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Original scientific paper

MACHINE LEARNING ASSISTED OPTIMIZATION AND ITS APPLICATION TO HYBRID DIELECTRIC RESONATOR ANTENNA DESIGN

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Abstract. *Machine learning assisted optimization (MLAO) has become very important for improving the antenna design process because it consumes much less time than the traditional methods. These models' accountability can be checked by the accuracy metrics, which tell about the correctness of the predicted result. Machine learning (ML) methods, such as Gaussian Process Regression, Artificial Neural Networks (ANNs), and Support Vector Machine (SVM), are used to simulate the antenna model to predict the reflection coefficient faster. This paper presents the optimization of Hybrid Dielectric Resonator Antenna (DRA) using machine learning models. Several regression models are applied to the dataset for optimization, and the best results are obtained using a random forest regression model with the accuracy of 97%. Additionally, the effectiveness of machine learning based antenna design is demonstrated through comparison with conventional design methods.*

Key words: *Dielectric Resonator Antenna, Machine Learning, Gaussian Process Regression, ANNs, SVM*

1. INTRODUCTION

Antenna design optimization is a topic that has received a lot of attention in previous few years. That is because methodologies of conventional antenna design are comprehensive and do not have any guarantee of producing effective results because of the complications of the latest antennas fabrication and execution necessities [1]-[3]. Despite the fact that design automation via optimization goes with conventional approaches of antenna design, optimization of antenna designs has many problems [3]-[5]. The significant issues cover the

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efficiency and optimization capacity of accessible techniques to address a wide extent of antenna design issues thinking about the developing details of current antennas. The methods presented in this report can have an effect on the upcoming development of antennas for an abundance of applications. The frequencies which are in the microwave range of their measurements of current (I) and voltage (V) become very difficult [6]-[8].

At higher frequencies, we do not measure current or voltage. It is preferred to measure power. As it goes to higher microwave frequencies, it is hard to carry out the short circuit and open circuit for the AC signals over the broad bandwidth. To control this problem, at the microwave range, we use S parameters. S parameters are stated in terms of incident and reflected traveling waves. They are easy to use in the analysis. S parameters can simply be measured using network analyzers the acceptances of the use of such parameters have been growing rapidly [8]. S-parameters are a complex matrix that shows Reflection/Transmission characteristics (Phase/Amplitude) in the frequency domain. There are various parameters on which this parameter depends, such as Frequency Bandwidth, Return Loss and Radiation Pattern [9]-[11].

Some academics have concentrated on this issue and forecast antenna performance using various ML techniques in the open literature. Sharma et.al. suggested using LASSO (Least Absolute Shrinkage and Selection Operator), ANN, and KNN approaches to optimize a T-shaped monopole. To train the model at two separate frequency bands, 2.5 GHz and 5.5 GHz, 450 data set points were collected [12]. Gao et al. optimized the Yagi Uda, shaped printed antenna, and dual-mode printed antenna using the Gaussian process and support vector machines [13]. J. P. Jacobs suggested using ML techniques based on Gaussian Process Regression to optimize a U-shaped slot-loaded microstrip antenna. The aforementioned antenna is compatible with both 2.75 GHz and 3.75 GHz frequency bands [14].

This paper deals with hybrid antennas that combine passive and active architecture and its optimization using different machine learning techniques. Hybrid antennas are widely used antennas with important applications including radar display control systems for managing self-driving cars, or automated equipment control systems using radar signal inputs.

2. BACKGROUND

2.1. Artificial Neural Network

ANNs were acquainted with the EM field and microwave designing during the 1990s [15]. Artificial Neural Networks have discovered applications in antennas, design of radar circuit, remote sensing, measurement difficulties and various fields. Neural networks intended to demonstrate the manner by which the individual mind plays out a specific undertaking. An overall meaning of a neural network is given as massive. In the late twentieth century, ANNs were first acquainted with MIMO antennas. ANN was used to transform the design parameters, including the dielectric constant, and antenna’s dimensions. As of late, ANNs include many hidden layers, which are generally alluded to as Deep Neural Networks (DNNs) or Deep Learning, that have been presented to solve antenna parameter and problems of optimization.

The output in ANN can be predicted as follows:

$$Y = X_{input} * \text{Weights} + b(\text{bias}) \tag{1}$$

$$Y_{final} = (x_1 * w_1) + (x_2 * w_2) + \ldots + (x_n * w_n) \tag{2}$$

2.2. Support Vector Machine

The SVM can take up classification as well as the regression problems. In the problems of regression, on a high-dimensional space called a feature space, the input space of SVM is mapped here with the help of linear functions regression that can be accurately performed [16]. In the antenna design field in contrast to ANNs, the SVM is introduced because of its better generalization capability. In practical applications, the sets of training data generated by full-wave EM simulations are mainly of finite size, which causes overfitting in certain Artificial Neural Networks applications. Also, SVM needs fewer training patterns to give precise results, which fastens procedure of training.

2.3. Gaussian Process Regression

As of late, the GPR has received broad attention in the area of EM designing, including for antenna design. Rather than the other 2 ML techniques, the GPR can tell the uncertainty at new design points for the predicted results, which will assist creator with investigating worldwide optima when hardly any points for training are given, the GPR was acquainted with model antenna responses containing the reflection coefficient, gain performance and crosstalk level for 3 distinctive antenna models [17].

2.4. Antenna Architecture

For this study a hybrid dielectric resonator antenna is used. In the hybrid structure, every antenna is designed to radiate in its own separate band. The hybrid resonator can offer ultra-wideband operation if the different bands are sufficiently close. Ultra-wideband bandwidth is possible in hybrid resonators to offer ultra-wideband operation by using the techniques of bandwidth improvement in DRA and in other antennas as well. Fig. 1 displays the structural layout of the DRA antenna, and Table 1 shows the dimensions of the proposed hybrid CP radiator. In this radiator, the ring-shaped ceramic material is excited by dual linked circular ring-shaped space.

Table 1 Dimensions of proposed hybrid CP radiator

Symbols	Dimensions (mm)	Symbols	Dimensions (mm)
$L_S = W_S$	50.0	H	13.0
T_2	4.0	LF	31.0
H_s	1.6	WF	3.0
R_1	13.5	D3	10.0
R_2	2.0	D4	4.0
T_1	2.0	L1	12.0

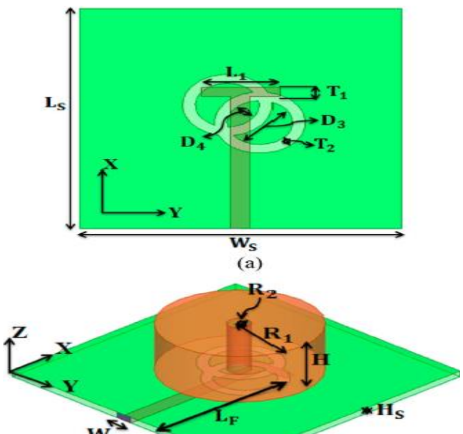
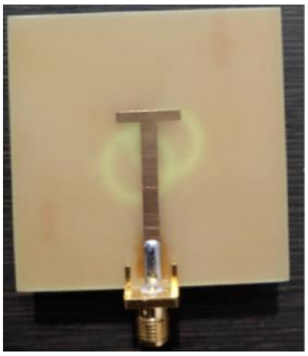


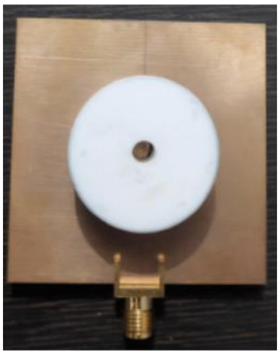
Fig. 1 Structural Layout of DRA Antenna: a) Dual linked circular ring aperture; b) Panoramic view

Fig. 2 shows the fabricated prototype of proposed CP antenna. Alumina material (relative permittivity of ceramic material = 9.8; dielectric loss tangent = 0.002) is used to make the ring-shaped ceramic. Alumina material is fixed over FR-4 substrate (relative permittivity of FR-4 material = 4.4; dielectric loss tangent

= 0.02) with the assistance of a quick fix. The thickness of the proposed antenna is 1.6 mm. Dual linked circular ring-shaped aperture and T-shaped microstrip lines have been carved over the substrate.



a)



b.

Fig. 2 Fabricated prototype of proposed CP Antenna: (a) Bottom View; (b) Top View

2.5. S-parameter

Electrical systems represent the relationship between input and output by the designation of their port. For example, when having 2 ports named Port 2 and Port 1, the power that transfers from Port 1 to Port 2 is called S_{12}. S_{21} is transfer of power from Port 2 to Port 1

When it comes to antennas, S_{11} speaks about amount of reflected power from the antenna, which is called its reflection coefficient. If S_{11}=0 dB, at that point 100% power will return back from the antenna and radiated value will be 0. If S_{11}= -10 dB, this depicts, if 3 dB of power is transmitted to the antenna, -7 dB will be the power that will reflect back. The remaining power was delivered to the antenna. This accepted power is either transmitted or consumed as losses inside the antenna itself. Since antennas are commonly intended for a low loss, preferably most of the power delivered to the antenna is radiated. Fig. 3 shows the simulated and measured S_{11} parameter of the reference antenna.

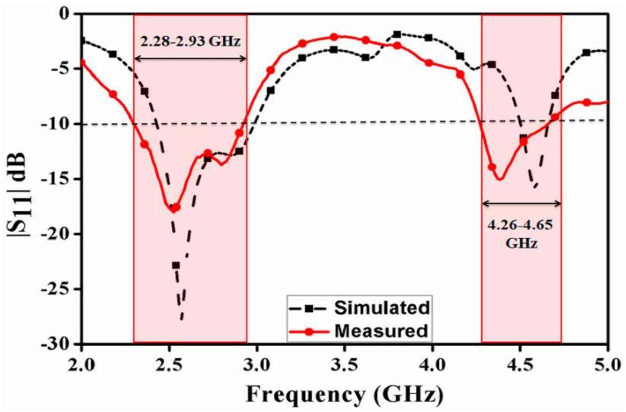


Fig. 3 Variation of S-parameter with Frequency

Reflection coefficient is a specification which expresses the amount of a reflected wave because in the transmission medium impedance discontinuity is presented. It is equivalent to the ratio of the amplitude of the reflected wave to the incident wave, with each represented as phasors. For instance, it is utilized in optics when we measure the proportion of light reflected back from surface whose index of refraction is different, such as a glass, or in an electrical transmission line to compute line the amount of the electromagnetic wave is reflected due to impedance.

3. Implementation and Results

This segment depicts various steps of the methodology section in more details along with the actual implementation details.

3.1. Data Collection

By altering various parameters of the Hybrid DRA antenna, the data was first collected by using the HFSS Software. The data exported from this software includes various parameters related to the antenna such as height, frequency, as well as the corresponding S_{11} parameters. In this collected dataset the frequency parameter varied from 2.00GHz to 5.00GHz, whereas the height parameter discretely varied from 5mm to 15mm. The dataset contained the value of S_{11} parameter for every pair for height and frequency.

3.2. Data Preprocessing and Sampling

As can be seen from the sample dataset in Fig. 6, the dataset exported contained some random, unrelated entries which needed to be removed. The exported dataset was also not in proper format and thus some rearranging of columns and rows was required. In this particular step, we mostly performed such operations on the exported dataset, and finally the exported dataset was dumped into a CSV via bash script. This CSV will serve as an input to our machine learning model algorithms. To build any machine learning model from a dataset, the first step is the sampling of data. In the dataset provided to the model for as CSV input, a sampling procedure was acted upon so as to separate it into various subsets with each one having its own utility. It is normally expected that if we have more data to construct a model, it will give better outcomes. Typically, the dataset is isolated like this with their individual utility.

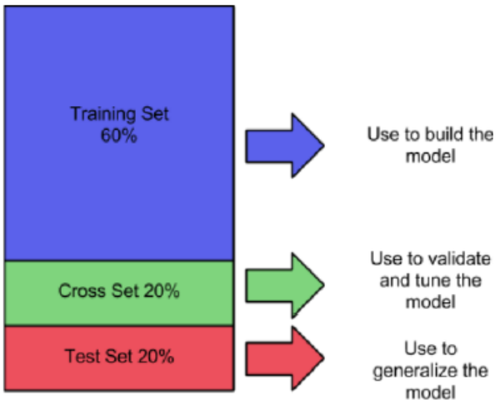


Fig. 4 Sampling over the dataset

As the name demonstrates, the training set is utilized in the training of the learning algorithm. Fig. 4 depicts different stages of sampling which is done on the dataset. For the validation and optimization of the model crossvalidation set is used. To ensure that our model extracted the proper patterns from the data and did not introduce too much noise, crossvalidation is utilized. And here the fold value is 5. We cannot check the model on this set because the results would be very optimistic as the model is built by using the training set. To perceive how properly the learning algorithm performs with unknown data, we used the test set.

3.3. Building ML Model

Building any ML model starts with loading the CSV dataset into the python code for ML modeling, after that different machine learning models are applied on that data set according to the requirement of the programmer and for training and running various ML models over the dataset google collab platform is used.

3.4. Unpacking of Data

The dataset of height, frequency and S_{11} parameter obtained after preprocessing and filtering comes in a .csv file format to our model implementation. To read the dataset shown in Fig. 5, from those files a small python code is implemented and dumped into the data frame for object serialization, fast and easy access. Fig. 6 it shows that how data is stored in the CSV file.

```
[ ]  from google.colab import files
     import pandas as pd
     # To upload the file from local disc
     uploaded = files.upload()
     # Load data from CSV
     d = pd.read_csv(io.BytesIO(uploaded['f_data.csv']))
     d.head()
```

Fig. 5 Python Code for Reading CSV

	f	h5	h6	h7	h8	h9	h10	h11	h12	h13	h14	h15
0	2.000000	-1.611335	-1.644312	-1.819660	-1.718275	-2.064616	-2.107892	-2.205608	-2.294297	-2.369450	-2.458636	-2.584394
1	2.006012	-1.618241	-1.651923	-1.830887	-1.722741	-2.079000	-2.124654	-2.225389	-2.317150	-2.396203	-2.485986	-2.617122
2	2.012024	-1.625091	-1.659542	-1.842153	-1.727715	-2.093501	-2.141616	-2.245443	-2.340463	-2.423358	-2.514393	-2.650846
3	2.018036	-1.631891	-1.667174	-1.853461	-1.733183	-2.108129	-2.158790	-2.265786	-2.364247	-2.450946	-2.543860	-2.685569
4	2.024048	-1.638643	-1.674827	-1.864817	-1.739130	-2.122894	-2.176191	-2.286439	-2.388512	-2.479000	-2.574395	-2.721297

Fig. 6 Sample Data as read from CSV

3.5. Preparing Final Data for Input

As can be seen in the previous image the data read from CSV contains S11 values for corresponding pairs of frequency and height (from 5 to 15). After that prepare a data frame consisting of all three values (frequency, height and S11) in one row so that it can be used as actual data for our models, i.e., with features and responses defined clearly. Preparation of final data frame is indicated in Fig. 7.

```
data = []
for ind in d.index:
  data.append({'frequency': d['f'][ind], 'height': 5, 's11': d['h5'][ind]})
  data.append({'frequency': d['f'][ind], 'height': 6, 's11': d['h6'][ind]})
  data.append({'frequency': d['f'][ind], 'height': 7, 's11': d['h7'][ind]})
  data.append({'frequency': d['f'][ind], 'height': 8, 's11': d['h8'][ind]})
  data.append({'frequency': d['f'][ind], 'height': 9, 's11': d['h9'][ind]})
  data.append({'frequency': d['f'][ind], 'height': 10, 's11': d['h10'][ind]})
  data.append({'frequency': d['f'][ind], 'height': 11, 's11': d['h11'][ind]})
  data.append({'frequency': d['f'][ind], 'height': 12, 's11': d['h12'][ind]})
  data.append({'frequency': d['f'][ind], 'height': 13, 's11': d['h13'][ind]})
  data.append({'frequency': d['f'][ind], 'height': 14, 's11': d['h14'][ind]})
  data.append({'frequency': d['f'][ind], 'height': 15, 's11': d['h15'][ind]})
df = pd.DataFrame(data)
df.head()
```

Fig. 7 Preparing Final Data Frame

3.6. Data Visualization

The final data frame created in the previous step was then visualized in to get insights from the data, shown in Fig. 8 and to decide on which models can be leveraged for such a dataset.

Treating frequency and height as independent variables and S_{11} will be a dependent variable. Relation of all these three variables is shown in Fig. 9.

```
sns.set_style("whitegrid")
fig = plt.figure()
ax = fig.add_subplot(111, projection='3d')
ax.scatter(df['frequency'], df['height'], df['s11'])
ax.view_init(20, 160)
ax.set_xlabel('frequency')
ax.set_ylabel('height')
ax.set_zlabel('s11')
plt.show()
```

Fig. 8 Data Visualization

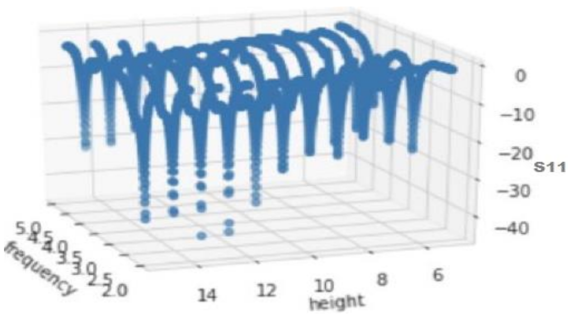


Fig. 9 3D Visualization of Dataset

3.7. Multiple Regression

The very first model used here for dataset was Multiple Regression. The Multiple Regression was used because of our dependent variable (S_{11}). In linear regression, the relationship between dependent variable and independent variable X_1, ..., X_p is given by equation:

$$y = f(x) + \epsilon \tag{3}$$

Since there are multiple independent variables (height and frequency) and a dependent variable (S_{11}) to predict, the multiple regression model will be given by:

$$f(x) = \beta_0 + \beta_1 X_1 + ... + \beta_p X_p \tag{4}$$

Where to calculate dependent variable (f{x}), $\beta_{0...p}$ are the coefficients of the model and $X_{1...p}$ are the independent variables used to ensure maximal prediction of the dependent variable from the set of independent variables.

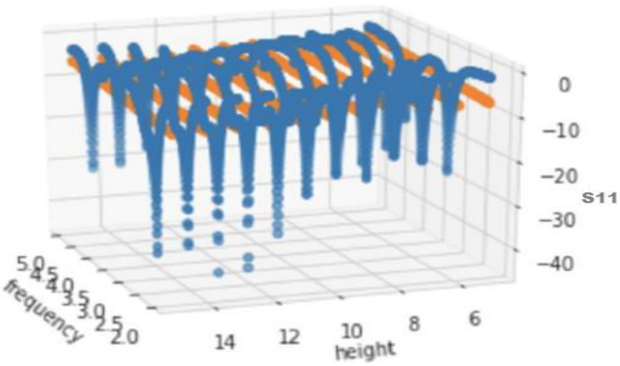


Fig. 10 Multiple Regression Predictions versus Actual S_{11}

This multiple regression model was not that much aligned with the dataset and we got only 23% of accuracy for our test dataset. This can be referred from Fig. 10.

3.8. Polynomial Regression

It is one of the types of linear regression where connection amidst the dependent and independent variable y and x is demonstrated as an nth degree polynomial. A nonlinear relationship is fitted on this regression between an estimation of x and the subsequent mean of y, denoted by E(y|x). Polynomial regression is used for many reasons:

1. All the curvilinear relationships include polynomial terms.
2. Inspection of residuals. On the off chance of a curved data a linear model is fitted, A Graph consists of a predictor (*X*-axis) and a scatter plot of residuals (*Y*-axis) is having many positive residuals in the center consequently, in these cases it is not suitable.
3. A speculation in different multiple linear regression analysis talks about independent variables. In a polynomial regression model, this supposition is not fulfilled.

$$y = a + b_1X_1 + b_2X_2 + ... + b_nX_n + \epsilon \tag{5}$$

On the variable x, y is dependent, intercept of y is the rate of error. Therefore, using Least Square technique, computed y is the response value. Another important thing to note is that the Polynomial Regression is very delicate from the outliers and in the proximity of countable outliers which are present in the data of a nonlinear analysis can change the results drastically.

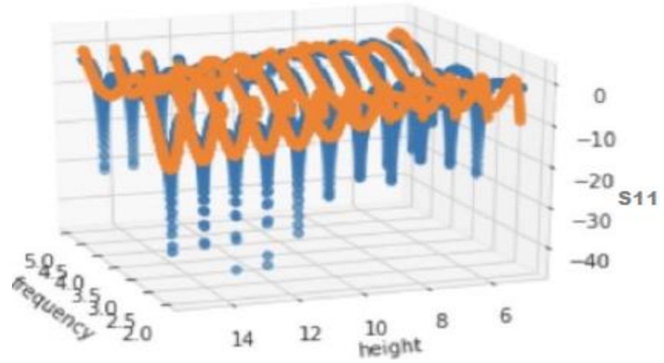


Fig. 11 Polynomial Regression Predictions Vs Actual S11

Starting with the 2nd Degree Polynomial, polynomial regression did not achieve the desired result. When the degree is increased, it is also observed that accuracy increases; within this model accuracy is up to 62%. Actual and predicted value using polynomial regression predictions are displayed in Fig. 11.

Random Forest regression

Random forest is a supervised learning algorithm. The “forest” it builds is an ensemble of decision trees[18]. This is based on a gathering method based on bagging. The classifier functions are demonstrated in this way:

1. D is the classifier that primarily makes k bootstrap specimens of D, and each of the specimens symbolizes Di .
2. A Di has almost the same number of tuples as D that is tested with substitution from D.
3. Along inspecting on substitution, in such a manner as a portion belonging to the real tuples of D may should not contain Di, although further can happen more than once. The classifier at that point builds a decision tree dependent on each Di.

Accordingly, a “forest” that comprises k decision trees is made. For categorizing an obscure tuple, X, every tree gives back its class forecast considering a single vote. The ultimate choice of X’s group is allocated and given to that tree which has the maximum votes. The working of random forest regression is portrayed in Fig. 12.

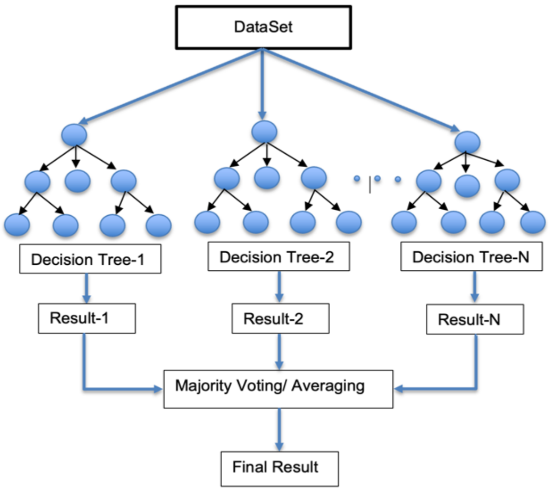


Fig. 12 Random Forest Regression

For its tree induction this project uses Gini index. For D, the Gini index is computed as:

$$\mathrm{Gini}(D) = 1 - \sum_{i=1}^{m} pi^2 \tag{6}$$

Where pi is the likelihood that a tuple in D belongs to class Ci. The Gini index measures the contamination of D. If the index value is lower than better D was divided.

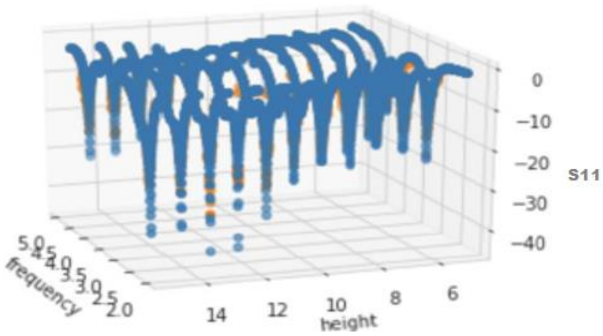


Fig. 13 Random Forest Regression Predictions Vs Actual S11

Random forest regression is tried with a different number of estimators, and after multiple training, the results were extraordinary for the provided dataset, and the accuracy that is achieved is 97%. This model also has the best fit as compared to all other models that were tried on given dataset as can be seen in the Fig. 13.

4. CONCLUSION

This paper is implemented on Python. On analyzing the dataset, Random Forest Regression gave the highest accuracy rate of 97%, and the Polynomial Regression algorithm 62%. This multiple regression model was not a good fit with the dataset and we got only 23% of accuracy for our test dataset. So, multiple regression model has the worst results among all the models used in this paper. It is seen that machine learning is a good option for the optimization of antenna parameters and to predict the variation of S_{11} with different values of height and frequency. It saves a lot of time and material which was getting wasted in traditional designing. With these ML models, a near prediction based on real values was made (obtained from HFSS). The ML models are further supported by experimental findings. The proposed antenna operates between 2 to 5 GHz. The optimized design validates its suitability for the application in hybrid DRA by exhibiting stable radiation characteristics within the operating frequency range.

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