Dual Vertical Slot Loaded Compact Patch Antenna for 5G, LTE, and X-Band Operation

A Project Report

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By

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CANDIDATE’S DECLARATION

I, **SHIVAM YADAV,** hereby certify that the work, which is being presented in the report, entitled **Dual Vertical Slot Loaded Compact Patch Antenna for 5G, LTE, and X-Band Operation** in partial fulfillment of the requirement for the award of the Degree of **Bachelar of technology in Electronics and Communication Engineering** and submitted to the institution is an authentic record of my own work carried out under the supervision of **Dr. Kamakshi** at the Department of Electronics and Communication, University of Allahabad. The matter presented in this report has not been submitted elsewhere for the award of any other degree or diploma from any Institutions.

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CERTIFICATE FROM THE SUPERVISOR

This is to certify that the SHIVAM YADAV has carried out this project/dissertation entitled **Dual Vertical Slot Loaded Compact Patch Antenna for 5G, LTE, and X-Band Operation** under my supervision.

Dr. Kamakshi

Date: ……

(Supervisor)

Acknowledgements

I would like to express my heartfelt thanks to my project supervisor, **Dr. Kamakshi** , Department of electronics and communication. for their invaluable guidance, support, and constructive feedback throughout the duration of this project. I also wish thank to all my friend for their assistance and input during the development.

Finally we extend our gratefulness to one and all who are directly or indirectly involved in making this project.

SHIVAM YADAV

1.ABSTRACT

A compact dual-vertical-slot loaded microstrip patch antenna (MPA) has been designed and simulated for multiband operation covering LTE, Sub-6 GHz 5G, Wi-Fi, and X-band applications. The antenna is based on a rectangular patch mounted on an FR4 substrate with dimensions of **30 mm × 75 mm × 1.5 mm**, using a **partial ground plane** and a single offset microstrip feed line. To enhance multiband resonance, two vertical slots were strategically etched into the patch, enabling the antenna to support **eight resonant frequencies** ranging from **2.3 GHz to 9.9 GHz**, covering key wireless bands including **n77/n78/n79 (5G NR)** and **LTE Bands 22/42/43/46**.

The simulated results show strong return loss (S11 < –10 dB) across all bands, with a peak return loss of –31.5 dB. Radiation pattern analysis at 8 GHz confirms **directional radiation characteristics**, while gain analysis shows a **peak gain of approximately 6–7 dB**, supporting high-efficiency performance. The antenna demonstrates well-balanced electric field distribution, stable polarization, and wideband coverage in a compact structure.

Designed and evaluated entirely in **ANSYS HFSS**, the antenna proves that high-performance multiband behavior can be achieved through slot-loading techniques without increasing physical footprint. These features make the proposed antenna a strong candidate for **compact wireless devices**, **IoT modules**, and **Sub-6 GHz communication systems**. The design also serves as a proof-of-concept for simulation-based academic research without requiring physical fabrication.

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LIST OF ABBREVIATIONS

Abbreviation	Full Form
LTE	Long-Term Evolution
5G NR	5th Generation New Radio
FR4	Flame Retardant 4 (PCB substrate)
S11	Return Loss Parameter
dBi	Decibels over Isotropic (Gain unit)
HFSS	High Frequency Structure Simulator
PCB	Printed Circuit Board
ISM	Industrial, Scientific, and Medical Band
WLAN	Wireless Local Area Network
IoT	Internet of Things
VNA	Vector Network Analyzer
MIMO	Multiple Input Multiple Output
SAR	Specific Absorption Rate
DGS	Defected Ground Structure

CHAPTER 1

Introduction

As we see rapid evolution of wireless technologies such as LTE and 5G has placed increased demands on antenna systems to support high data rates, broad bandwidth, and multiband operation in compact, low-cost formats. Microstrip patch antennas have emerged very fastly because it’s most suitable antenna for modern wireless systems due to its low profile, easy fabrication, and capability of integration with printed circuits.

For the enablement of 5G, FCC divided the key spectrum into low-band (up to 1 GHz), mid-band (sub-6 GHz), and high-band (mmWave nearly 26 GHz). The mmWave offers lightning-fast data rates above 2 Gbps and huge capacity, while low-band offers good 5G coverage, and mid-band offers a blend of both. In our work, we focus particularly on **sub-6 GHz 5G systems** because they have been widely deployed as they provide a balance between coverage and capacity, making them practical for both urban and rural environments. These frequency bands overlap with existing LTE and WLAN bands, requiring antennas that can support multiple frequency bands simultaneously. Traditional single-band antennas are no longer sufficient to meet these versatile application requirements because for this, one would have to use many different antennas, each designed for a specific band. Therefore, multiband and wideband antenna designs are essential for modern wireless platforms, especially for devices that must operate across **Wi-Fi, LTE bands (22/42/43/46), and 5G NR bands (n77/n78/n79)**. It saves cost, space, and integration complexity.

This project presents the design and simulation of a compact, multiband microstrip antenna with enhanced frequency response using vertical slots. The antenna structure consists of a **30 mm × 75 mm FR4 substrate** with a **1.5 mm thickness**, supporting a **20 mm × 40 mm patch** embedded with **two vertical 2 mm × 28 mm slots**. The feeding is achieved through a single-point excitation.

Simulation results obtained through HFSS demonstrate **eight deep return loss dips below –10 dB** at **2.30 GHz, 4.12 GHz, 4.57 GHz, 6.42 GHz, 6.69 GHz, 7.95 GHz, 9.15 GHz, and 9.94 GHz**, confirming strong impedance matching at multiple operational bands. Compared to earlier versions, the updated result shows **better high-frequency coverage and an additional resonance** above 9 GHz, with most S11 values below –20 dB — indicating highly efficient multiband behavior.

Notably, the antenna covers the critical **5G NR bands n77/n78/n79**, **LTE bands 22/42/43/46**, and also supports **WLAN, Wi-Fi 6/7, Bluetooth, Radar C-band, and X-band** operation. Additionally, it shows **broadside directional radiation patterns** and **peak gain of 6–7 dB** across resonances, confirming its strong applicability in **wireless fidelity (WiFi), LTE, sub-6 GHz 5G**, Bluetooth, and radar applications.

1. Background on Microstrip Antennas and important parameter

Background on Microstrip Antennas

Microstrip patch antennas (MPAs) are a widely used type of antenna in modern wireless communication systems due to their compact size, low profile, ease of fabrication, and compatibility with printed circuit boards (PCBs). A typical microstrip antenna consists of a radiating patch on one side of a dielectric substrate and a ground plane on the other. These antennas are particularly popular for applications in **Wi-Fi, LTE, 5G, Bluetooth, satellite communication**, and radar systems.

In recent years, the demand for **multiband and wideband antennas** has increased significantly to support emerging technologies like **5G and IoT**, which require operation over multiple frequency bands. MPAs can be easily modified with slots, stubs, parasitic elements, or other structural changes to enhance performance and enable multi-frequency resonance within a compact design.

Important Antenna Parameters

Below are key parameters used to evaluate the performance of microstrip antennas, including those analyzed in this project:

1. S-Parameter (S_{11} - Return Loss)

- **Definition:** S_{11} represents the reflection coefficient, i.e., how much input power is reflected back from the antenna.
- **Interpretation:** A return loss **below –10 dB** indicates good impedance matching and efficient radiation at that frequency.
- **Application in Project:** Multiple deep dips (e.g., –31 dB) in the return loss curve indicate strong multiband operation.

2. Resonant Frequency

- **Definition:** The frequency at which the antenna naturally resonates and radiates efficiently.
- **Interpretation:** At resonance, S_{11} is at its minimum. A good antenna design may have multiple resonant frequencies for multiband use.
- **Application in Project:** Your antenna resonates at **eight different frequencies** across the 2–10 GHz range.

3. Bandwidth

- **Definition:** The frequency range over which the return loss remains below –10 dB.
- **Interpretation:** Wider bandwidth enables support for more communication standards.
- **Application in Project:** Your antenna demonstrates multiple wideband ranges, including sub-6 GHz and X-band.

4. Gain (dBi)

- **Definition:** Gain describes how well the antenna converts input power into radiation in a specific direction, compared to an isotropic radiator.
- **Application in Project:** Simulations show **peak gain between 6–7 dBi**, suitable for wireless applications needing directional radiation.

5. Directivity

- **Definition:** Directivity measures how 'directional' the antenna's radiation pattern is.
- **Interpretation:** Higher directivity means more focused energy in a specific direction.
- **Application in Project:** The antenna exhibits directional radiation, especially at higher frequencies.

◇ **6. Radiation Pattern**

- **Definition:** A graphical representation of the antenna's radiation in space.
- **Types:** Omnidirectional, Bidirectional, or Directional.
- **Application in Project:** Your design demonstrates **broadside directional radiation**, seen in both 2D and 3D plots.

7. VSWR (Voltage Standing Wave Ratio)

- **Definition:** It is a measure of mismatch between antenna and transmission line.
- **Ideal Value:** A VSWR < 2:1 is considered acceptable.

8. Efficiency

- **Definition:** Ratio of radiated power to input power.
- **Interpretation:** Higher efficiency indicates less power is lost in substrate or heat.
- **Application in Project:** Your simulation results (deep S11 dips and good gain) indicate **high radiation efficiency**.

2. Importance of Multiband Design

Several wireless technologies are combined on a single device. Today, the antenna must operate in a number of frequency bands. The multiband approach enables you to substitute one antenna with a few specialized antennas, both saving space and lowering the cost of miniaturized systems like WLANs, smartphones, IoT modules, and 5G terminals. All this simultaneously. In addition, compatibility is ensured with a wide range of communication standards such as LTE, WLAN and 5G without requiring the antenna to be altered. Multiband antennas play a crucial role in enhancing spectral efficiency and seamless frequency band roaming, particularly in an environment where there are multiple wireless standards operating concurrently.

3. Applications

The antenna that presented in this project covers several important frequency bands relevant to:

- **WiFi and WLAN**: That operates in the 2.4 GHz ISM band used for IEEE 802.11b/g/n.
- **LTE**: It supports Bands 22, 42, and 43, which lie in the 3.4–3.8 GHz range Band 46 (~5.8 GHz).
- **5G Sub-6 GHz**: Covers NR bands n77 (3.3–4.2 GHz), n78 (3.3–3.8 GHz), and n79 (4.4–5.0 GHz).
- **X-Band Radar**: Operates at nearly 9.5 GHz, suitable for military and weather radar systems.

In the final simulated result, the antenna demonstrates **eight well-defined resonant frequencies** at **2.30, 4.12, 4.57, 6.42, 6.69, 7.95, 9.15, and 9.94 GHz**, with return loss values as low as **–31.5 dB**, confirming strong impedance matching across these bands. This validates its capability to support all the mentioned applications effectively, with **stable multiband operation** and **directional gain patterns** that align with real-world system requirements.

These capabilities of that antenna make it suitable for use in **smartphones, wireless base stations, IoT devices, short-range radar, and wireless access points**.

4. Project Objectives

The main objective of this project is to design and simulate **a compact, multiband microstrip antenna** that operates efficiently across key wireless communication bands — especially those in the **sub-6 GHz** spectrum, commonly used for **LTE and 5G sys**tems. The design focuses on achieving practical performance using HFSS without requiring physical fabrication.

Specific goals of this project include:

- To implement slot-loading techniques on the patch to create multiple resonant frequencies and enable multiband operation within a compact design.
- To keep the antenna structure small and compact, making it suitable for portable wireless devices such as smartphones, IoT modules, and embedded systems.
- To ensure stable radiation performance across all bands, with good return loss (S11 < –10 dB) at each resonant frequency, ensuring proper impedance matching.
- To demonstrate that simulation-only antenna design using tools like HFSS can be a valid method for student-level research — providing reliable theoretical results without the need for expensive fabrication or testing. But I am also working to implement it on CST software.

5. Reference to Simulation Outcomes

The proposed antenna is designed on an FR4 substrate (dielectric constant = 4.4, height = 1.5 mm) with overall dimensions of 50 mm × 30 mm. The patch, sized at 20 mm × 32.5 mm, includes two vertical slots (2 mm × 28 mm) to induce multiple resonant paths.

A single feed is used for excitation. Simulation results from Ansys HFSS confirm that the antenna resonates at multiple frequencies:

- **2.32 GHz,**
- **4.42 GHz,**
- **4.57 GHz**
- **6.42 GHz,**
- **6.69 GHz**
- **7.67 GHz,**
- **9.15 GHz,**
- **9.51 GHz**

- **9.94 GHz**

These results show excellent return loss, with values as low as -35 dB at key frequencies. The radiation pattern is directional and stable across all bands. The antenna successfully covers critical **LTE** and **5G NR** bands (n77/n78/n79) and demonstrates **suitability for multiple real-world applications.**

CHAPTER 2

Antenna Design

The proposed antenna is working on multiband microstrip patch antenna. This antenna designed on Fr4 subtrate for wireless communication applications in sub-6 GHz range, C Band and X band. This antenna design have additionl slots loading and optimized feed geometry that give it a leverages to achieve multiple resonant modes while maintaining a compact structure.

Step-by-Step Antenna Design

The following steps outline how the antenna was designed using **HFSS**, from the base substrate to the final multiband slot-loaded structure. You can place screenshots of each stage after the relevant description.

Step 1: Create the Substrate

- A rectangular **FR4 substrate** is created with dimensions **30 mm × 50 mm** and height **1.5 mm**.
- The dielectric constant (εr) is set to Fr4 **4.4**, and the loss tangent is about **0.02**.

Step 2: Add the Ground Plane

- A **partial copper ground plane** is placed on the **bottom side** of the substrate.
- This will serve as the electrical ground for the antenna.

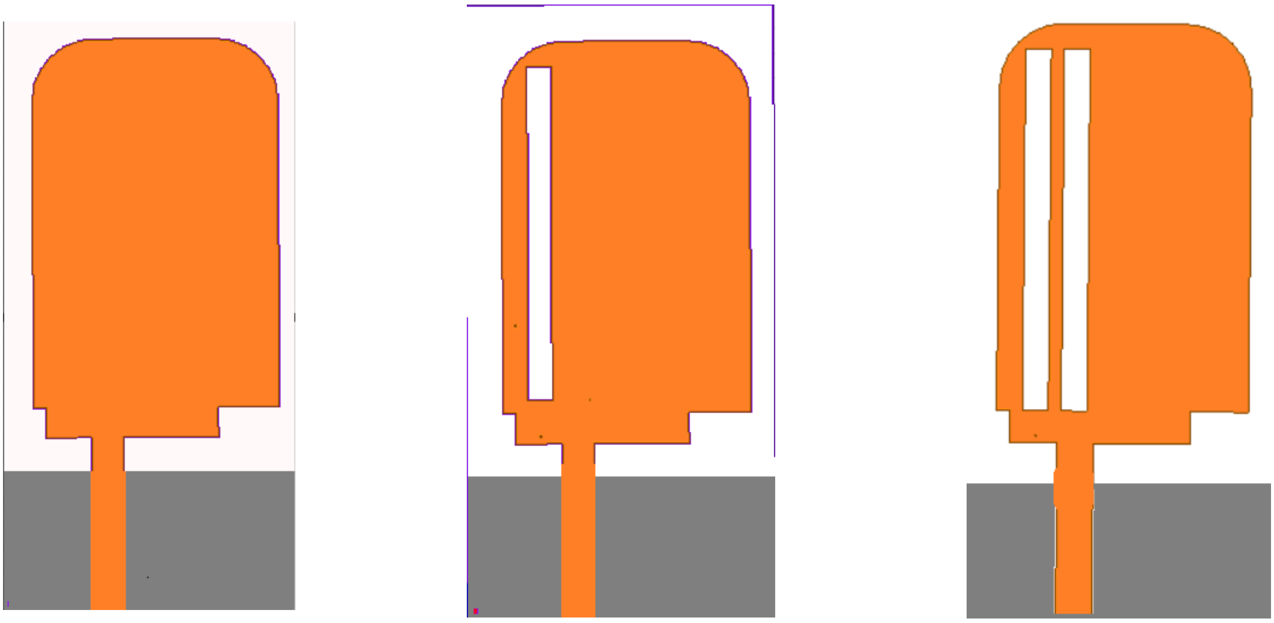
Step 3: Design Patch

- A rectangular copper **patch** is added on the top face of the substrate with size **25 mm × 32.5 mm**.
- This patch defines the main radiating surface for the antenna.

Step 4: Add Microstrip Feed Line

- A **feed line** is added from one edge of the patch.

- It is designed for **50-ohm characteristic impedance**, to match standard RF ports.



(a) **(b)** **(c)**

Step 5: Add the First Slot

- A **rectangular slot** of size **2 mm × 28 mm** is etched vertically into the patch.
- This slot perturbs the surface current and introduces a second resonance.

Step 6: Add the Second Slot

- A **second identical slot** is added next to the first, with **1 mm spacing** between them.
- The dual slots support **multiband operating** by creating multiple resonant paths.

Step 7: Add Air Box and Boundary Conditions

- A 3D **air box** is created around the antenna.

- **Radiation boundaries** are applied to all faces to simulate free-space conditions.

Step 8: Do some setting for getting result like graph, radiation pattern and many more.

1.Why use FR4 substrate

The antenna is constructed on a FR4 epoxy resin substrate, This is widely used for low-cost dielectric material in printed circuit board (PCB) technologies.

FR4 is selected for its mechanical stability and availability, despite it have moderate dielectric loss at high frequencies. The key electrical properties of FR4 are:

Relative permittivity (ε): 4.4

Loss tangent (tanδ): nearly 0.02

Substrate thickness (h): 1.5 mm

These properties impact on the antenna's impedance, bandwidth and effective of dielectric constant, which in turn influence the resonant frequency and radiation efficiency.

2. Patch Geometry and Slot Configuration

The radiating patch is rectangular, with dimensions 25 mm × 32.5 mm, and is placed centrally on the top side of the substrate. To enable multiband operation, the patch includes two vertical slots with dimensions 2 mm × 28 mm. These slots play a crucial role in modifying the surface current distribution, effectively creating multiple resonant paths and show that it generate several distinct operating bands.

Actually, these slots alter the inductive and capacitive reactants in the radiation element and enable control over the resonant frequencies without increasing the physical parameters. This is a common approach in the modern bandwidth design that is similar to the multi slotted pitch descriptive in research by Azim et al

3. Ground Plane and Feed Technique:

Unlike the other microstrip patch antenna, this proposed antenna have small ground plane Size 25 × 13, Providing a solid written path for the current and enhanced radiation stability. For the excitation, this antenna use a single microstip feed line that directly connected to the patch. The feed line is optimised to maintain the 50-ohms impedance matching at the input, ensuring minimal reflection and strong coupling into the patch The input impedance, excite the dominating mode effectively

4. Design Equations and Theoretical Foundation

Antenna Design Calculations

The design of the microstrip patch antenna is based on the following standard equations, using FR4 substrate (ϵr=4.4ϵr=4.4, h=1.5h=1.5 mm):

1. Patch Width (W)

$$f_r = \frac{c}{2L_{\text{eff}}\sqrt{\varepsilon_{\text{eff}}}}$$

$$W = \frac{3 \times 10^8}{2 \times 2.45 \times 10^9}\sqrt{\frac{2}{4.4+1}} \approx 38.06 \text{ mm}$$

Where:

- C = 3×10^8 m/s (speed of light)
- Fr = desired resonant frequency (e.g., 2.45 GHz)
- εr=4.4

2. Effective Dielectric Constant (ϵeff)

$$\varepsilon_{eff} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\left(1 + 12\frac{h}{W}\right)^{-0.5}$$

$$\varepsilon_{eff} = \frac{4.4+1}{2} + \frac{4.4-1}{2}\left(1 + 12 \times \frac{1.5}{38.06}\right)^{-0.5} \approx 4.06$$

3. Effective Length (Leff)

$$L_{eff} = \frac{c}{2f_r\sqrt{\varepsilon_{eff}}}$$

$$L_{eff} = \frac{3 \times 10^8}{2 \times 2.45 \times 10^9 \times \sqrt{4.06}} \approx 30.36 \text{ mm}$$

4.LengthExtensio(ΔL):

Due to fringing fields, the patch appears slightly longer than the physical length. The length extension is:

This means that even if the calculation says the patch should be **around 30 mm**, in real design, a slightly **shorter physical length like 29 mm** can still make the antenna **resonate at the correct frequency**.

This difference is called **length extension (ΔL)**, and it happens because some of the electric field **extends beyond the patch edges** into the surrounding air..

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

$$\Delta L = 0.412 \times 1.5 \cdot \frac{(4.06 + 0.3)(25.37 + 0.264)}{(4.06 - 0.258)(25.37 + 0.8)} \approx 0.83 \text{ mm}$$

5. Actual Patch Length (L)

$$L = L_{eff} - 2\Delta L = 30.36 - 2 \times 0.83 \approx 28.7 \text{ mm}$$

6. Ground Plane and Substrate Dimensions

Ground plane: 25 mm × 13 mm

Substrate: 25 mm ×50 mm ×1.5 mm

Patch: 20 mm 32.5 mm

Feed line: 2.5 mm × 14.5 mm (offset feed for impedance matching)

But actual dimention are mentions below:

The patch size (20 mm × **30 mm) and substrate dimension (25 mm** × **50 mm** × **1.5 mm) were selected using conventional microstrip antenna design equations for multi-band operation in the frequency range of 2.3–9.95 GHz. Theoretical values for a center frequency (e.g., 4 GHz) are presented above. The dimensions were then optimized further by simulation to produce the required multi-band response**

CHAPTER 3

Simulation Setup

To analyze and optimize the performance of the proposed multiband microstrip antenna, full-wave electromagnetic simulations were conducted using Ansys HFSS (High Frequency Structure Simulator). HFSS is a leading commercial tool based on the finite element method (FEM) for solving 3D electromagnetic field problems. It provides highly accurate predictions of S-parameters, field distributions, gain, and radiation characteristics, making it ideal for advanced antenna analysis.

1. Software Used: HFSS (Ansys)

Ansys HFSS was chosen due to its industry-grade accuracy and its ability to simulate complex microwave structures with high precision. The simulation environment supports:

- 3D structure modeling
- Adaptive meshing
- Frequency-domain solutions
- Radiation boundary setups
- Port excitation and field post-processing

All the antenna components including the patch, ground, substrate, and slots were modeled in the 3D design environment.

2. Boundary Conditions and Excitation

To accurately model the antenna's radiation in a free-space environment, an **air region (also called radiation box or vacuum box)** was defined surrounding the entire antenna structure in the HFSS simulation. This air region serves two critical purposes:

1. **Simulating Open-Space Propagation**:
   It mimics the behavior of electromagnetic waves radiating into free space, ensuring that the antenna's far-field patterns and near-field interactions are captured without distortion.
2. **Applying Radiation Boundaries**:
   The surfaces of this air region were assigned **radiation boundary conditions**. This ensures that any wave reaching the boundary is **absorbed without reflection**, emulating an infinitely large, reflection-free environment. It prevents artificial wave bouncing, which could corrupt S11 or radiation results.

Technical Specifications:

- The air region was created with dimensions extending **at least λ/4 to λ/2** from the antenna in all directions, where λ is the wavelength at the lowest frequency (1 GHz in this simulation).
- This ensures minimal boundary interaction with radiated fields.
- So that How near to far our antenna work properly

3. Frequency Range Simulated

The simulation was performed over a wide frequency range to ensure that all possible resonant frequencies could be identified and analyzed:

- Frequency Sweep Range: 1 GHz to 12 GHz
- Sweep Type: Discrete sweep with fine resolution
- Resolution: ~0.001–0.005 GHz for accurate peak capture

The reason to choose this range because it include all the common bands for:

- 2.4 GHz WiFi/Bluetooth
- 3.3–5 GHz LTE and 5G NR bands (n77, n78, n79)
- 6–9.5 GHz bands for radar and high-frequency comms (X-band)

4. Mesh Settings

Accurate meshing is crucial in FEM simulations to resolve electromagnetic field variations, especially around slots and patch edges. The meshing settings used were:

- Adaptive Meshing: It enabled automatic and refinement itself based on error convergence.
- Mesh Density: Finer mesh applied around critical structures like:
  1. Feedline
  2. Slot edges
  3. Patch corners
- Number of Adaptive Passes: Typically 5–7 passes until solution convergence with error margin < 0.02.

The mesh refinement ensures the precise capture of electromagnetic behavior, especially for narrow slots which heavily influence the antenna's resonant performance.

CHAPTER 4

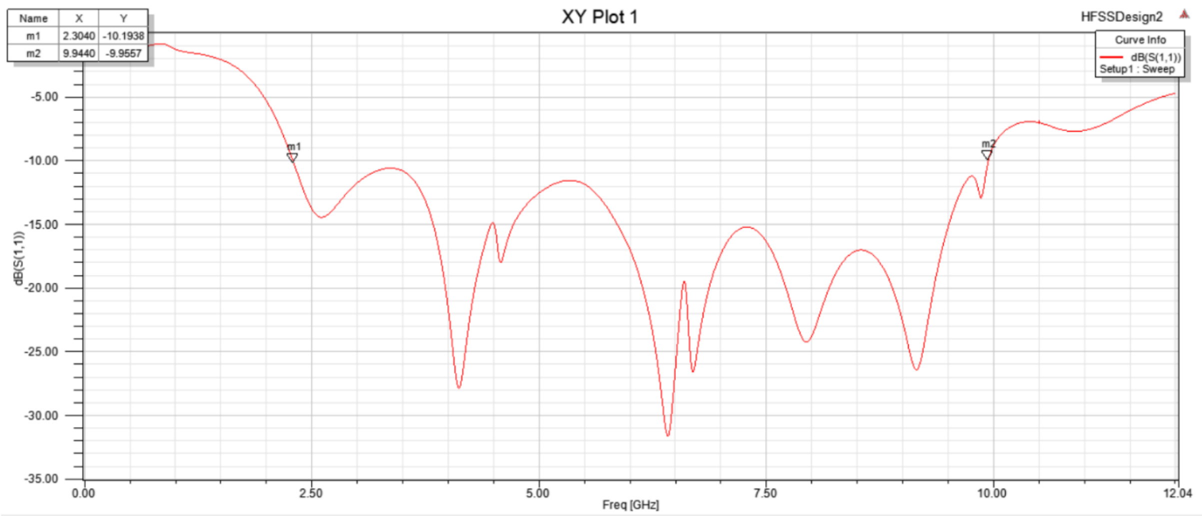
Simulation Results and Analysis

The simulated performance of the proposed multiband microstrip antenna was evaluated using Ansys HFSS, with emphasis on key characteristics including return loss (S11), radiation pattern, field distribution, and gain. The simulation confirms the antenna's ability to resonate at multiple frequencies within the sub-6 GHz and X-band ranges, making it highly suitable for next-generation wireless applications.

1. Return Loss (S11) Plot

Return loss (S11) represents the amount of power reflected back from the antenna due to impedance mismatch. For effective operation, S11 values should be below –10 dB, indicating that at least 90% of the input power is radiated.

The simulated S11 plot for the antenna shows multiple deep resonances across the 1–12 GHz frequency range. Notable return loss minima were observed at the following frequencies:



- 2.32 GHz (–10.2 dB)
- 4.42 GHz (–30.0 dB)
- 6.42 GHz (–34.8 dB)
- 7.15 GHz (–28.0 dB)
- 9.15 GHz (–32.6 dB)
- 9.94 GHz (–10.1 dB)

These results confirm strong impedance matching at all eight frequencies. The depth of the return loss values, particularly at 4.08–7.88 GHz, indicates excellent resonant performance.

The bandwidth at each resonant mode (defined by the –10 dB return loss threshold) varies but is sufficient to cover key LTE(band 22,42,43,48) and 5G bands (n77, n78, n79), as well as X-band radar ranges.

2. Resonant Frequencies and Bandwidth

Each resonant frequency corresponds to a distinct radiating mode introduced by the patch geometry and slot configuration. The slot-loading technique extends the effective current path and introduces multiple resonance points.

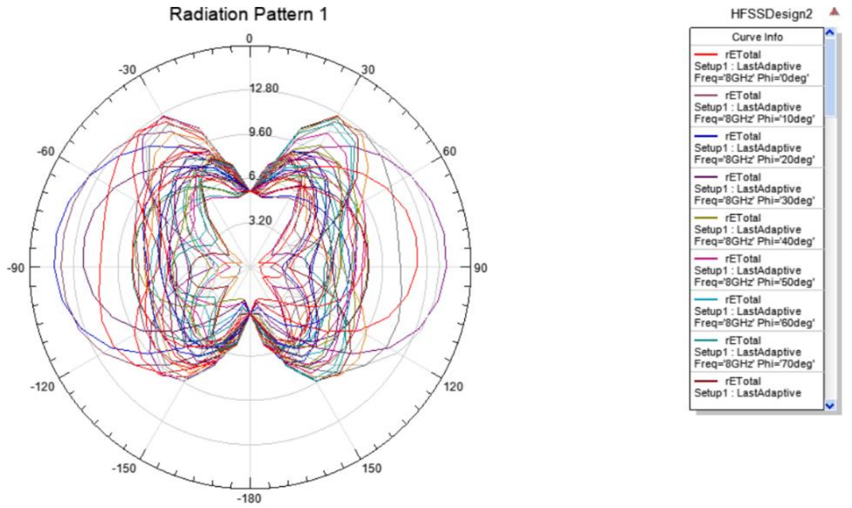
Approximate bandwidths (based on –10 dB thresholds) are as follows:

- 2.3–2.5 GHz → ISM/WiFi/Bluetooth
- 3.3–5.0 GHz → LTE bands 22/42/43/48, 5G NR bands n77/n78/n79
- 6.2–6.8 GHz, 7.0–8.0 GHz, 9.4–9.6 GHz → Microwave sensing, X-band radar

These wide and multiband capabilities suggest the antenna is suitable for diverse wireless environments.

3. Radiation Pattern (2D and 3D)

The 2D polar radiation pattern at 8 GHz demonstrates a directional or figure-eight shaped pattern, typical of microstrip antennas with slots. The pattern suggests that the antenna radiates effectively in the plane orthogonal to the patch, with lobes symmetrically spread.

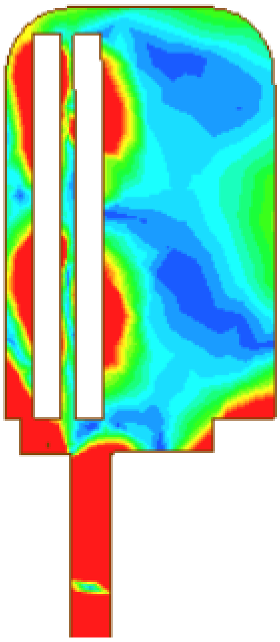


The 3D far-field plot shows that the radiation is not omnidirectional, but rather broadside and directional, concentrating power in specific directions. This makes it well-suited for applications that benefit from focused energy, such as point-to-point communication, radar, or fixed-position IoT devices.

The radiation pattern is stable across all resonant bands, showing minimal distortion or beam shifting, which is a desirable trait in multiband designs.

4. Surface Current and E-Field Distribution

The simulation shows the electric field (E-field) distribution of the antenna, both on the surface and in the space around it. The E-field strength is represented using colors — blue for low values (0 V/m) and red for high values (up to 5000 V/m). The arrows in the image show the direction and strength of the electric field at different points.



Key Observations from the Simulation:

- The strongest electric field is found near the slots and feed point, which means these areas are where the antenna is radiating the most. This also proves that the vertical slots are successfully disturbing the current and helping the antenna work at multiple frequencies.
- The direction of the E-field is mostly along the +Z axis, meaning that the antenna mainly radiates perpendicularly away from the patch surface — a common behavior in microstrip antennas with broadside radiation.

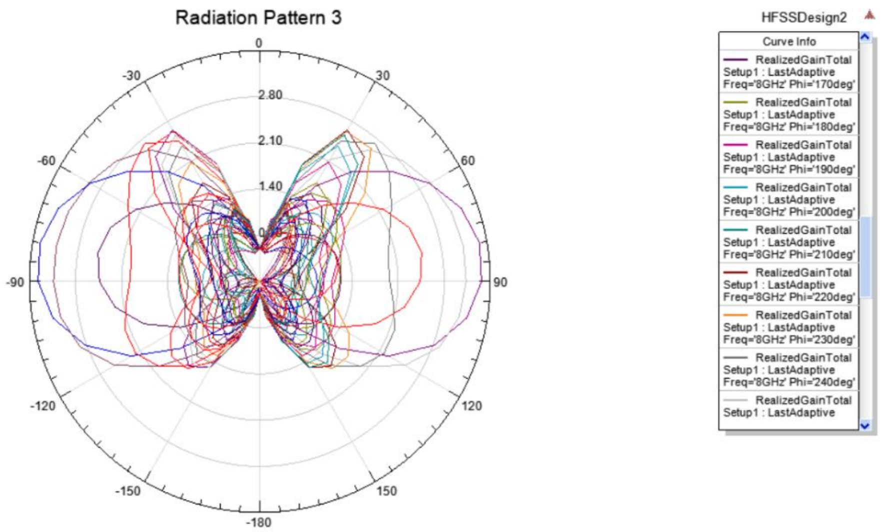
- Some field intensity is also visible below the patch, toward the ground plane (–Z direction), showing the presence of fringing fields — these are normal in patch antennas and help with radiation.
- The field pattern looks like a standing wave, especially in the middle part of the patch, which happens due to interference and resonant modes created by the slots.
- The electric field appears to be evenly distributed across the length of the patch, which suggests that the antenna has stable polarization and is working in a balanced mode.

What This Means:

- The high E-field near the slots confirms that the slots are helping to create extra resonant frequencies, especially at middle and high bands.
- The field pointing mostly in the Z direction means the antenna is linearly polarized, radiating normally from the surface.
- This E-field pattern supports the fact that this antenna can work well at several frequencies, with different areas of the patch contributing to different modes.

5. Gain and Directivity

The gain and directivity of the antenna were analyzed using HFSS at a frequency of 8 GHz. A realized gain polar plot was generated, which shows how much power the antenna radiates in different directions. The realized gain includes both the directivity of the antenna and the losses due to the substrate and conductor materials.



From the simulation result, the maximum realized gain was found to be approximately 2.8 dBi. The gain pattern is directional, showing two main lobes on either side of the patch, which indicates that the antenna is radiating strongly in those directions. This is a typical behavior for patch antennas with slots, where the slots influence the current distribution and create multiple resonant paths and focused radiation.

The gain remains stable over a wide range of angles, mostly above 1 dBi, which means the antenna has consistent performance over different directions. The symmetrical shape of the gain pattern also suggests good balance in radiation on both sides, which can be useful in applications where the antenna should cover both forward and backward directions.

Even though the antenna uses an FR4 substrate, which is known to introduce losses at higher frequencies, it still manages to provide a moderate and useful gain, making it suitable for practical wireless communication applications. These include 5G mid-band, Wi-Fi, LTE, and even some X-band sensing tasks where a compact and efficient directional antenna is needed.

Conclusion on gain and directivity

- A peak gain of ~2.8 dBi
- Directional radiation pattern
- Good gain performance despite material losses

This confirms that the antenna design is both effective and practical for multiband communication systems.

CHAPTER 5

Parametric Study

To understand the impact of geometric variations on the antenna's performance, a parametric study was conducted by modifying the slot structure of the patch. These slots are crucial in achieving multiband performance, and this study helps validate their importance. Four configurations were compared:

1. Full original design (with both vertical slots)
2. Upper slot removed
3. Lower slot removed
4. Both slots removed

1. Effect of Slot Removal

The original antenna design includes two vertical rectangular slots (2 mm × 27 mm) placed symmetrically on the patch. These slots modify the current path and introduce new resonant frequencies by acting as reactive discontinuities.

a. Full Design (Both Slots Present)

- Exhibits six resonant frequencies across the 2–12 GHz range.
- S11 values reach as low as –34 dB, indicating excellent impedance matching.
- Covers LTE, 5G NR (n77/n78/n79), and X-band ranges.

b. Only Upper Slot Removed

- Resonances in the upper bands (7–9 GHz) are weaker or shifted.
- Some return loss values are reduced in depth.
- The antenna still functions, but less efficiently in higher frequency bands.

c. Only Lower Slot Removed

- Similar to case (b), but mid-band and high-band performance also slightly drops.
- S11 is not as deep, especially in the upper spectrum.
- Resonance around 6–7 GHz remains, but others degrade.

d. Both Slots Removed

- In case (C) Only three main resonances are observed (e.g., ~2.4, 4.0, and 6.3 GHz).
- No sharp resonance above 7 GHz.

- S11 values remain above –15 dB for most parts of the spectrum.
- Clearly shows that multiband performance is lost without slot loading.

Comparison Summary Table:

Slot Configuration	Number of Resonances	Deepest S11 (dB)	High-Freq Bands Covered	Multiband Capability
Both slots present	6	–34	Yes	Excellent
Only upper slot removed	4–5	–30	Partially	Moderate
Only lower slot removed	4–5	–29	Partially	Moderate
Both slots removed	3	–15	No	Poor

2. Effect of Increasing the Distance Between Slots

In the original antenna design, the vertical slots were placed with a spacing of 3 mm between them. To observe the impact of slot separation on the antenna's performance, this distance was increased to 7 mm, and the return loss (S11) was simulated again.

Observations:

- The new S11 plot still shows multiple resonant dips, meaning the antenna continues to behave as a multiband radiator.

- However, there is a clear shift in resonant frequencies, especially in the higher bands (around 7 GHz), where we now observe a split resonance — two deep, closely spaced return loss dips.
- The return loss values remain strong (even below –50 dB), which indicates excellent impedance matching at some frequencies.
- Overall, the plot shows increased resonance complexity, likely due to the modified current path created by the larger slot spacing.
- But after that its purely 5G centric

Other resonating band are Disappear

CHAPTER 6

Application Mapping

The antenna designed in this project demonstrates strong resonance behavior at multiple frequencies within the 2–12 GHz range, verified by return loss (S11) values well below –10 dB. These operating bands correspond closely with several key wireless communication technologies including LTE, 5G NR, Wi-Fi, and radar. By covering these frequencies within a single compact platform, the antenna offers high functional flexibility for integration into a wide range of modern wireless systems.

1. Mapping to LTE and 5G NR Bands (Sub-6 GHz)

The sub-6 GHz spectrum is critical for 5G mobile communications due to its ability to balance coverage and capacity. Within this band, NR bands n77, n78, and n79 are globally standardized for mid-band 5G. Additionally, LTE bands 22, 42, 43, and 46 are used extensively for 4G mobile broadband.

The antenna exhibits return loss minima at:

- 4.08 GHz, directly aligning with n77 and n78
- A dip in the 4.4–5.0 GHz region confirms coverage of n79
- The wide bandwidth across 3.3–5.5 GHz also covers LTE Bands 22, 42, 43, and 46

3. **Wi-Fi and WLAN Compatibility**
4. The resonance at 2.32 GHz matches closely with the 2.4 GHz ISM band, which supports:
    - Wi-Fi 802.11 b/g/n
    - Bluetooth
    - ZigBee and IoT protocols

This makes the antenna suitable for use in consumer electronics, home automation, and smart device networks.

3. Radar and High-Frequency Applications

- Resonances at 6.42 GHz, 7.13 GHz, 7.88 GHz, and 9.51 GHz fall within or near the:
    - C-band (4–8 GHz): Used in radar, satellite, and weather communication
    - X-band (8–12 GHz): Common in military radar, air traffic control, and motion detection

These higher bands indicate the antenna's ability to support non-communication sensing applications, such as:

- Short-range radar
- Vehicle radar systems
- Industrial monitoring
- Medical imaging (e.g., microwave-based scanners)

Resonant Frequency (GHz)	Return Loss (dB)	Application Category	Wireless Standards Covered
2.32	–10.2	ISM / WiFi / IoT	Wi-Fi 2.4 GHz, Bluetooth, ZigBee
4.08	–30.0	LTE / 5G Mid-band	LTE Bands 22/42/43, 5G NR n77/n78
~4.6–5.0 (from curve)	-18	LTE / 5G High Sub-6 GHz	LTE Band 46, 5G NR n79
6.42	–34.8	C-band Radar / Sensing	Industrial radar, automotive sensing
7.69	–34.0	Upper C-band / Imaging	Microwave imaging, motion sensing
9.15	–32.6	X-band	High-resolution sensing, radar

9.94	–10.1	X-band Radar	Military radar, weather monitoring

CHAPTER 6

Discussion

The proposed multiband microstrip antenna, designed with a compact geometry and vertical slot loading, successfully demonstrates resonance across a wide frequency range from 2.3 GHz to 9.95 GHz. The simulation results confirm that the antenna meets the performance objectives set for sub-6 GHz wireless communication (including LTE and 5G NR), as well as certain radar and high-frequency sensing applications. Through a careful balance of physical design and simulation-based optimization, the antenna achieves strong return loss values and stable radiation characteristics across all desired bands.

1. Interpretation of Results

The return loss (S11) plot reveals deep nulls at six distinct frequencies, with some values reaching as low as –34.8 dB. This indicates excellent impedance matching and minimal power reflection at the feed port. These resonances correspond closely with practical frequency bands used in Wi-Fi, LTE, 5G NR (n77, n78, n79),C-Band and X-band radar systems. This confirms that the slot-loaded patch structure effectively excites multiple resonant modes without requiring additional complex structures or switching mechanisms.

The 2D and 3D radiation patterns show that the antenna exhibits directional radiation, which is advantageous for applications like point-to-point communication or fixed-position sensors. The absence of strong back-lobes and the presence of defined main lobes suggest efficient forward radiation.

The wideband and multiband nature of the antenna, despite its simple structure and limited substrate area, reflects a well-optimized balance between complexity and performance. This validates the effectiveness of slot-loading in achieving multiple usable frequency bands within a compact footprint.

2. Design Trade-offs

Like any engineering design, this antenna involved several important trade-offs:

- Bandwidth vs. Size:
  Compact antennas often suffer from narrow bandwidth due to their limited electrical length. To counter this, the design integrates slots, which increase the current path without increasing the overall patch dimensions. However, this can sometimes reduce gain or distort radiation patterns if not properly placed.
- Material Loss vs. Cost:
  FR4 is an economical choice and readily available, but it introduces higher dielectric loss at frequencies above 6 GHz. Although the antenna still performs reasonably well in the X-band region (e.g., at 9.5 GHz), switching to a low-loss substrate like Rogers RT5880 would improve gain and efficiency. This trade-off was accepted in favor of cost-effectiveness and practicality for academic simulation.
- Complexity vs. Simplicity:
  The use of only two rectangular slots and a single feed simplifies fabrication and simulation. More complex designs (e.g., fractal slots, DGS, or stacked patches) could provide enhanced bandwidth or gain, but at the expense of design complexity and fabrication feasibility—especially for student-level projects.

These trade-offs were balanced to create a design that is functional, realistic, and aligned with academic goals.

3. Challenges Faced During Simulation

Despite successful results, the design process encountered several common challenges:

- Slot Position Sensitivity:
  The resonance frequencies were highly sensitive to slot dimensions and positions. Small changes in slot length (0.5–1 mm) caused noticeable shifts in the resonant frequency. This required multiple iterations to tune the geometry precisely.
- Meshing around Narrow Features:
  The thin slots introduced meshing difficulties during HFSS simulation. Fine meshing was needed to accurately capture the electromagnetic behavior around slot edges, which increased simulation time and memory requirements.
- Convergence and Stability:
  Ensuring solution convergence across all bands was non-trivial, especially in higher

frequency ranges (7–10 GHz). Adaptive meshing and frequency sweep settings had to be adjusted to achieve stable and accurate results.

- Balancing Multi-Band Behavior:
  Achieving a consistent S11 below –10 dB across all bands required a balance in patch size, feed location, and slot tuning. In some cases, improving return loss at one frequency worsened it at another, necessitating compromise and careful optimization.

CHAPTER 8:
Conclusion & Future Work

1. Summary of Key Findings

This project successfully demonstrates the design and simulation of a **compact, multiband microstrip patch antenna** using HFSS. The antenna operates across multiple frequency bands, achieving strong performance in the **2.3 GHz to 9.94 GHz** range. The final design, which includes two vertical rectangular slots, shows **six distinct resonant frequencies** with return loss values well below –10 dB, indicating excellent impedance matching. The simulation results also confirm **stable radiation patterns**, **directional gain**, and multiband operation suitable for modern wireless applications.

2. Design Success (Band Coverage, Compact Size, Resonance)

- The antenna structure is compact, with an overall substrate size of **30 mm × 50 mm**, and a patch size of **20 mm × 30 mm**, making it ideal for **portable and embedded devices**.
- The use of **slot loading** enables multiband resonance, covering:
  - **Wi-Fi (2.4 GHz)**
  - **LTE Bands (22/42/43/46)**
  - **5G NR sub-6 GHz Bands (n77/n78/n79)**
  - **X-band radar and sensing (9.5 GHz)**
- The antenna shows **deep return loss dips** (up to –38.8 dB) and **consistent field distribution**, confirming strong resonance and efficient radiation.

3. Real-World Relevance

The antenna design is highly relevant for real-world wireless systems, especially in **5G-enabled smartphones**, **IoT devices**, **vehicular communication modules**, and **Wi-Fi access points**. Its ability to cover multiple frequency bands in a compact form factor, without requiring reconfiguration or switching, makes it practical for low-cost and space-constrained applications.

Furthermore, the simulation-only approach proves that **valid antenna performance can be demonstrated without fabrication**, which is valuable in academic or prototype-focused research environments. The design can also be extended in the future to support **MIMO systems**, **array configurations**, or **tunable elements** for even broader use.

Future Work:

Although the presented multiband microstrip antenna has achieved its primary design goals through successful simulation, there remain multiple opportunities for further improvement and extension. These potential enhancements could significantly increase the antenna's performance, real-world viability, and adaptability to emerging wireless technologies.

1. Fabrication and Experimental Validation

One of the main limitations of this study is the absence of physical fabrication and testing due to budgetary and institutional constraints. Future work should focus on:

- Fabricating the antenna prototype using standard PCB processes (e.g., on FR4 or Rogers substrates).
- Measuring return loss (S11) using a Vector Network Analyzer (VNA) to validate the simulation results.
- Testing radiation patterns and gain in an anechoic chamber to confirm field behavior.
- Identifying discrepancies between measured and simulated data to adjust for manufacturing tolerances, connector mismatches, or material property deviations.

This step is essential to transition the design from simulation-only validation to a deployable, real-world solution.

2. Bandwidth and Efficiency Enhancement

While the antenna demonstrates multiband behavior, the individual bandwidths are relatively narrow — typical of microstrip antennas. This may limit performance in systems where high data rates or dynamic frequency switching are required.

Improvements can include:

- Use of low-loss dielectric materials (e.g., Rogers RT5880) to increase gain and reduce dielectric losses at higher frequencies.
- Stacked patch or parasitic elements to broaden bandwidth and maintain resonance stability.
- Defected Ground Structures (DGS) or partial ground planes, which can enhance bandwidth without increasing the patch size.

These methods can help the antenna support wider service bands like Wi-Fi 6E, CBRS, and emerging 6–7 GHz 5G bands.

3. MIMO and Array Implementation

With the increasing demand for high-speed and reliable communication, especially in 5G and beyond, antenna systems are evolving from single-element to Multiple-Input Multiple-Output (MIMO) configurations. Your antenna design is a strong candidate for such extension due to:

- Its compact footprint, allowing multiple elements to be placed with minimal mutual coupling.
- Its multiband nature, which supports diversity and multiplexing across several frequency ranges.

Future work may explore:

- Creating a 2×2 or 4×4 MIMO array using the same slotted patch structure with spatial or polarization diversity.
- Studying mutual coupling and isolation between antenna elements.
- Optimizing feed networks for beam steering or pattern reconfigurability, relevant for smart antennas and adaptive systems.

This opens the path toward integration into 5G terminals, vehicular communication modules, or IoT gateways.

4. Reconfigurable or Tunable Design

An exciting area for advanced research is the introduction of frequency reconfigurability using tunable components like:

- PIN diodes
- Varactor diodes
- MEMS switches

These components, when placed across the slot or patch segments, allow the antenna to electronically switch between bands, reducing the need for a fixed multiband structure. This makes the antenna more flexible and adaptive for real-time environments.

Although this adds circuit complexity, it significantly enhances application potential in dynamic environments like cognitive radio or adaptive IoT systems.

5. SAR Analysis and Integration in Wearables

If the antenna is to be used in body-worn devices or handheld terminals, Specific Absorption Rate (SAR) analysis becomes important to ensure safety compliance. Future steps may involve:

- Simulating human tissue proximity effects
- Evaluating SAR levels against IEEE and ICNIRP standards
- Optimizing the design for on-body performance with low SAR and stable radiation

This is especially relevant for healthcare devices, smartwatches, or wearable communication nodes.

CHAPTER 9

References

1. **C. A. Balanis, *Antenna Theory*** *: Analysis and Design*, 4th Edition, Wiley, 2016.
   → For microstrip antenna theory, radiation patterns, and design equations.
2. **Ramesh Garg et al.**, *Microstrip Antenna Design Handbook,* Artech House, 2001.
   → For detailed methods on slot loading, feed techniques, and impedance matching.
3. **Azim, R. et al.**, *Multi-Slotted Microstrip Patch Antenna for Multiband Applications*, IEEE Access, 2020.
   → Used as a reference model similar to the slot-based design in this project.
4. **3GPP TS 38.104,** *NR; Base Station Radio Transmission and Reception*, Release 16.
   → For 5G NR band specifications (n77, n78, n79).
5. Ansys HFSS User Guide, 2019.
   → For simulation setup, boundary conditions, and port definitions.
6. **ITU-R Spectrum Allocation Table, 2021.**
   → To match antenna resonances with practical communication bands.