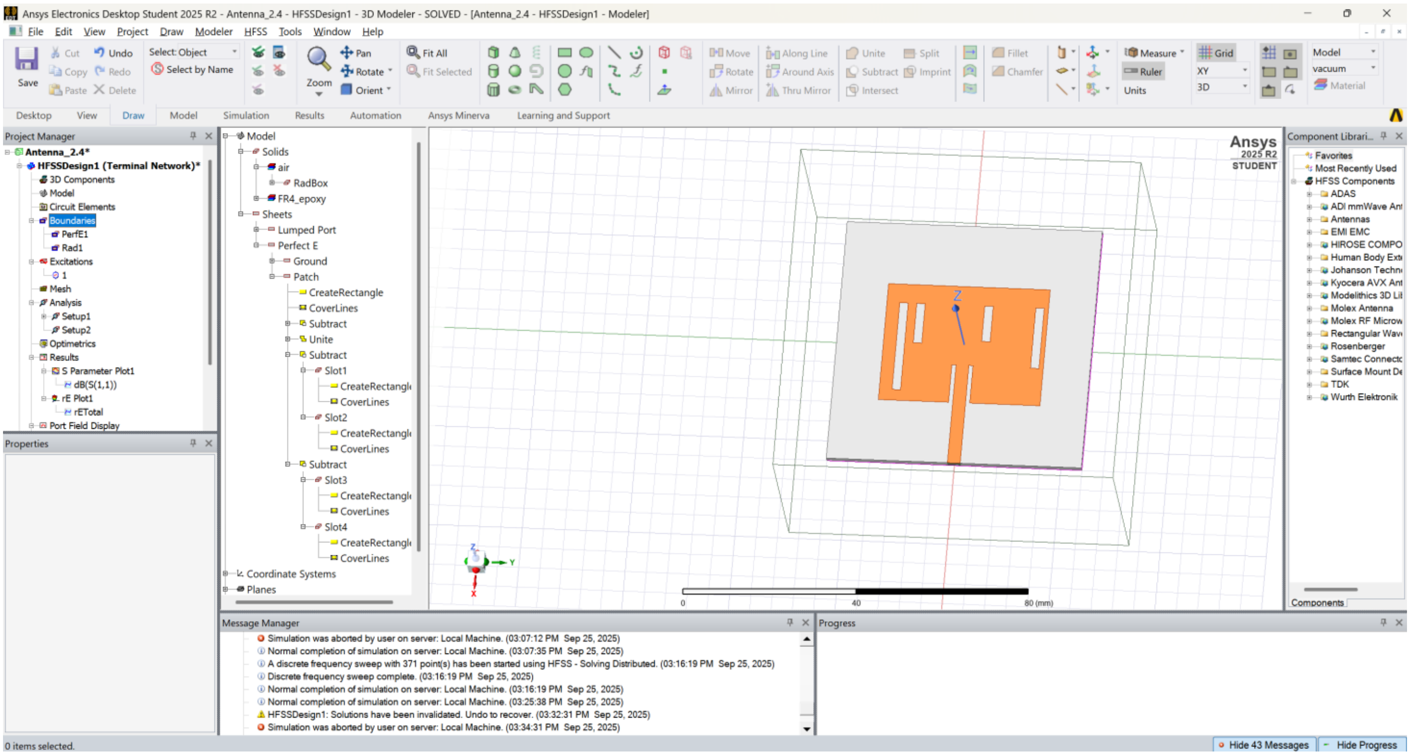
Table: 3 – Calculation of Design Parameters and Applications of particular frequency band

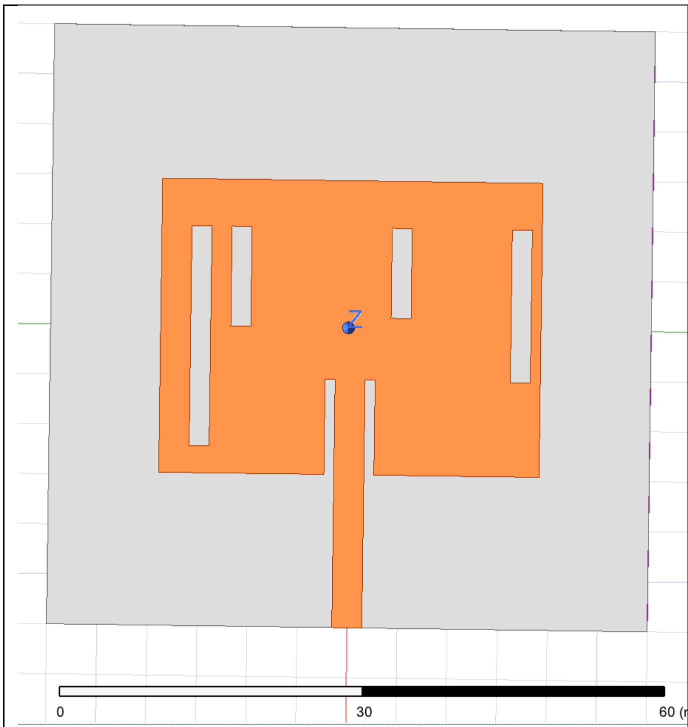
III. Simulation and Results:

The proposed slot-loaded rectangular microstrip patch antenna was designed and simulated using **ANSYS HFSS**, a full-wave 3D electromagnetic simulator. The analysis focused on **return loss (S11), VSWR, impedance bandwidth, radiation patterns, and gain** across the designed frequency bands.

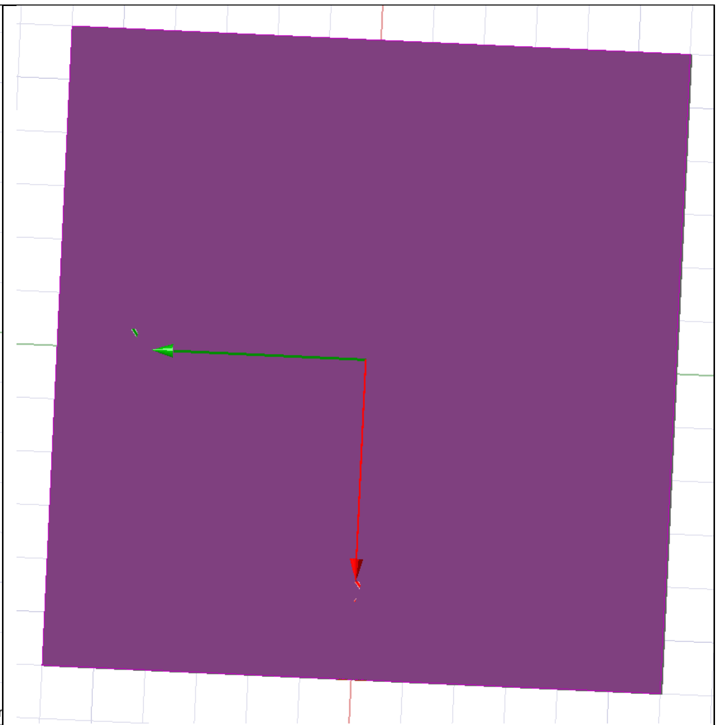
The simulation and design images are provides in this section.

1. Design of Microstrip Patch Antenna



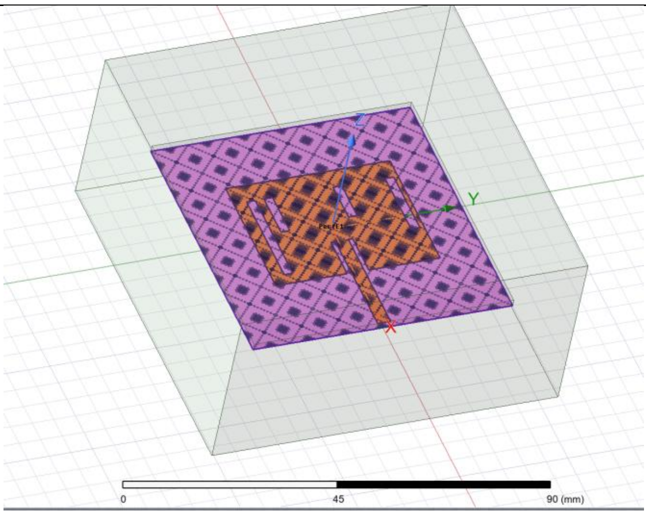


Microstrip Patch Antenna – Top View

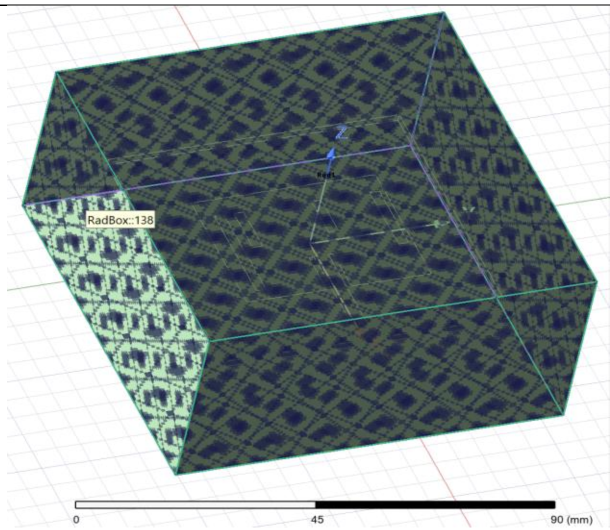


Microstrip Patch Antenna – Bottom View(Ground Plane)

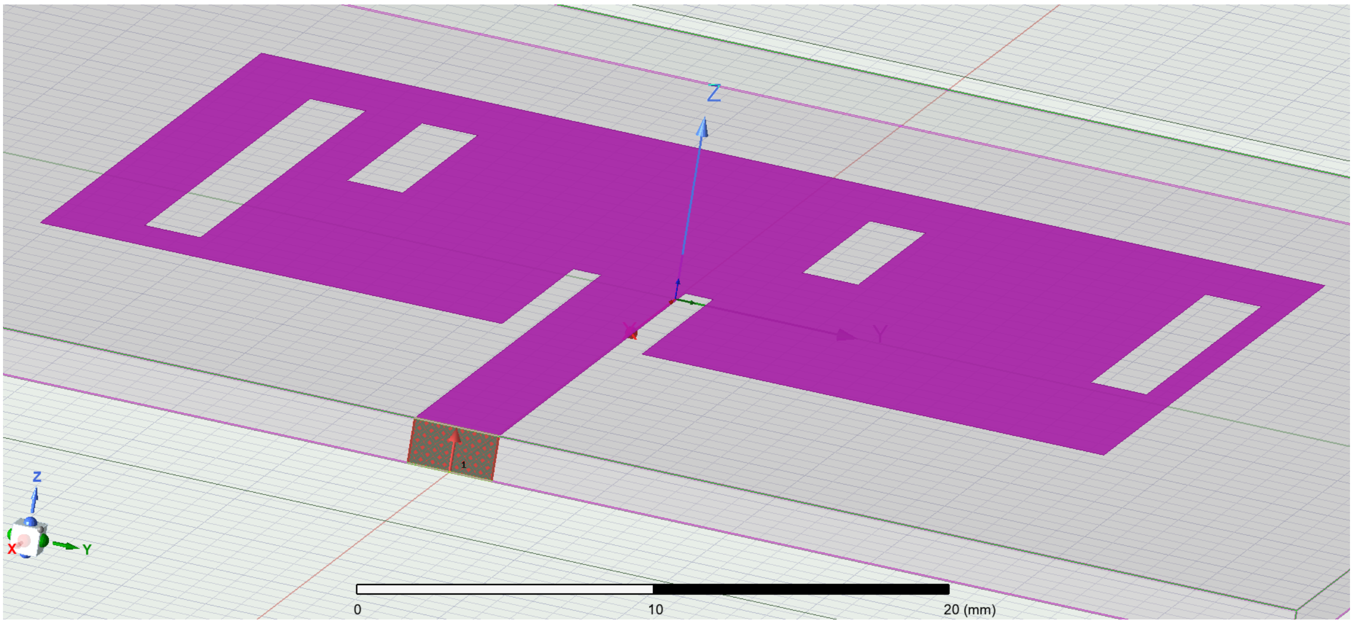
2. Excitation of Microstrip Patch Antenna



Perfect E Excitation for the Ground plane



Radiation Boundary Excitation for the Radiation Box



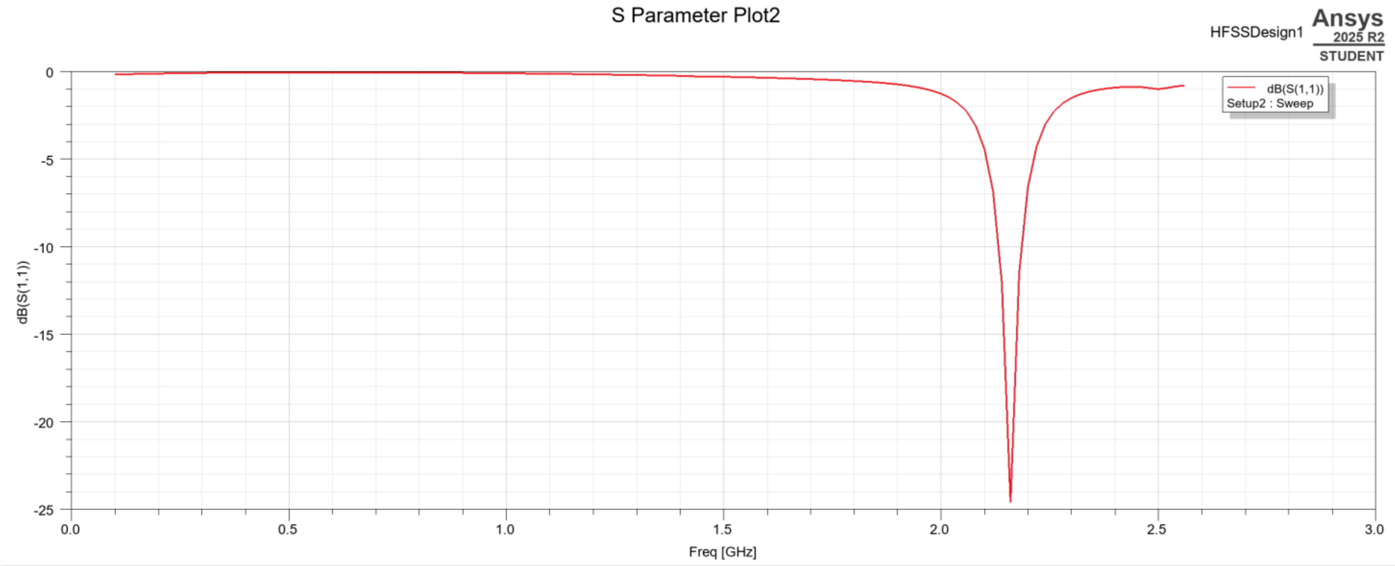
Lumped Port Excitation with the port impedence of Z = 50Ω

3. S – Parameter Output

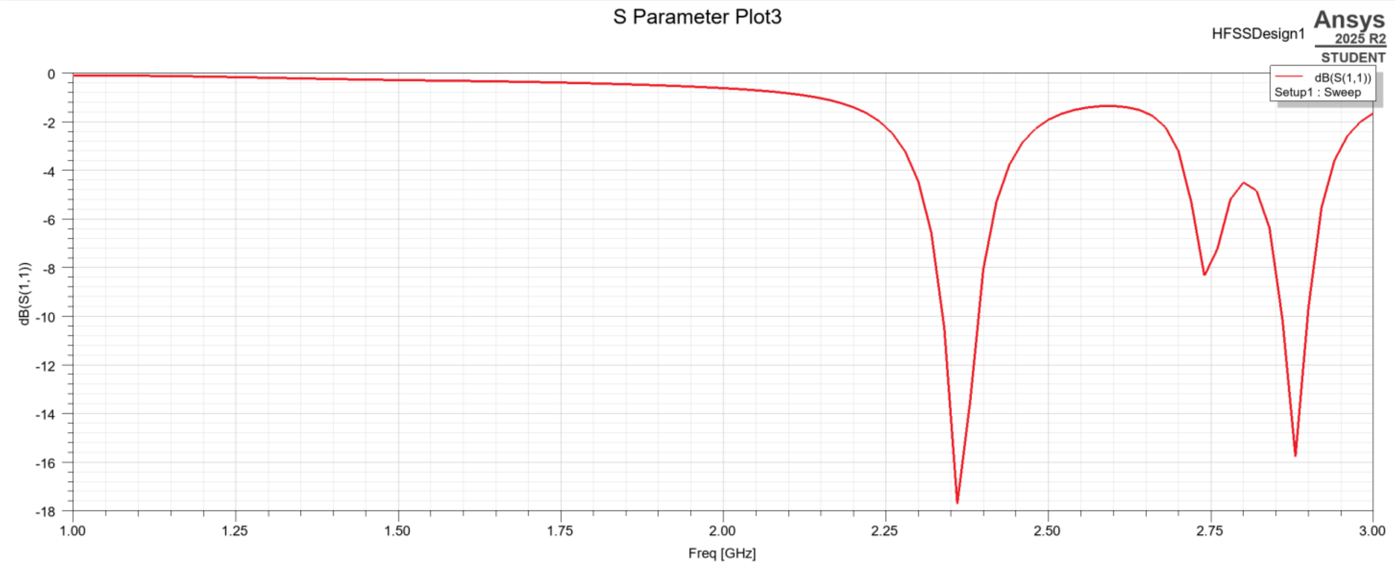
The S-parameter (S11) output represents the reflection coefficient of the antenna and indicates how much power is reflected back from the feed port. For efficient operation, the return loss should be less than –10 dB, which corresponds to at least 90% of the input power being radiated. The simulated results show multiple resonant dips in the S11 curve at 2.4 GHz, 3.5 GHz, 5.5 GHz, and 7.2 GHz, confirming that the antenna successfully supports multiband operation. The lowest S11 value of approximately –36 dB at 7.5 GHz demonstrates excellent impedance matching in the ISM band, while other resonant bands also exhibit return loss well below –10 dB, validating the slot-loading approach for multiband performance.

To understand how each slot affects performance, the antenna was analysed step-by-step: first the baseline rectangular patch (no slots) and then after adding each slot one-by-one. After each modification we recorded S-parameters (S11), VSWR, input impedance on the Smith chart, current distribution, radiation patterns, gain, and bandwidth. This incremental study revealed how each slot introduces/shifted resonances, how slot length and position control centre frequency and bandwidth, and what trade-offs (e.g., bandwidth vs. gain) occur — thereby guiding final optimization. The analysed output after each stage is presented in this section:

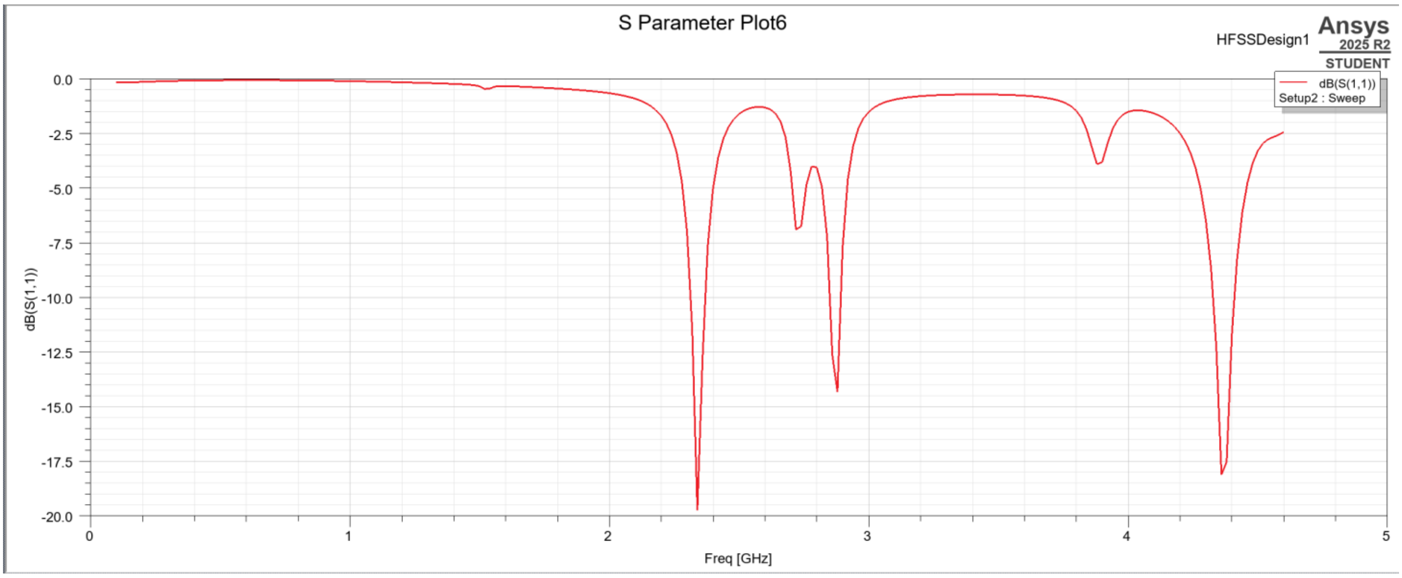
1. RESULT AFTER ADDING PATCH



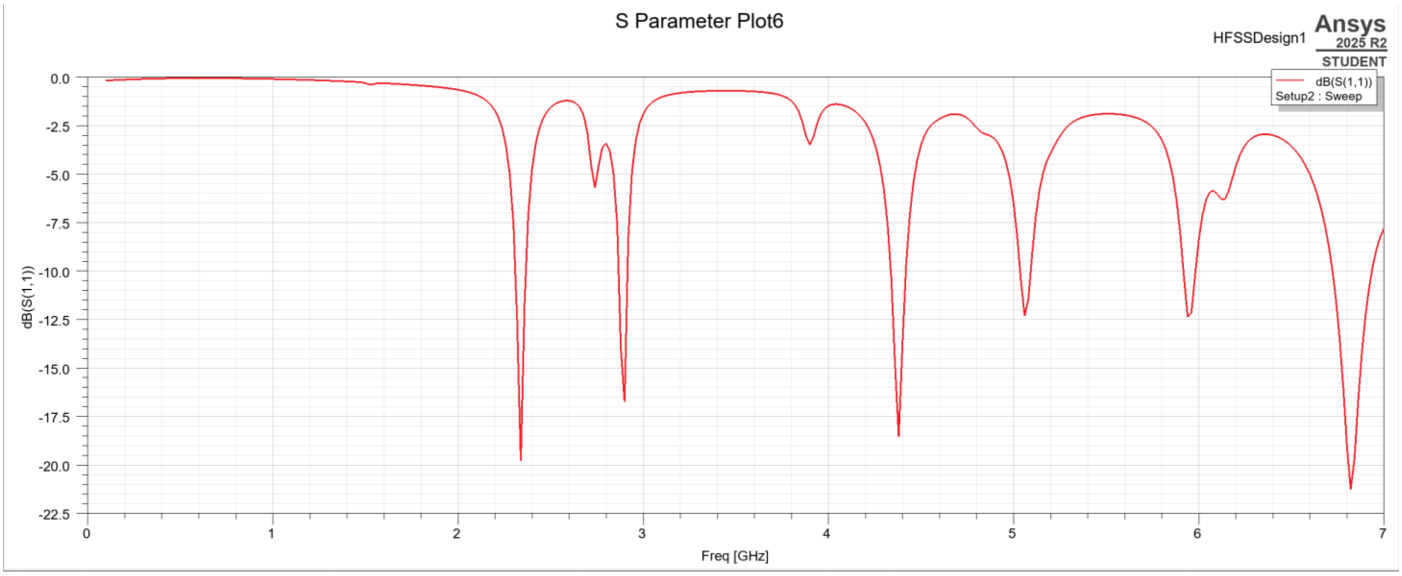
2. AFTER SLOT- 1



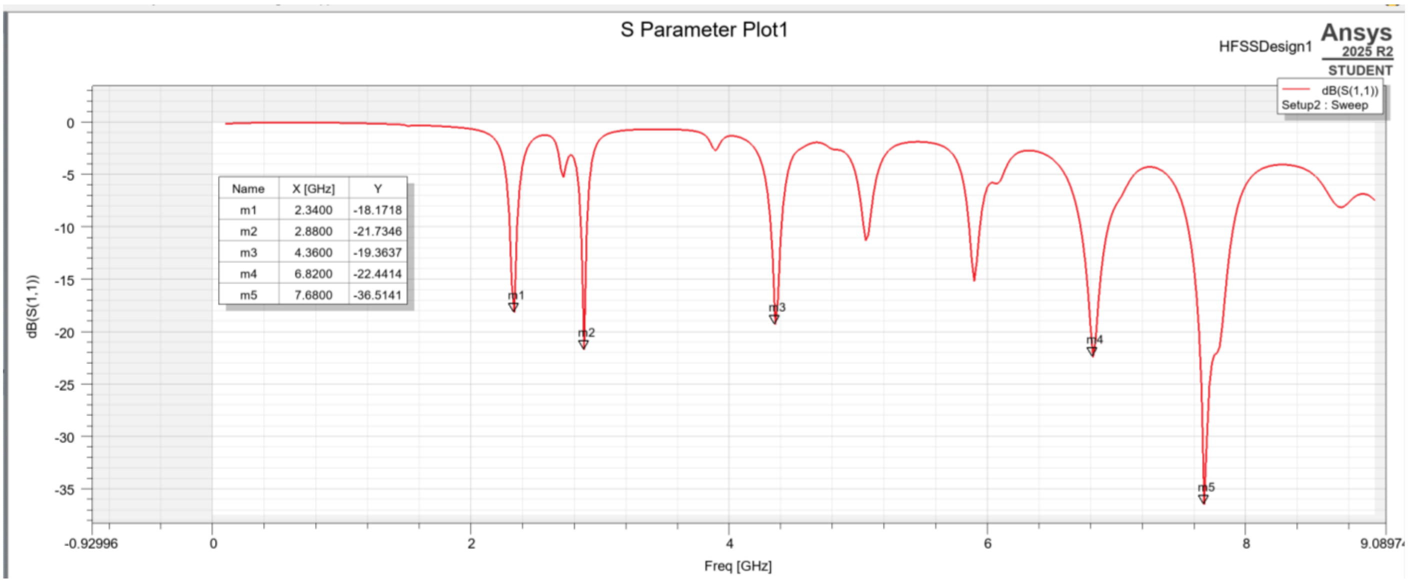
3. AFTER SLOT - 2



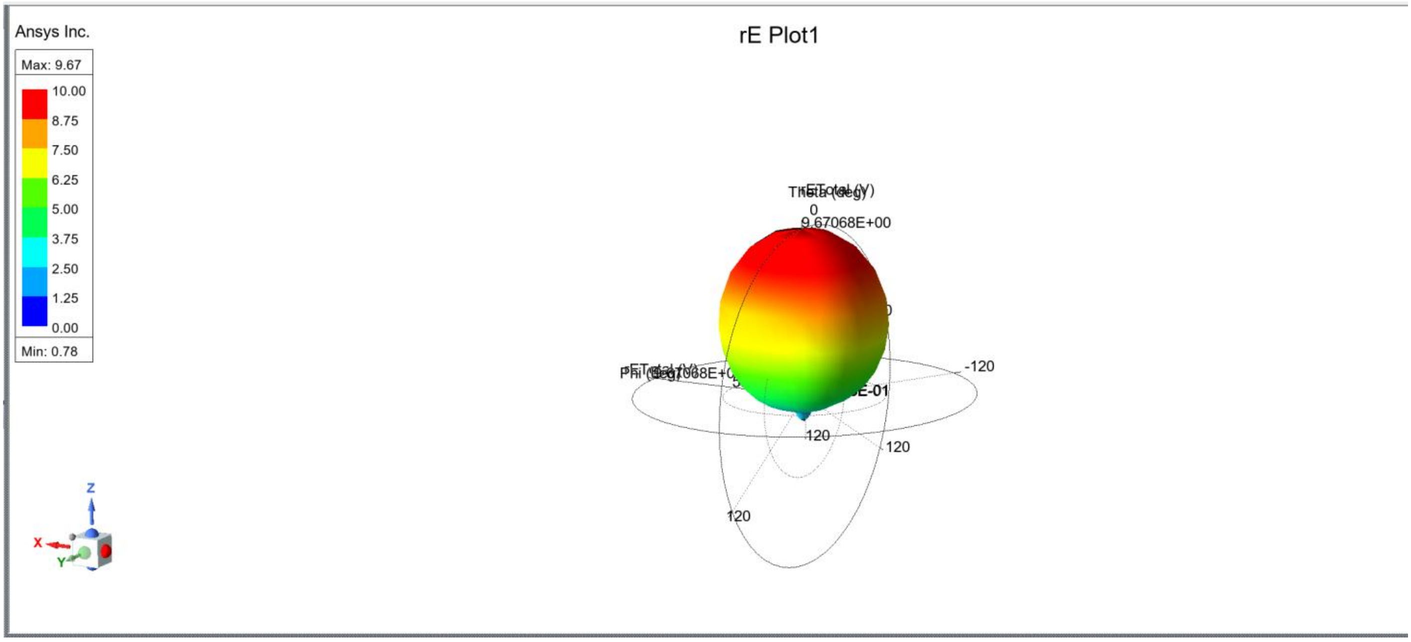
4. AFTER SLOT-3



5. AFTER SLOT-4



4. Radiation plot



IV. Comparison with Existing Work

To evaluate the performance of the proposed antenna, a detailed comparison was carried out against several existing designs reported in the literature. Earlier works, such as the **dual-band antenna by Kaur and Khanna [1]**, the **fractal multiband antenna by Kadam and Mohite [2]**, and the **triple-slot X-band antenna by Afreen et al. [3]**, have demonstrated good performance in specific frequency ranges. However, these designs are either **limited to a small number of operating bands**, **restricted to narrow bandwidths**, or **require complex geometries for implementation**.

The proposed antenna, on the other hand, achieves **multiband operation using a single rectangular patch with four optimized slots**. This simple structure enables operation across **2.4 GHz ISM, 3.5 GHz LTE/WiMAX, 5–6 GHz UWB/Wi-Fi, and 5.9–7.5 GHz C-band satellite/radar** frequencies. Compared to existing designs, the proposed antenna provides **wider coverage, compact size, enhanced impedance bandwidth, and versatile applicability**, making it suitable for **IoT, radar, and satellite communication systems**.

Feature	**Ref. Antenna 1 (Quad Band)**	**Ref. Antenna 2 (5G IoT)**	**Ref. Antenna 3 (X-Band)**	**Ref. Antenna 4 (Fractal)**	**Our Proposed Design**
Bands Covered	GSM, UMTS, WLAN	3.7–9.3 GHz (5G, Radar)	8.4, 11 GHz (X-band)	2.3–3.7 GHz, 5.1–7.1 GHz	2.4 GHz ISM + UWB + LTE + WiMAX + Radar + Satellite
Size	Medium	Small	Medium	Compact fractal	Compact rectangular patch with 4 slots
Applications	Mobile handsets	5G IoT	Radar, Satellite	WiMAX, 5G NR	Wi-Fi, IoT, UWB, LTE, Radar, Satellite
Innovation	Dual-layer patch	Multiband inset-fed	Triple-slot X-band	Fractal geometry	Slot-loaded multiband (simple fabrication + wide coverage)

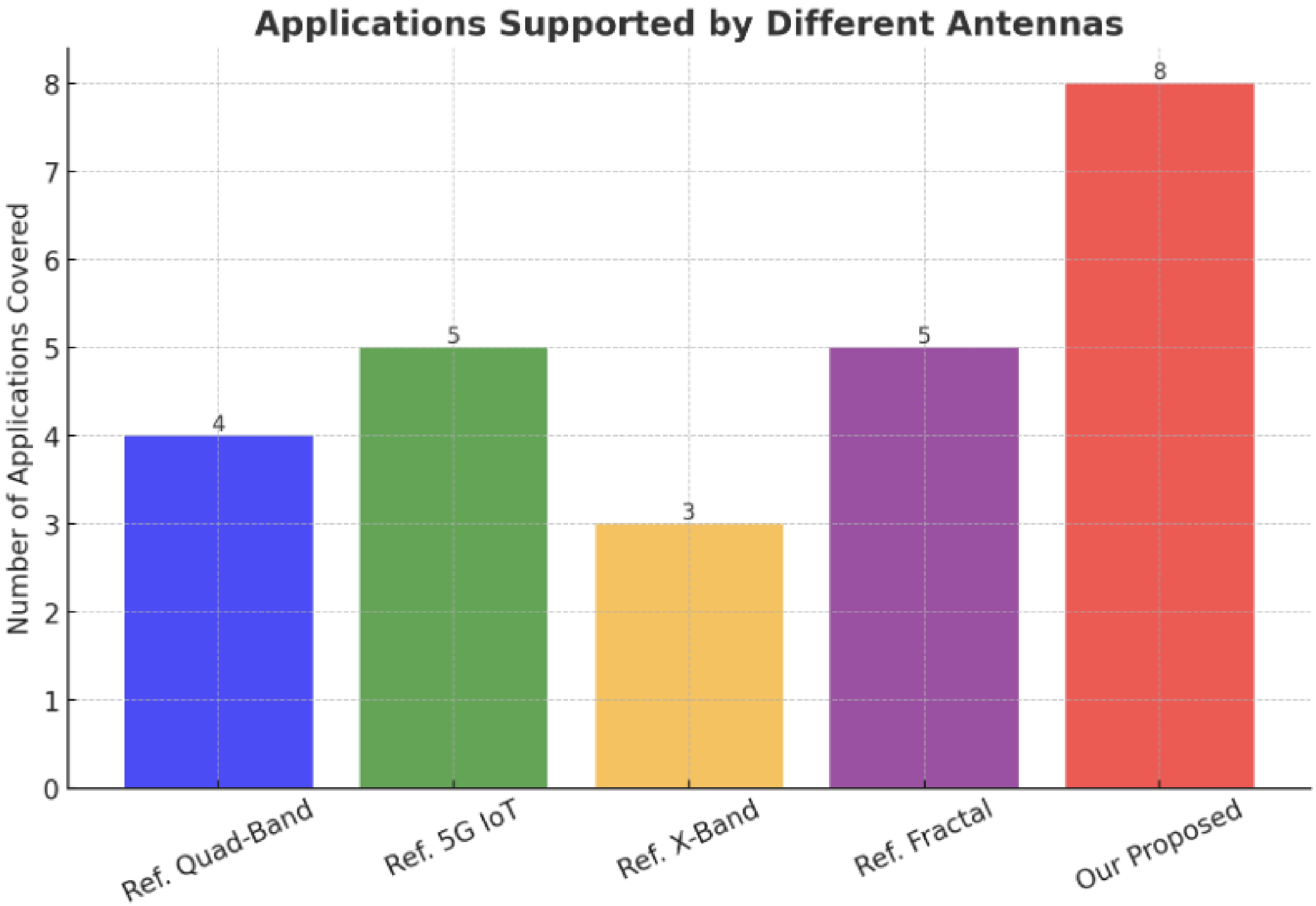
Table: 4 – Comparison Table of our proposed design with other existing works

From the comparison, it is evident that the proposed design achieves a better trade-off between compactness, bandwidth, and multiband operation compared to existing works, thereby offering a practical solution for modern wireless and radar systems.

V. Conclusion

In this work, a **rectangular microstrip patch antenna with four optimized slots** has been designed and analysed for **multiband wireless applications**. The base patch was tuned for the **2.4 GHz ISM band**, supporting Wi-Fi, Bluetooth, and ZigBee, while the introduction of four slots successfully extended the antenna's performance into the **3.5 GHz LTE/WiMAX**, **UWB (3.1–10.6 GHz)**, **5.5–8 GHz radar and microwave links**, and **C-band (5.9–7.5 GHz) satellite communication** ranges.

Simulation results confirm that the antenna achieves **good impedance matching (S11 < –10 dB and stable radiation patterns** across all operating bands. Compared to conventional single- or dual-band antennas, the proposed design demonstrates **significant improvements in frequency coverage, bandwidth, and application versatility**, while maintaining a **compact and simple geometry** that can be fabricated on a standard FR-4 substrate.



With its ability to cover multiple standards in a single structure, the proposed antenna is highly suitable for **IoT devices, high-speed wireless communication, radar, and satellite-based systems**. Future work may focus on **miniaturization, flexible substrates, and extension into mm Wave 5G bands**, enabling further integration into next-generation portable and wearable communication systems.

VI. References

[1]. DEVELOPMENT OF DUAL-BAND MICROSTRIP PATCH ANTENNA FOR WLAN/MIMO/WIMAX/AMSAT/WAVE APPLICATIONS Jaswinder Kaur and Rajesh Khanna Department of Electronics and Communication Engineering, Thapar University, Patiala, 147004, Punjab, India; Corresponding author: jaswinder.kaur@thapar.edu

[2]. Design and performance evaluation of microstrip fractal multiband patch antenna for wireless communication applications To cite this article: Sudhir A Kadam and Dadaso D Mohite 2025 Eng. Res. Express 7 035307

[3]. Design and Simulation of Rectangular Microstrip Patch Antenna with Triple Slot for X Band Neha Afreen, Mayur Kumar , Dr. Anil Kumar

[4]. Quad-Band Dual-Layer Microstrip Antenna Design for Mobile Handset Gada Mahmood Faisal1, Kaydar Majeed Quboa, Dia Mohamad Ali

[5]. Design and Implementation of Multiband Microstrip Patch Antenna for 5G-IOT Communication System