Compact and Efficient modelling of Wideband Semi-Circled U-slot Microstrip Patch Antenna using ML

[1]**Guttula Venkataramana**, [2]**Srinu Injeti**, [3]**Ravi Sankar Ponnada**,

[1]Assistant Professor, Department of ECE, V S M College of Engineering, Ramachandrapuram, A.P

[2]Assistant Professor, Department of EEE, V S M College of Engineering, Ramachandrapuram, A.P

[3]Assistant Professor, Department of ECE, Pragati Engineering College, Kakinada Dt, A.P

[1]guramana417@gmail.com, [2]sreenuinjeti@gmail.com, [3]ravisankar.p@pragati.ac.in

Abstract:

The main objective of this work is to design an efficient wideband Semi-circled U-slot loaded antenna using Machine Learning (ML) algorithm. The proposed concept is for predicting the resonance frequency of the U-slot loaded antenna by providing the dimensions of the antennas. Antenna is designed for WiMAX application with operating frequency band in the range between 0.4856–7.8476 GHz. The HFSS tool is being used for designing and analysing fractal antennas and generating the training data. Parametric analysis of the designed U-slot-loaded half circled antenna is developed by altering the half-circle radius, length of the U-slot and width. The data set is then given to the ANN back-propagation ML algorithm for training the model. The ANN back-propagation contains remarkably high processing speed and contains features like parallelization, cache optimization, and out-of-core computation which makes the perfect algorithm for predicting the resonance frequencies. U-slot loaded half circled antenna offers a substantial size reduction, a wide impedance bandwidth, and a uniform radiation pattern on all sides.

Keywords: Machine Learning, Semi-circled, resonance frequency, Microstrip Patch Antenna, Gaussian process, Synthesis.

1. Introduction

Full-wave electromagnetic simulation software has become an important tool for antenna design, however, its high-fidelity simulation is very expensive. Therefore, the use of electromagnetic simulation solvers for antenna optimization design may be limited due to their high computational cost. To solve this problem, fast and accurate machine learning (ML) surrogate models can be utilized. ML can learn features from input data and give prediction results. Up to now, many algorithms have been applied to modelling microwave devices, such as Gaussian process (GP), support vector machines (SVM), deep learning (DL) etc. Machine learning has significantly advanced the field of microwave research, particularly in the areas of modelling, simulation, and optimization. Notably, the work by Naser-Moghaddasi et al. [5] demonstrated the application of heuristic artificial neural networks to analyze and synthesize the performance characteristics of rectangular microstrip antennas. Their approach highlighted the potential of neural networks to predict antenna behaviour effectively, thereby streamlining the design process. Building upon such foundational studies, this paper extends the use of machine learning to model a broader range of transmission line characteristics. Specifically, we expand the application of machine learning models to include various types of transmission lines such as Microstrip, Slotline, Stripline, Co-Planar Waveguide (CPW), Co-Planar Strip (CPS), and Microstrip Patch Antenna, employing both Linear Regression and advanced Neural Networks.

2. Literature Survey

A microstrip antenna is made up of three layers: patch, dielectric (RT- duroid), and ground. The length of the patch, the dielectric constant, and the slot width were the variables utilised to determine the resonant frequency. Inverse correlation exists between length and resonance frequency [1].The fact that microstrip patch antennas have a U-shaped slot and have a reasonably high resistance (about 30%) is well known. Explains how coupled-mode theory affects the behaviour of a typical U-slot patch shape using characteristic mode analysis [2]. Modern wireless communication systems use ultra-wide-band (UWB) technology because of its advantages in reducing complexity and size. Miniaturised antennas were developed because a multi-hit notch frequency band was required to prevent interference with other narrowband communication systems [3]. A common type of antenna with a particular chip design on one side is a microstrip antenna. One of the most widely used patch antennas is the rectangular one [4]. The antenna's primary function is to absorb frequencies between 3.1 and 10.6 GHz while rejecting frequencies in the C-band and Wi-Fi band. It was made using a copper-etched PCB with a certain chip shape to prevent interference. The Descartes Circle (DC) theorem and iterations of self-similar design were used to produce the circular shape antenna [5], [6]. Techniques for machine learning (ML) include reinforcement, unsupervised, and supervised learning. The difficulty of establishing a relationship between geometric parameters grows with the number of parameters [7], [8]. The 2.4GHz frequency band, which has a resonance frequency in the antenna, is the one used by Wi-Fi. ML seeks to shorten the time required for antenna design by obtaining high precision and making accurate predictions of antenna performance [9]. The suggested antenna was created using a hybrid technique in CST Microwave Studio [10]. A stack patch antenna's dimensions also take into account how far apart the two patches are from one another. The ANN algorithm builds a black-box model for resonance frequency using these inputs [11], [12]. An equilateral triangle-shaped microstrip antenna with a poor ground structure must meet certain design criteria, including patch length and triangle side. This antenna is trained using the Gaussian Process Regression (GPR) algorithm, which outperforms the Artificial Neural Network (ANN) approach [13]. For a UHF U-slot RFID antenna's return loss, an ML algorithm made a prediction. operational resonance frequency. Several ML methods were used for complicated and linear scattering characteristics to measure the models' prediction ability. RFID antenna was built using Antenna Magus. Polynomial regression, random forest, Bayesian ridge, and gradient boosting estimate linear scattering parameters [14], [15].

3. Antenna Design using Machine Learning:

Antennas become a most favourable class of antennas to build an advanced device for communication systems, due to their notable merits such as cost-effective, easy fabrication, compactness, conformable, and adequate gain. The machine learning techniques speed up the design process of an antenna by providing high accuracy, minimum error, less execution time, accurate prediction of the antenna operation, good computational efficiency, and minimum number of required simulations.

Below steps are involved in the process of antenna optimization using machine learning:

1. Data collection: The first step is to collect data on the performance of the antenna. This can be done through simulations or measurements of the antenna's radiation pattern, gain, and other relevant metrics.

2. Feature extraction: The data collected in step 1 is then processed to extract relevant features that describe the antenna's performance. These features can include parameters such as frequency, bandwidth, and polarization.

3. Model training: Once the features have been extracted, a machine learning algorithm is trained on the data to learn the relationship between the antenna parameters and the performance metrics.

4. Optimization: With a trained machine learning model, the antenna design can be optimized by using the model to predict the performance of different antenna configurations. The optimization process typically involves exploring the design space using techniques such as genetic algorithms or reinforcement learning.

5. Validation: Finally, the optimized antenna design is validated using simulations or measurements to ensure that it meets the desired performance metrics.

The antenna optimization using machine learning algorithms provides a powerful tool for engineers to design and optimize antennas with improved performance characteristics.

Antenna Geometry: A microstrip antenna is composed of essential elements including the patch, substrate, ground plane, feedline, and optionally a matching network as shown in Figure 1. The patch, typically constructed from metal, is positioned on top of a dielectric substrate, with the ground plane situated beneath it. The feedline links the patch to the transmitter or receiver. Optionally, a matching network can be incorporated to enhance impedance matching.

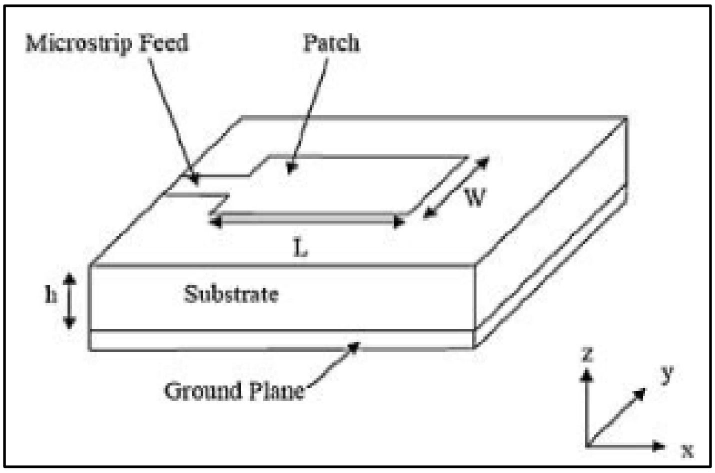

Figure 1: Microstrip antenna

The structure of the antenna governs its radiation pattern, impedance characteristics, and bandwidth. Through meticulous design of these components, microstrip antennas can effectively transmitter receive electromagnetic waves across designated frequency spectrums, catering to diverse application needs. The process of designing microstrip antennas using Ansys HFSS, encompasses several crucial stages. It starts by creating elements such as the patch, ground substrate, and radiation box, followed by conducting simulations with frequency sweeping. The procedure entails initial geometry setup and material property specification, along with defining excitation sources and meshing the structure. Simulation parameters are configured, and analyses are performed to evaluate antenna performance, including factors like return loss and radiation pattern. Optimization methods may be utilized to enhance performance, and post-simulation tools aid in result analysis. Ultimately, the design undergoes validation and refinement as needed. Ansys HFSS offers a comprehensive platform for microstrip antenna design and optimization across various applications.

The radiation effectiveness, impedance matching, and reflection coefficient of existing antennas can also be assessed using HFSS. Antenna optimisation and troubleshooting will be simple with this. Here is a picture of the proposed U-slot loaded half-circle microstrip patch antenna. Figure 2

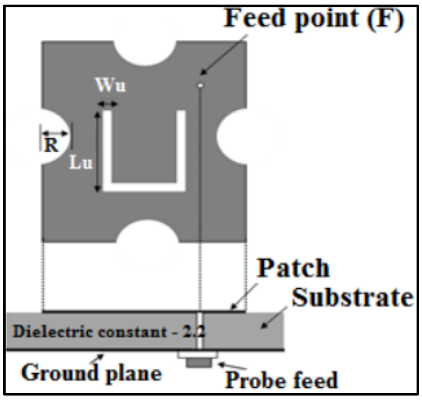

Figure 2: Proposed patch antenna design

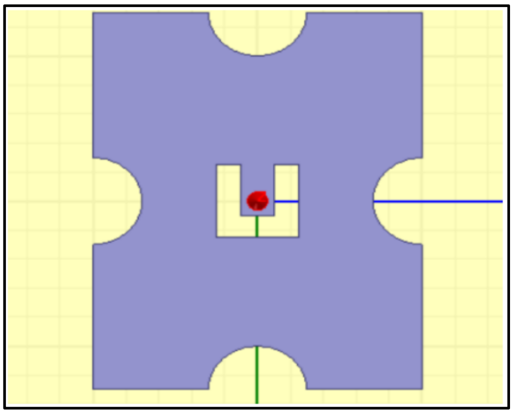

Figure 3: U-slot loaded semi-circle design in HFSS software

Design of of U-slot Loaded semi-Circle Patch Antenna:

The antenna has a resonance frequency of wide range is built using HFSS software as a U-Slot loaded Half-circled Patch Antenna with coaxial feed. The length and breadth of the U-slot, the radius of the half-circles, the length and width of the patch, and the length of the coaxial feed are all elements in the antenna design. These parameters are listed in Table 1. The frequency, emission pattern, and other characteristics of the antenna are controlled by these factors. The substrate of the antenna is fabricated from a base material with dielectric properties, such as RT-Duroid. based on the ground plane and patch's measurements, the material is divided into a particular dimension and form. The substrate is then positioned below the ground plane, which is formed of copper material and has the same dimensions as the substrate. The patch is then attached to the substrate using copper material after being measured according to the specified operating frequency. The Uslot in the patch is then created by shrinking the patch to a specific shape and dimension dependent on its length and width. The recommended antenna length is selected using equation 1.

$$f = \frac{c}{2L\sqrt{\varepsilon_r}} \quad \text{...} (1)$$

Where f = Resonating frequency of the antenna L = Electrical length of the patch εr = Relative permittivity of the substrate c = Velocity of the Light The antenna's frequency will be raised and its emission characteristics will be strengthened thanks to the U-slot. The signal travels through the coaxial feed from the ground plane to the patch and is then transferred to the antenna. The length of the coaxial input is another important component that has an impact on the antenna's resistance and effectiveness.

Table 1: Microstrip Patch Antenna Design Parameters

SL. NO	Name of the Parameter	VALUE	UNIT
1	Length of U-Slot	5	mm
2	Width of U-Slot	1.5	mm
3	Radius of half circle	3	mm
4	Length of Patch	26	mm
5	Width of Patch	20	mm
6	Length of Co-axial feed	4	mm

After the simulation has started, there will be some downtime. Check the simulation results to see if they meet the performance criteria, including those for S parameters, radiation pattern, and efficiency. We must change the patch and U-size slots in order to enhance the design and get the necessary performance. When attaching an antenna to a coaxial feed, the antenna's design is crucial to ensuring that the feed and antenna are properly matched. Additional potential fixes include adjusting the feed's position and size as well as the matching network's elements, like the quarter-wave transformer.

Synthesis and Analysis Problem for Microstrip Patch Antenna Using ANN:

ANN is one of the approaches used in ML to map nonlinear data efficiently based on experience (training),

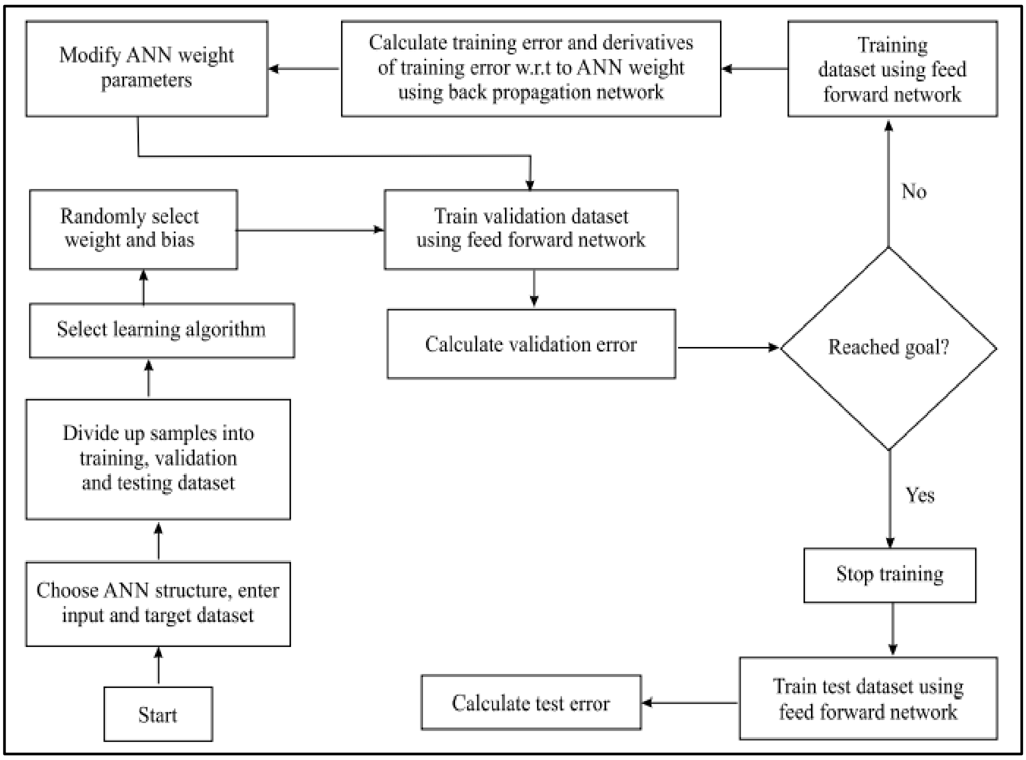

Figure 4: Flowchart of ANN back-propagation algorithm.

while dealing with new data. Basically, three logic layers are distinguished in ANN architectures. The first is known as the input layer, while the last is referred to as the output layer. Between the input and the output layer, there is a number of hidden layers. Each hidden layer has one or more neurons. The number of the hidden layers, neurons, the activation function and the learning algorithm are all specific to the application. There are no rules to determine the number of hidden layers and neurons, but in most problems two to three hidden layers are used at the most in order to approximate all types of mathematical functions. The performance of ANN model depends upon the data collection, learning algorithm, weight initialization, change in an activation function, etc. In the case of antenna design, data should be collected either through simulations or measurements. The range of data always extends, marginally, beyond the model's utilization range [38]. Initially, data samples are divided into three sets, known as training (with the usage ratio of 70%), testing (15%), and validation (15%). According to the needs of a specific application, the percentages may be different. Next, the network size is chosen, i.e. the number of hidden layers and neurons in each of them is determined. Finally, the algorithm is selected based on feed-forward, back propagation, and feed-forward back propagation, to train the ANN and obtain the model. A flowchart of ANN feed-forward back-propagation algorithms is presented in Figure 4. To achieve the minimum mean squared error (MSE) It is necessary to train the model with accurate data. In this case, a total of 80 samples has been collected by simulating H-shaped RMSA using IE3D software. To minimize MSE, different ANN algorithms have been tested by varying the number of hidden layers and neurons in each hidden layer. Finally, the best combination for the proposed model was selected. To train the ANN model, highly accuracy.

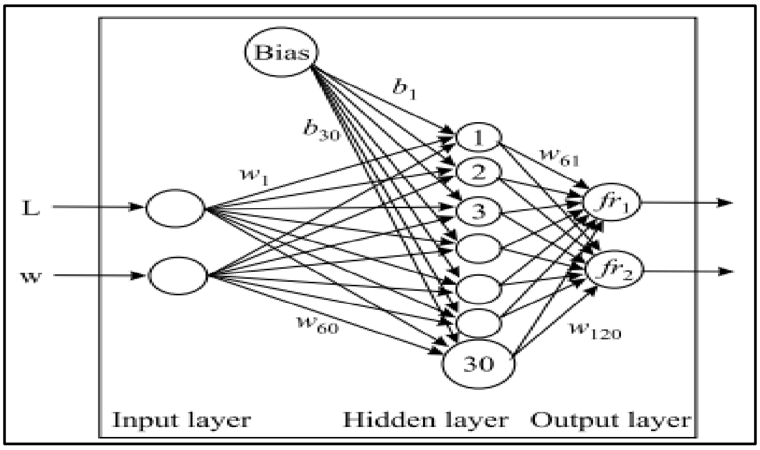

Figure 5: Proposed ANN model for the analysis of compact H-shaped RMSA.

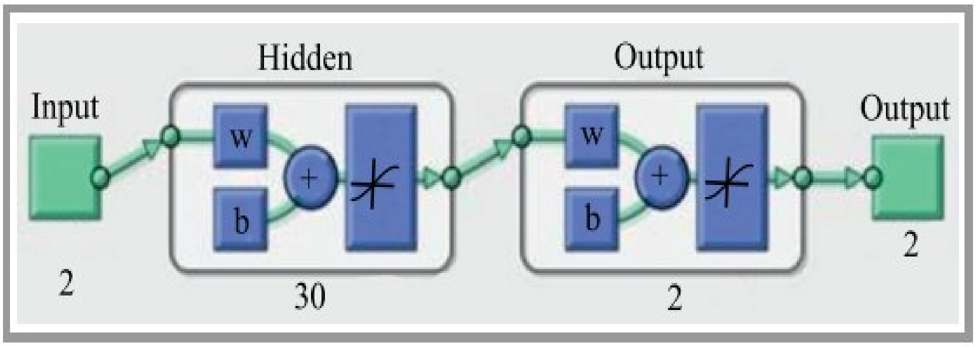

Figure 6: ANN network architecture to train physical-to-electrical parameter.

rate back propagation algorithms with minimum MSE were used [9]. Figure 5 shows a detailed architecture of the hidden layer of the proposed ANN model which uses the train set and predicts the dual resonant frequencies (fr1, fr2), as well as the physical aerial parameters, i.e. slot length (L) and width (W) as input values. The Levenberg-Marquardt (LM) back propagation algorithm is used as ANN. ANN network architecture is shown in Figure 6 with two input and output parameters, one hidden layer and 30 neurons.

4. Results:

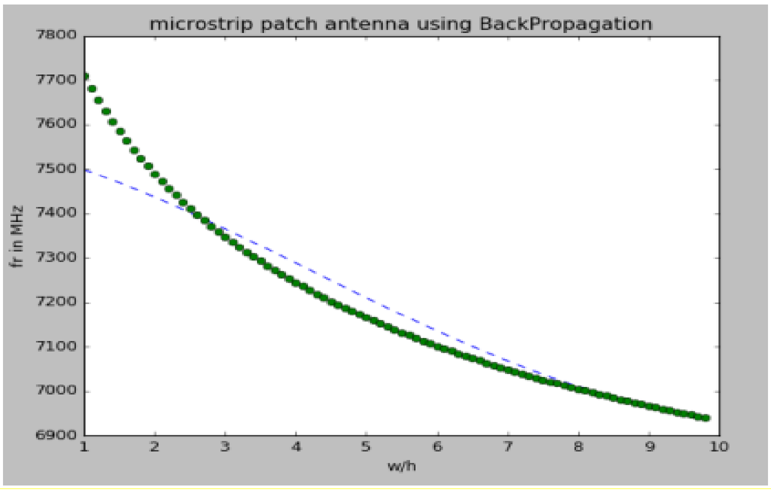

Figure 7: Impedance Vs. w/h for Patch using neural networks

Above screen shot sown in figure7 captured in HFSS which represents impedance and w/h ratio for patch antenna using proposed neural networks.

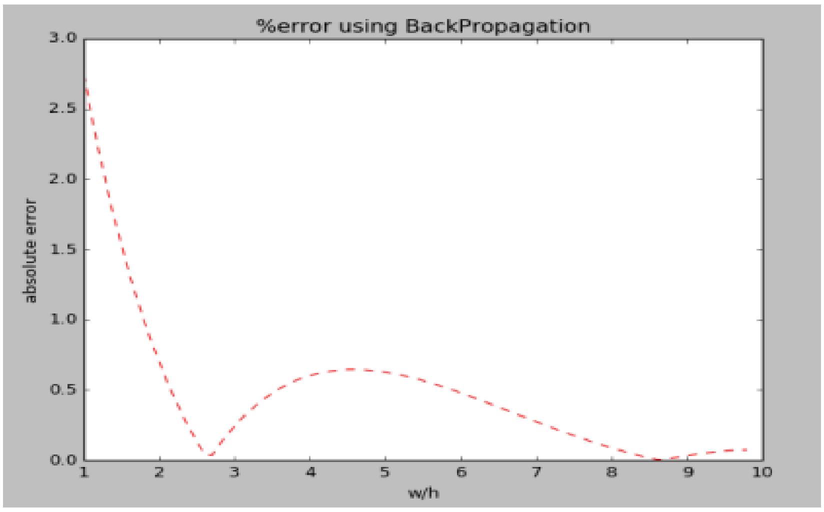

Figure 8: Absolute Error Vs. w/h for Patch using neural networks

Above screen shot sown in figure8 captured in HFSS which represents Absolute Error and w/h ratio for patch antenna using proposed neural networks.

This study has systematically investigated various neural modelling techniques for predicting the characteristics of transmission lines, specifically examining their applicability and accuracy compared to traditional computational methods. Our analysis utilized actual impedance and frequency measurements from microstrip lines to evaluate the performance of neural networks and linear regression algorithms.

Table 2: Frequency vs. w/h for Microstrip with Error Percentage

w/h	Fr in MHz (actual)	neural networks	Linear Regression	% Error (neural networks)	% Error (Linear Regression)
1.0	7710.557	7692.914	7529.473	0.229	2.349
1.5	7585.017	7593.029	7491.309	0.106	1.235
2.0	7489.211	7493.143	7453.145	0.053	0.482
2.5	7411.994	7397.386	7414.982	0.196	0.041
3.0	7347.491	7348.534	7376.518	0.309	0.399
3.5	7292.474	7298.629	7338.654	0.084	0.633
4.0	7244.707	7251.310	7300.490	0.091	0.770
4.5	7183.698	7204.505	7262.326	0.291	0.821
5.0	7165.336	7157.707	7242.162	0.106	0.821
5.5	7131.843	7123.441	7185.999	0.118	0.756
6.0	7101.594	7100.492	7147.835	0.014	0.651
6.5	7074.102	7077.537	7109.671	0.049	0.503
7.0	7048.982	7054.582	7107.507	0.081	0.320
7.5	7025.921	7031.627	7033.343	0.081	0.106
8.0	7004.661	7008.061	7059.510	0.010	0.400
8.5	6984.887	6985.717	6957.016	0.010	0.993
9.0	6966.719	6962.762	6918.852	0.057	0.687
9.5	6949.706	6939.807	6880.688	0.142	0.993

Conclusion:

Machine learning is one of the methods used to design antennas quickly. The proposed model is simple, time efficient and does not require any complex mathematical calculations. It may easily predict, with high accuracy, the physical or electrical parameters within the range of data provided for training, for a wide-band [0.4856–7.8476] GHz. compact microstrip antenna that may be used in a variety of wireless applications. This method offers several benefits, such as precise resonant frequency prediction, identification of crucial design factors, study of intricate relationships, and reduction of time and expense.

Future Scope:

Future Scope To further improve the model's accuracy, future research could focus on increasing the dataset size by automating the simulation process or leveraging advanced simulation techniques to generate more data efficiently. Additionally, exploring other machine learning algorithms and combining them with random forest regression might enhance prediction accuracy for parameters like return loss. Investigating feature engineering techniques to better capture the relationships between design parameters and performance metrics could also contribute to improved models. The effectiveness of machine learning practices in optimizing rectangular patch antennas is demonstrated in this paper. Established techniques are accurate but computationally intensive. Using the Random Forest Regressor algorithm, the process achieves optimized performance metrics, particularly frequency and return loss, against several design parameters. The reduced MSE for frequency predictions indicates enhanced design efficiency. Given modern communication systems' increased complexities and performance requirements, the future of ML-driven antenna design is promising. Expanding the dataset to cover more design parameters and performance metrics will further improve prediction accuracy and model robustness.

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