SHRI RAMDEOBABA COLLEGE OF ENGINEERING AND MANAGEMENT, NAGPUR

DEPARTMENT OF ELECTRONICS & COMPUTER SCIENCE ENGINEERING

Session: 2024-25

Project Report

Project1(ECSP310) VI sem B.Tech (ECS)

By Rishi Thakre, Ameya Bahadure, Tushar Sanodiya, Komal Patle

Guided by Prof. Archana Tiwari

Design and Optimization of Antenna Using Machine Learning Algorithms

1.Abstract:

Microstrip patch antennas are widely used in wireless communication due to their compact size, lightweight structure, and cost-effective fabrication. Circular microstrip patch antennas offer symmetrical radiation patterns, improved bandwidth, and better circular polarization purity compared to rectangular patch antennas. Traditional design methods using electromagnetic (EM) simulators require iterative simulations and manual tuning, which are time-consuming and computationally expensive. Integrating machine learning (ML) algorithms, such as artificial neural networks (ANNs), supervised and unsupervised learning models, random forests, and support vector machines (SVMs), can optimize the antenna design process by reducing computational costs and improving performance. The objective of this project is to develop an ML-based framework to predict optimal antenna parameters, ensuring efficient and high-performance wireless communication systems. This project focuses on the design and optimization of a circular patch antenna using machine learning techniques.

2.Objectives:

PART - 1

- Design a simple microstrip patch antenna using EM Simulator.
- Optimize the antenna for frequency, bandwidth, gain and return loss by using DGS

PART - 2

- Generate the dataset for antenna performance parameters to facilitate ML Model training.
- Analyze different machine learning (ML) models to incorporate for antenna design.
- Implement the generated data set on machine learning algorithms to optimize antenna performance and improve key parameters.
- Investigate the predicted output with the results obtained from the EM simulator.

3.Introduction:

An antenna is a crucial device used for the transmission and reception of electromagnetic waves, including radio waves, microwaves, and, in some advanced applications, even visible light. Functioning as a transducer, it converts electrical signals from a transmitter into electromagnetic waves that can propagate through space and vice versa at the receiver end.

In modern wireless communication systems, antennas play a pivotal role in ensuring effective signal propagation, data transfer, and system reliability. With the growth of wireless technologies such as Wi-Fi, 5G, IoT, radar, satellite, and GPS, the demand for compact, efficient, and high-performance antennas has significantly increased.

Among the various types of antennas, the Microstrip Patch Antenna (MPA) has gained popularity due to its low profile, ease of fabrication, lightweight structure, and compatibility with integrated circuits. However, microstrip patch antennas typically suffer from limitations such as narrow bandwidth, lower gain, and surface wave losses. These drawbacks necessitate the need for performance optimization.

One effective technique for improving antenna performance is the use of Defected Ground Structures (DGS). By introducing slots or patterns in the ground plane, DGS can suppress unwanted surface waves, enhance impedance bandwidth, and improve gain and return loss characteristics.

Furthermore, with the rise of machine learning (ML), new opportunities have emerged for automated design and optimization of antennas. By training ML models on simulation data, it's possible to predict antenna performance and discover optimal design parameters without the need for repeated EM simulations. This data-driven approach significantly reduces the design cycle and enables smart, adaptive antenna development.

Through this integration, the project explores how intelligent algorithms can contribute to the future of antenna engineering

4.Microstrip Patch Antenna Overview:

A Microstrip Patch Antenna (MPA) is a type of planar antenna widely used in wireless communication systems because of its low profile, lightweight design, and ease of integration with printed circuit boards (PCBs). It is especially effective in the UHF and microwave frequency ranges, making it suitable for applications like mobile communications, GPS, radar, and satellite systems. An MPA typically consists of three key components: the patch, the substrate, and the ground plane.

The **patch**, which is the radiating element, is made from a thin layer of conductive material such as copper or gold and is printed on the top of the dielectric substrate. It is responsible for emitting or receiving electromagnetic waves and is typically sized around half the wavelength ($\lambda/2$) of the operating frequency in the dielectric medium. Common patch shapes include rectangular, square, circular, and more complex forms like E or U slots, which help enhance performance.

The **substrate** is a dielectric layer between the patch and the ground plane. It provides structural support and influences key antenna parameters such as efficiency, bandwidth, and radiation characteristics. Substrate materials like FR4 ($\varepsilon r \approx 4.4$), Rogers RT/Duroid, and Taconic are commonly used, with their thickness and dielectric constant significantly affecting performance.

The **ground plane** is a metallic layer on the bottom of the substrate, acting as a reflector to direct electromagnetic waves outward and reduce energy loss. Its size and shape can also impact antenna performance, particularly in designs that incorporate Defected Ground Structures (DGS) to enhance bandwidth, return loss, and overall efficiency.

4.1 Types of Patches in Microstrip Patch Antennas:

Microstrip patch antennas can be fabricated in a variety of shapes depending on the desired application, performance requirements, and design constraints. The geometry of the patch significantly influences the resonant frequency, bandwidth, radiation pattern, and polarization of the antenna. Among the most commonly used patch types are **rectangular**, **circular**, and **square**.

Rectangular Patch

The rectangular patch is the most widely used due to its simplicity and ease of analysis. It provides good performance for linear polarization and is easy to fabricate. The dimensions are typically chosen such that the patch length (L) is approximately half the wavelength ($\lambda/2$) in the dielectric medium. This shape is advantageous for its simple mathematical modeling, effectiveness in narrowband applications, and the ability to support higher-order modes if needed. Common applications include mobile communication, RFID systems, Wi-Fi modules, and GPS devices.

Circular Patch

The circular patch employs a circular disc as the radiating element. Its circular symmetry makes it ideal for applications that require circular polarization. The resonant frequency of a circular patch is primarily determined by its radius. Circular patches are known for their compactness at a given frequency and their suitability for polarization diversity. They are commonly used in satellite communications, aerospace systems, and other high-frequency communication platforms.

Square Patch

A square patch is a special case of the rectangular patch where the length and width are equal (L = W), providing geometrical symmetry. While it shares similar radiation characteristics with the rectangular patch, its symmetric layout makes it particularly advantageous in array configurations. Square patches are valued for their balanced design and are often used in integrated circuit boards, phased antenna arrays, and experimental research setups where compact and symmetric geometries are preferred.

4.3 Key Parameters of Antennas:

To evaluate and optimize an antenna's performance—whether through electromagnetic simulation or machine learning—a clear understanding of key antenna parameters is essential. These parameters determine how effectively an antenna radiates or receives electromagnetic energy.

Radiation Pattern is a graphical representation of the radiation properties of an antenna as a function of space coordinates. It illustrates how the radiated power varies with direction and is commonly depicted in two-dimensional (azimuth and elevation planes) or three-dimensional plots. There are different types of patterns, such as omnidirectional patterns, which radiate uniformly in all directions like a dipole antenna, and directional patterns, which focus radiation in one or more specific directions, as seen in patch or horn antennas. Understanding the radiation pattern is important for visualizing beam direction, beamwidth, and sidelobes, which are critical for antenna alignment and coverage area design.

Bandwidth refers to the range of frequencies over which the antenna performs efficiently. It is typically defined within the range where the return loss (S11) is less than -10 dB or the Voltage Standing Wave Ratio (VSWR) is below 2. Bandwidth is expressed either in megahertz (MHz) or as a percentage of the center operating frequency. A wider bandwidth allows an antenna to support more communication channels and tolerate frequency drift or variations in operating conditions, making it essential for broadband and multi-band applications.

Gain is a measure of how well the antenna converts input power into radio waves in a specific direction. It is expressed in decibels, either dBi (relative to an ideal isotropic radiator) or dBd (relative to a dipole). Antenna gain combines both the directivity and efficiency of the antenna. A higher gain implies that more power is radiated in the intended direction, thereby improving signal strength, coverage, and communication range. It is especially important in long-distance and point-to-point communication systems.

Efficiency is defined as the ratio of power actually radiated by the antenna to the total power input. Several factors influence efficiency, including dielectric losses in the substrate material, conduction losses in the metal parts of the antenna, and surface wave losses within the structure. High-efficiency antennas ensure that the majority of the input power is radiated effectively rather than being lost as heat or dissipated in non-radiating modes. Efficient designs are crucial for energy conservation and effective performance, especially in battery-powered or low-power communication devices.

5. Circular Microstrip Patch Antenna

Circular patch antennas are gaining popularity in modern wireless communication systems due to their unique characteristics and advantages over other antenna types. One of the primary reasons for their widespread use is their compact size. These antennas require significantly less physical space compared to conventional rectangular patch antennas, making them highly suitable for miniaturized devices and applications where space constraints are a critical consideration. The reduced size does not compromise performance, making circular patch antennas a preferred choice in portable and handheld wireless devices.

Another distinct feature of circular patch antennas is their omni-directional radiation pattern. This pattern ensures that the antenna radiates electromagnetic waves uniformly in all directions within the plane, providing reliable and consistent coverage regardless of the orientation. Such a radiation pattern is particularly advantageous in environments where signals need to reach receivers from various angles, such as in mobile communication and indoor wireless systems.

Additionally, circular patch antennas offer higher bandwidth compared to their rectangular counterparts. The increased bandwidth allows for better signal transmission and reception, which is crucial in applications requiring high data rates, like Wi-Fi and modern communication protocols. This enhanced bandwidth is attributed to the symmetric structure of the circular patch, which inherently supports a wider range of frequencies without significant performance degradation.

Moreover, circular patch antennas are known for their ease of integration into wireless communication systems. Due to their planar structure and lightweight design, they can be seamlessly embedded into circuit boards and compact wireless modules. This compatibility with modern fabrication techniques, such as printed circuit board (PCB) technology, further enhances their practicality and cost-effectiveness in mass production.

5.1 Design Specifications of Circular Patch Antenna

The design of a circular patch antenna requires careful consideration of various parameters to achieve optimal performance. The following are the key design specifications chosen for this project:

Target Frequency: 2.45 GHz
The antenna is designed to operate at a target frequency of 2.45 GHz, which falls within the

Wi-Fi and Industrial, Scientific, and Medical (ISM) bands. This frequency range is widely used for wireless communication applications, including Wi-Fi networks, Bluetooth, and other short-range communication systems. Choosing this frequency ensures compatibility with standard wireless communication protocols and devices. Additionally, the ISM band is unlicensed and globally available, making it a suitable choice for various consumer and industrial applications.

Substrate Material: FR4 Epoxy
The substrate material selected for the antenna is FR4 Epoxy, a widely used and cost-effective dielectric material in printed circuit board (PCB) manufacturing. FR4 is favored due to its mechanical robustness, stability under varying environmental conditions, and excellent electrical properties. The material's durability makes it suitable for high-frequency applications while maintaining low manufacturing costs. Additionally, the ease of fabrication and availability make FR4 Epoxy a practical choice for prototype development and mass production.

Dielectric Constant (εr): 4.4
The dielectric constant of the chosen substrate material (FR4 Epoxy) is 4.4. This parameter plays a critical role in determining the size and resonant frequency of the antenna. A higher dielectric constant generally results in a smaller patch size for the same operating frequency, which is advantageous when designing compact antennas. However, it also affects the bandwidth and efficiency, requiring a balanced design to ensure optimal performance.

Substrate Thickness: 1.6 mm
The thickness of the substrate is chosen as 1.6 mm, which is a standard dimension for PCB materials. This thickness ensures a good compromise between mechanical strength and electromagnetic performance. A thicker substrate generally enhances bandwidth but can increase surface wave losses, while a thinner substrate may reduce bandwidth but improve efficiency. The selected thickness is optimal for maintaining performance while being structurally sound.

Feeding Technique: Microstrip Line Feed
The antenna uses a Microstrip Line Feed technique, which is straightforward to implement and allows easy integration with other circuit components. This technique provides a good impedance match and low insertion loss, which are essential for maintaining signal quality. Additionally, the microstrip line feed offers flexibility in adjusting the feeding position, which can be fine-tuned to minimize return loss.

Ground Plane Size: 70 mm x 70 mm
The ground plane dimensions are set to 70 mm x 70 mm. A sufficiently large ground plane is necessary to support proper radiation characteristics and reduce back radiation. The selected size ensures a stable radiation pattern and consistent gain while maintaining the compactness required for practical applications.

5.2 Radius (a) of the patch:

Following formula is used for calculating the effective radius:

$$a = \frac{F}{\sqrt{1 + \frac{2h}{\pi a \epsilon_r}\left(\ln\left(\frac{\pi a}{2h}\right) + 1.7726\right)}}$$

where:

$$F = \frac{8.791 \times 10^9}{f_0\sqrt{\epsilon_r}}$$

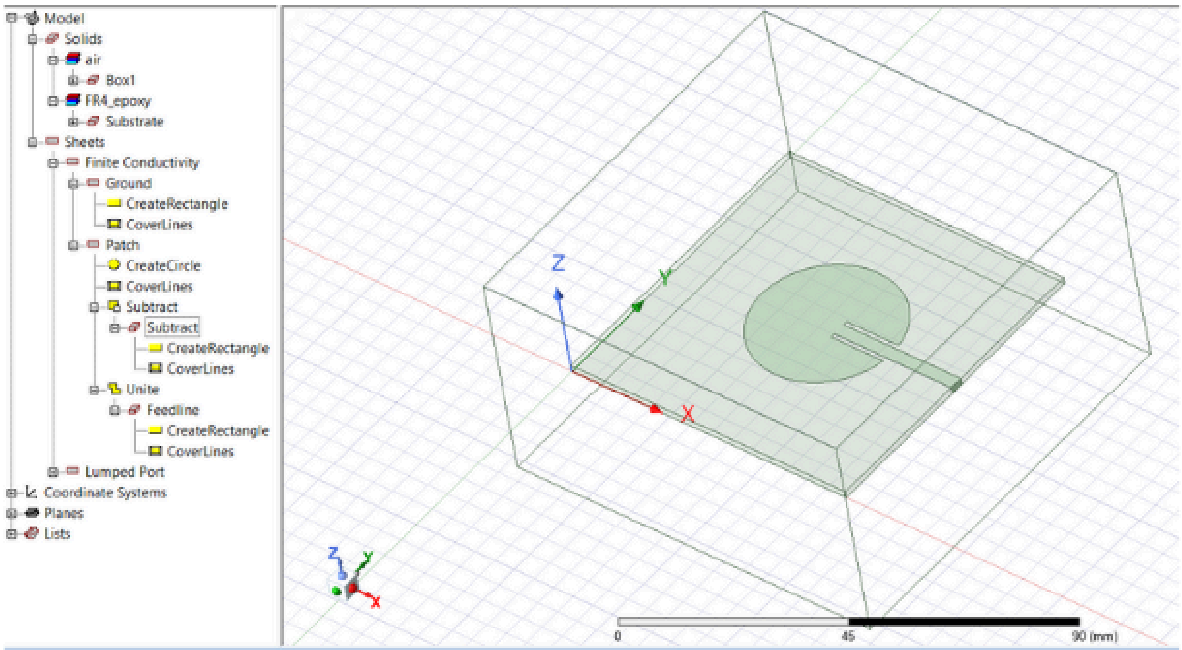
5.3 Feed Mechanism:

The feed mechanism in a circular antenna plays a crucial role in determining how power is delivered to the radiating patch, directly impacting impedance matching, bandwidth, and radiation efficiency. Common feeding techniques include the microstrip line feed, where a conducting strip connects directly to the patch, offering simplicity and ease of fabrication. The coaxial probe feed uses an inner conductor of a coaxial cable inserted through the substrate to the patch, allowing better control of impedance matching. The aperture-coupled feed separates the feed line from the patch using a ground plane with a slot, enhancing bandwidth and reducing spurious radiation. Lastly, the proximity-coupled feed uses two dielectric layers, providing high bandwidth but with increased design complexity. The choice of feed mechanism depends on the design goals, such as compactness, ease of fabrication, and desired frequency response.

5.4 Impedance Matching:

Ensure the input impedance matches the system impedance (usually 50 ohms) to minimize reflection losses. Adjust the feed point position to achieve this.

5.5 Final Design On HFSS

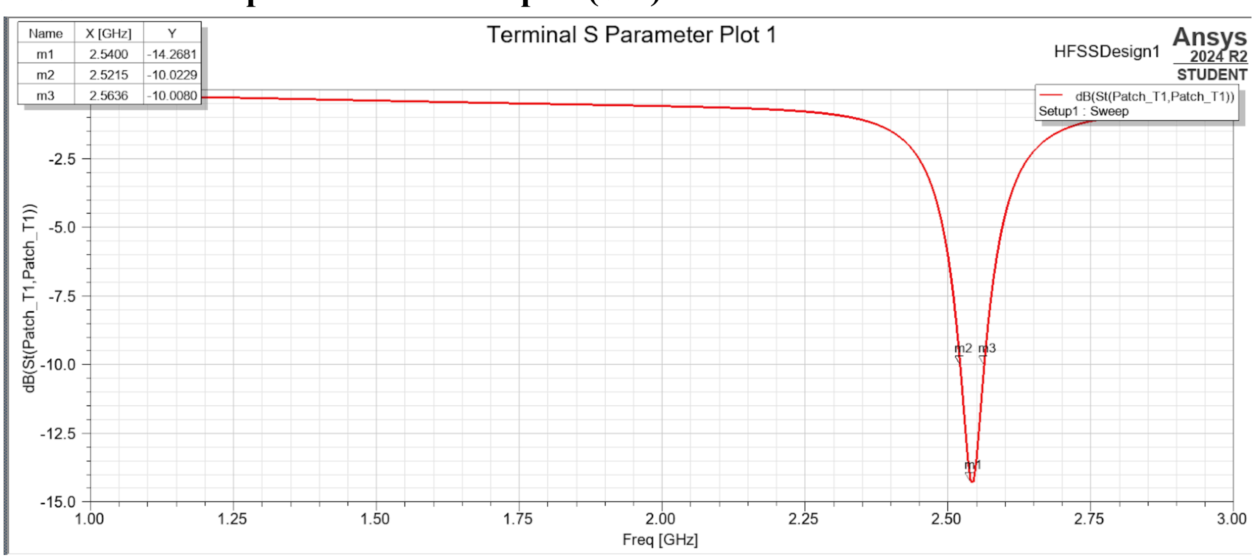


6. Results-

6.0 Design Parameters:

Circular microstrip patch antenna designed for 2.45 GHz with a 1.6 mm substrate height and dielectric constant of 4.4.

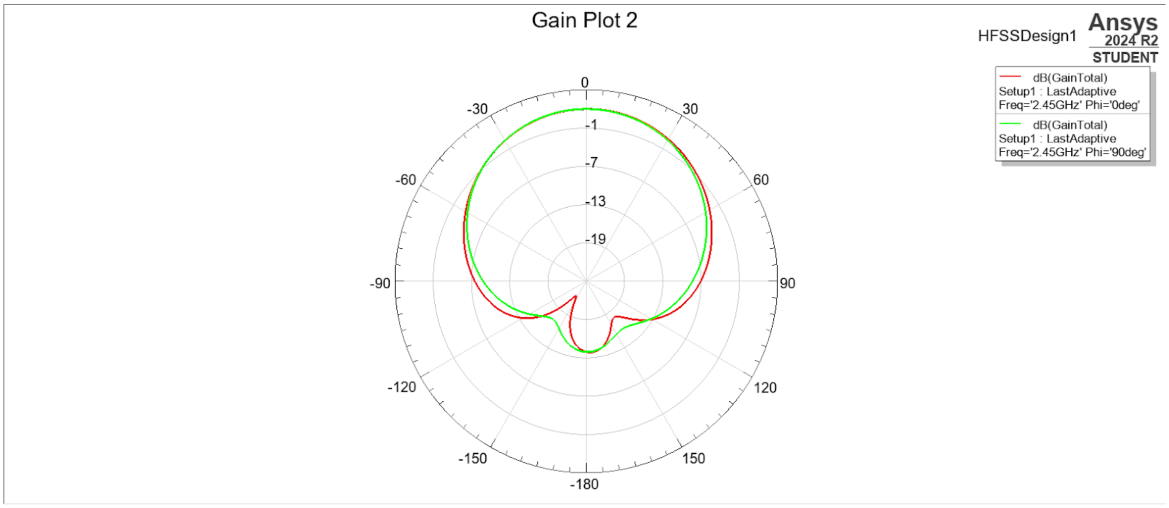
6.1 S Parameter plot or return loss plot (S11):



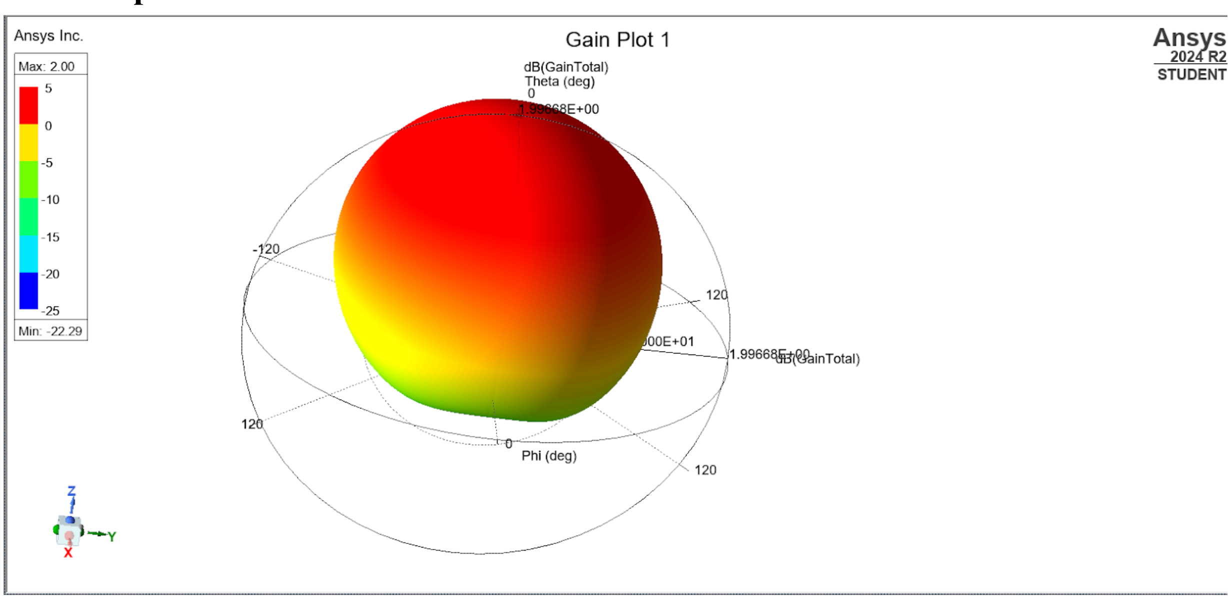
Minimum return loss: -14.2681 dB at 2.54 GHz (slightly shifted from 2.45 GHz).

Bandwidth: 42.1 MHz (from 2.5215 GHz to 2.5636 GHz, where S11 < -10 dB).

6.2 Gain plot 2D:



7.3 Gain plot 3D:



Maximum gain: 2.00 dBi.

Minimum gain: -22.29 dBi.

8.0 Defected Ground Structure (DGS) in Antenna Design

Defected Ground Structure (DGS) refers to the deliberate introduction of cuts, slots, or specific shapes into the ground plane of a microstrip or planar antenna. These intentional defects alter the current distribution and electromagnetic fields within the ground plane, resulting in modified signal propagation characteristics. By strategically designing and positioning these defects, DGS enables significant improvements in antenna performance, including bandwidth enhancement, size reduction, gain improvement, and radiation pattern control.

One of the primary advantages of incorporating DGS into antenna design is the enhancement of bandwidth. By introducing defects in the ground plane, the effective capacitance and inductance of the antenna system can be adjusted, leading to a wider operating bandwidth. Additionally, DGS facilitates size reduction, allowing the antenna to be more compact while maintaining its performance, which is particularly beneficial in modern communication devices where space is a critical factor.

Another notable benefit of DGS is the improvement in antenna gain. The altered current distribution can result in more focused radiation patterns, thereby increasing the effective gain of the antenna. Moreover, DGS can help control the radiation pattern by manipulating the surface current paths, which improves the directivity of the antenna. Furthermore, DGS effectively suppresses surface waves that typically degrade antenna efficiency and performance, ensuring that the radiated power is efficiently directed.

8.1 Types of Defected Ground Structure (DGS)

Defected Ground Structures (DGS) come in various shapes and configurations, each offering unique characteristics and performance enhancements when incorporated into antenna designs. The choice of DGS type largely depends on the desired antenna characteristics, such as bandwidth, size reduction, or frequency response. Below are some of the most commonly used types of DGS:

One of the most widely used DGS types is the Dumbbell-shaped DGS, characterized by two square or circular slots connected by a narrow slot, resembling a dumbbell. This structure is particularly effective in creating slow-wave structures and stopband filtering while also contributing to size reduction. The dumbbell-shaped DGS is advantageous due to its high-quality factor and effective suppression of surface waves, which improves the overall radiation efficiency and reduces interference.

Another common category includes Circular, Rectangular, and Triangular Slots, which are simple geometric shapes etched into the ground plane. These shapes are especially prevalent in microstrip patch antennas to enhance bandwidth and improve impedance matching. Their simple design and ease of integration make them versatile, and the effects they produce can vary significantly based on their specific geometric characteristics.

The Spiral or Meander-shaped DGS is another interesting variant, characterized by spiral or serpentine slots that effectively increase the current path length. These configurations are particularly useful for compact antenna designs, as they facilitate miniaturization while also functioning as slow-wave structures. Due to their ability to create multiband responses, spiral and meander-shaped DGS structures are often used in compact, multifunctional antennas.

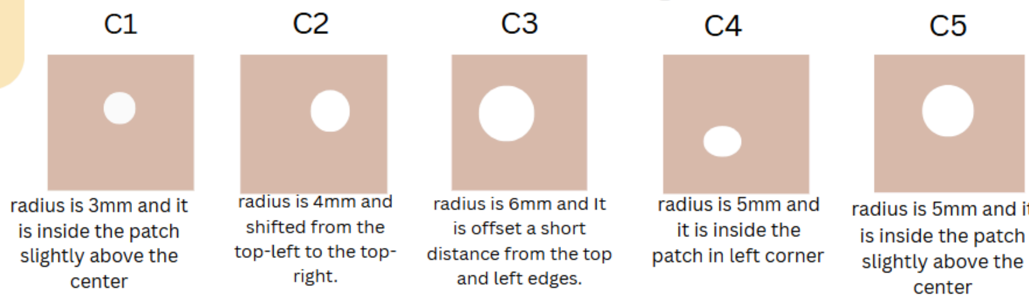
Lastly, the U-shaped or H-shaped DGS features U or H-shaped slots, which are beneficial for achieving multiple resonances. These designs are especially useful in filter applications and in dual or multiband antenna designs. The unique structure of these defects supports complex frequency responses while also enhancing isolation between antenna elements, which is crucial in applications requiring multi-frequency operations.

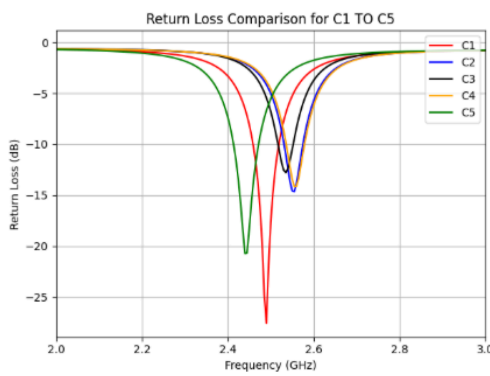
8.2 Working of Defected Ground Structure (DGS):

1. Defected Ground Structures (DGS) function by intentionally altering the current distribution and electromagnetic fields within the ground plane of microstrip circuits or antennas. This is achieved by etching specific shapes, such as dumbbell, circular, rectangular, or other geometric patterns, into the ground plane located beneath the transmission line or patch. The introduction of these slots effectively disrupts the uniform current flow, creating localized changes in inductance and capacitance.
2. The presence of a defect in the ground plane behaves like an LC resonator, combining inductive and capacitive effects. This characteristic leads to resonance at specific frequencies, thereby modifying the impedance characteristics of the antenna. As a result, the antenna exhibits unique frequency responses that can be controlled and fine-tuned by varying the shape and dimensions of the DGS.
3. One of the most significant effects introduced by DGS is the slow-wave effect, where the propagation of waves through the antenna is slowed down due to the altered current path. This phenomenon not only enables a more compact antenna design but also contributes to size reduction without compromising performance.

4. Furthermore, the ability to control the frequency characteristics makes DGS highly versatile in antenna design. By adjusting the size, shape, and placement of the defect, designers can manipulate the stopbands, enhance impedance matching, and precisely control the bandwidth. This flexibility makes DGS a powerful technique for optimizing the performance of microstrip antennas, especially when aiming to achieve compact, efficient, and multi-frequency designs.

Circular DGS design

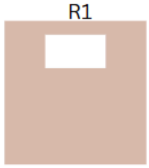




Variation	Gain	Return Loss	Frequency
C1	2.73db	-27.37db	2.49Ghz
C2	2.42db	-13.7db	2.52Ghz
C3	2.00db	-14.65db	2.55Ghz
C4	2.13db	-12.7db	2.53Ghz
C5	3db	-20.67db	2.44Ghz

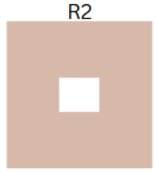
Rectangle DGS design

R1



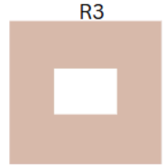
Rectangle with L:20 & W:10 cut from the ground within the patch radius

R2



Rectangle with L:10 & W:12 cut from the ground within the patch radius

R3



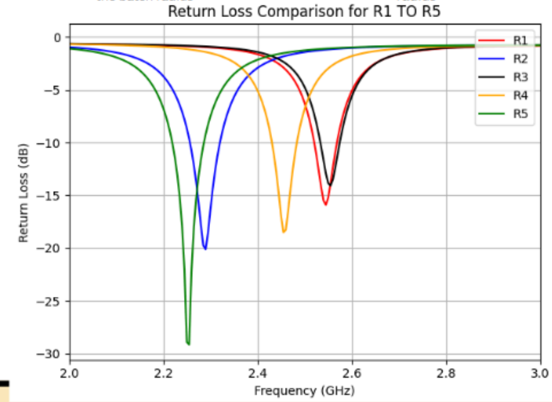
Rectangle with L:12 & W:15 cut from the ground within the patch radius

R4

Rectangle with L:10 & W:5 cut from the ground within the patch radius

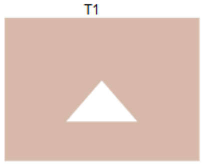
Variation	Return Loss	Gain	Frequency
R1	-16.49 db	2	2.54Ghz
R2	-20.10db	1.44	2.29Ghz
R3	-14.07db	1.85	2.55Ghz
R4	-18.49db	2.93	2.45Ghz
R5	-29.65db	1.05	2.25Ghz

Return Loss Comparison for R1 TO R5



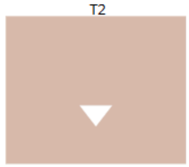
Triangular DGS design

T1



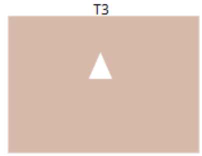
equilateral triangle cut from the ground within the patch radius

T2



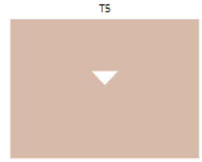
triangle cut from the ground within the patch radius on the feedline

T3



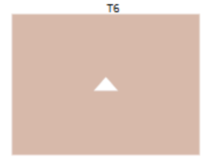
elongated triangle cut from the ground within the patch radius on the edges of the patch

T5



euilateral triangle cut from the ground within the patch radius at the centre pointing towards feedline

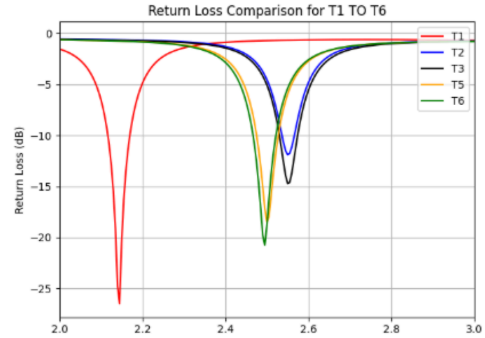
T6



euilateral triangle cut from the ground within the patch radius at the centre pointing against feedline

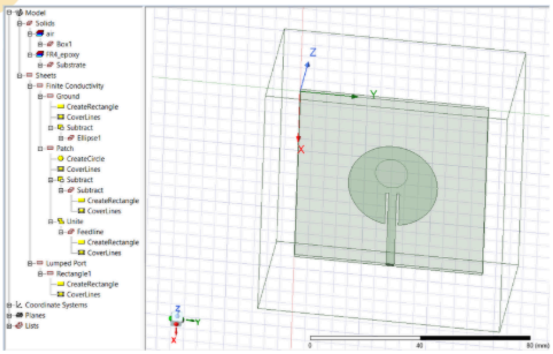
Variation	Return Loss	Gain	frequency
T2	-11.90db	2	2.55 Ghz
T1	-26.48db	**2**	2.14Ghz
T3	-12.65db at	2.11	2.54 Ghz
T5	-18.49db at	2.65	2.5Ghz
T6	-20.75db at	2.62	2.49Ghz

Return Loss Comparison for T1 TO T6

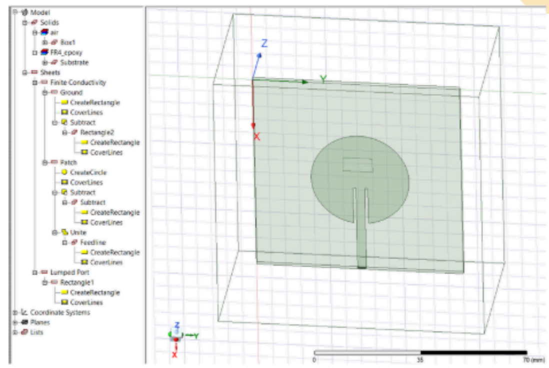


FINAL DESIGN

DESIGN 1



DESIGN 2



Results of original design:

Return loss = -14.26 dB

Frequency = 2.54 GHz

Bandwidth =2.5636 - 2.5215 = 42.1 MHz

Gain = 2.00 dB

Results for Design 1:

Return loss = -20.67 dB

Frequency = 2.44 GHz

Bandwidth = 2.4717 - 2.4135 = 58.2 MHz

Gain = 3.00 dB

Results for design 2:

Return loss = -18.5 dB

Frequency = 2.45 GHz

Bandwidth = 2.4835 - 2.4307 = 52.8 MHz

Gain = 2.93 dB

Conclusion :

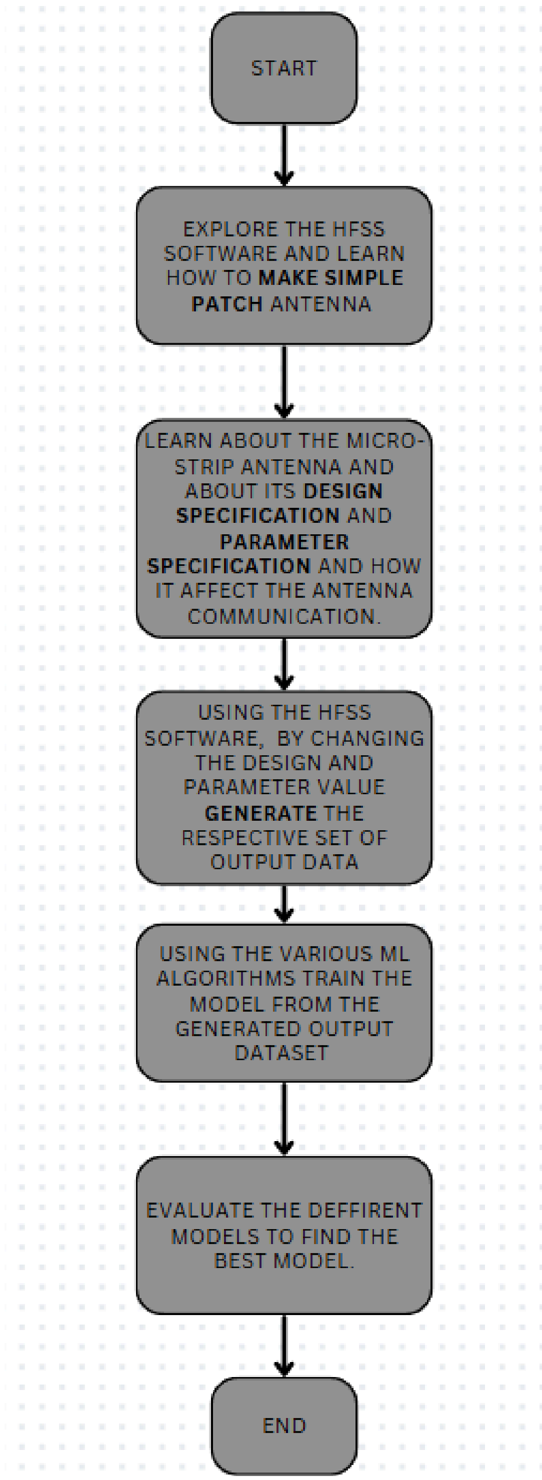
- Designed and simulated a circular patch antenna at 2.45 GHz
- Achieved good return loss, bandwidth, and gain by using DGS
- DGS leads to compact, high-performance antenna design.

Future Work :

- Now we are ready for data set generation and apply this dataset on machine learning algorithms.

8. Flow Diagram:

The block diagram of the project consists of the following components:



9. Innovative Component in the Project:

The innovative component of the project lies in the integration of machine learning into the traditionally manual and simulation-heavy process of antenna design. By using advanced ML techniques, such as reinforcement learning and neural networks, the project automates and accelerates the optimization process while improving the design's accuracy. Additionally, the real-time optimization capabilities will be a significant innovation, allowing engineers to quickly adapt antenna designs for varying specifications.

10. Month-wise Plan for the Execution of the Project:

- **Month 1:** Research and literature review on antenna design, machine learning algorithms, and optimization techniques.
- **Month 2:** Familiarize yourself with existing tools and resources & Design a circular patch antenna using HFSS software.
- **Month 3:**Start data collection and preprocessing. Gather antenna design data and define performance metrics.
- **Month 4:** Develop machine learning models for antenna design prediction. Start training models with data.
- **Month 5:** Simulate antenna designs and validate the optimized models. Fine-tune the machine learning model.
- **Month 6:** Final testing of optimized designs. Analyze results, write reports, and prepare for project submission.

9. Reference Papers/Patent:

1. Singh, O., Bharamagoudra, M. R., Gupta, H., Dwivedi, A. K., Ranjan, P., & Sharma, A. (2022). Microstrip line fed dielectric resonator antenna optimization using machine learning algorithms. *Sādhanā*, 47, Article 226. Retrieved from https://link.springer.com/article/10.1007/s12046-022-01989-x

2. Tiwari, R., Sharma, R., & Dubey, R. (2022). Microstrip Patch Antenna Parameter Optimization Prediction Model using Machine Learning Techniques. *International Journal on Recent and Innovation Trends in Computing and Communication*, 10(9), 53-58. Retrieved from https://www.researchgate.net/publication/364245259_Microstrip_Patch_Antenna_Parameter_

Optimization_Prediction_Model_using_Machine_Learning_Techniques

3. Kurniawati, N., & Zulkifli, F. Y. (2021). Predicting Rectangular Patch Microstrip Antenna Dimension Using Machine Learning. *Proceedings of the 2021 International Conference on Artificial Intelligence and Robotics for Industrial Applications (AIRIA)*, 1-6. Retrieved from https://www.researchgate.net/publication/354436732_Predicting_Rectangular_Patch_Microstrip_Antenna_Dimension_Using_Machine_Learning

4. Jankowski-Mihułowicz, P., & Bednarczyk, M. (2020). Designing a compact microstrip antenna using the machine learning approach. *Journal of Telecommunications and Information Technology*, 3, 45-51. Retrieved from https://www.jtit.pl/jtit/article/view/527

5. Kumar, A., & Singh, G. (2021). Efficient modelling of compact microstrip antenna using machine learning. *AEU - International Journal of Electronics and Communications*, 131, 153612. Retrieved from https://www.sciencedirect.com/science/article/pii/S1434841121001369
6. El Misilmani, H. M., & Naous, T. (2019). Machine Learning in Antenna Design: An Overview on Machine Learning Concept and Algorithms. 2019 International Conference on High Performance Computing & Simulation (HPCS).
7. Koziel, S., Pietrenko-Dabrowska, A., & Leifsson, L. (2024). Antenna Optimization Using Machine Learning with Reduced-Dimensionality Surrogates. Retrieved from https://www.nature.com/articles/s41598-024-72478-w.
8. Maind, S., & Wankar, P. (2014). Research Paper on Basics of Artificial Neural Network. International Journal on Recent and Innovation Trends in Computing and Communication.
9. Rokach, L. (2014). Random Forests: From Early Developments to Recent Advancements. Tandfonline. Retrieved from https://www.tandfonline.com/doi/full/10.1080/21642583.2014.956265.
10. Degachi, R., & Ghendir, S. (2024). Comparative Analysis of Machine Learning Models to Predict Rectangular Patch Antenna Dimensions. Retrieved from https://jart.icat.unam.mx/index.php/jart/article/view/2478/1170.
11. Mikki, S. M., & Kishk, A. A. (2020). Antenna Design Exploration and Optimization Using Machine Learning. Retrieved from https://ieeexplore.ieee.org/document/9135530/.
12. Khan, U. R., Sheikh, J. A., Junaid, A., Ashraf, S., & Balkhi, A. A. (2025). A Machine Learning Driven Computationally Efficient Horse-Shoe Shaped Antenna Design for Internet of Medical Things. Retrieved from https://journals.plos.org/plosone/article?id=10.1371/journal.pone.0305203.
13. Ghayoula, E., Ghayoula, R., Fattahi, J., Pricop, E., Chouinard, J. Y., & Bouallegue, A. (2017). Radiation Pattern Synthesis Using Hybrid Fourier-Woodward-Lawson-Neural Networks for Reliable MIMO Antenna Systems. Retrieved from https://ieeexplore.ieee.org/abstract/document/8123136/authors.

14. Zhong, Y., Renner, P., Dou, W., Ye, G., Zhu, J., & Liu, Q. H. (2022). A Machine Learning Generative Method for Automating Antenna Design and Optimization. Retrieved from https://ieeexplore.ieee.org/abstract/document/9906451/authors#authors.
15. Misilmani, M., Naous, R., Al-Husseini, M., & Kabalan, K. Y. (2020). Machine Learning in Antenna Design: An Overview on Machine Learning Concept and Algorithms. *2020 International Conference on High Performance Computing & Simulation (HPCS)*. Retrieved from https://ieeexplore.ieee.org/document/9188224

16. Zhong, Y., Renner, P., Dou, W., Ye, G., Zhu, J., & Liu, Q. H. (2022). A Machine Learning Generative Method for Automating Antenna Design and Optimization. *arXiv preprint arXiv:2203.11698*. Retrieved from https://arxiv.org/abs/2203.11698

17. Wu, Q., Chen, W., Yu, C., Wang, H., & Hong, W. (2022). Machine-Learning-Assisted Optimization for Antenna Geometry Design. *IEEE Transactions on Antennas and Propagation*, 70(7), 6136-6147. Retrieved from https://ieeexplore.ieee.org/document/9770664

GROUP MEMBERS-

1.Ameya Bahadure

2.Rishi Thakre

3.Tushar Sanodiya

4.Komal Patle

Prof . Archana Tiwari
PROJECT GUIDE