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Research Article

Machine Learning Supported Antenna Design for UHF RFID Applications

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Abstract – RFID (Radio Frequency Identification) systems are crucial for automatic identification and tracking processes in various industries, including logistics, supply chain management, retail, healthcare, and security. This study primarily aims to design antennas for UHF (Ultra High Frequency) RFID applications and subsequently enhance these designs using machine learning algorithms. For UHF band antenna design, the frequency range of 860-960 MHz is utilized. Traditional antenna design methods often rely on iterative and time consuming processes, which may not fully exploit the potential design space. In this paper, machine learning algorithms are integrated to improve the efficiency and effectiveness of antenna design. The research applies machine learning algorithms to determine optimal values for factors such as the dimensions of the RFID antenna and the location of the feed. Models are trained on a dataset to rapidly predict and optimize new designs. The optimized design achieved an optimal S_{11} value of -35.80 dB at 870 MHz using the Gradient Boosting algorithm, showing a significant improvement in resonant frequency. Multiple machine learning models were used, with Gradient Boosting and Random Forest showing the best performance, achieving RMSE values of 1.24 and 1.52, and R^2 values of 0.87 and 0.88, respectively. The findings highlight the potential of machine learning to optimize antenna design, offering more efficient and cost-effective solutions for UHF RFID applications.

Keywords – UHF, RFID, Antenna Design, Machine Learning, Gradient Boosting.

I. INTRODUCTION

Radio frequency identification (RFID) [1] is a type of automatic identification technology. It uses radio frequency to carry out noncontact two-way data communication. Recently, RFID technology has been greatly applied to many fields, such as public transportation, manufacturing companies, logistics, and so on [2]. It is considered to be one of the most potential information technologies in the 21st century. According to the communication distance, RFID can be divided into near-field and far-field [3], [4] system. Central to the efficiency of these systems are UHF (Ultra High Frequency) RFID antennas, which require precise design to optimize performance. For UHF band antenna design, the frequency range of 860-960 MHz is crucial due to its widespread usage across different regions. Traditional antenna design methods, reliant on manual calculations, heuristic approaches, and iterative simulations, often fail to explore the complete design space comprehensively. These methods are not only time consuming but also may not yield the most effective designs.

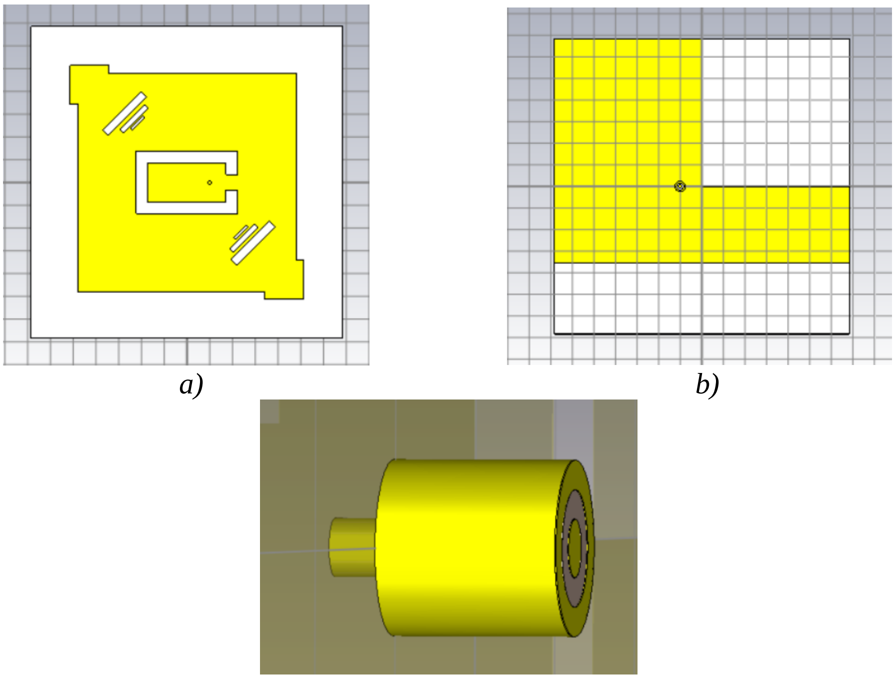
RFID reader antennas play a pivotal role in RFID systems. These antennas are designed to efficiently transmit RF signals to and receive signals from RFID tags. They come in various forms such as dipole antennas, patch antennas, and circular polarized antennas. Each type has distinct characteristics but in this paper patch antenna is designed. Patch antennas are known for their compact size and directional characteristics, patch antennas are suitable for applications where precise coverage and directionality are required. The microstrip antennas are easy to construct, presenting low profile and light weight, whereas low gain, low efficiency and narrow bandwidth are its main constraints[5]. Several open-slot antenna structures, including L-shape [6], cross-shape [7], perturbation [8], and T-shape [9], have been produced. RFID is a wireless technology for auto identification that uses radio frequency waves and consists of two main components: tag (transponder) and reader (interrogator), which both require antennas to communicate [10]. For the RFID system worked in the storage environment, more features, especially the performance between the tag and reader antennas, need to be concerned [11]. Because of its low cost, low profile, light weight, wide bandwidth, and easy matching, the microstrip slot antenna is widely used for wireless communication systems [12-16].

To address these limitations, this study aims to integrate machine learning algorithms into the UHF RFID antenna design process. By leveraging machine learning, we seek to enhance the efficiency and effectiveness of antenna design, ultimately achieving better results. The research specifically focuses on determining the optimal values for key antenna parameters, such as dimensions, feed location and predicted the optimal S_{11} value through the application of various machine learning models.

II. MATERIALS AND METHOD

A. *Antenna Design*

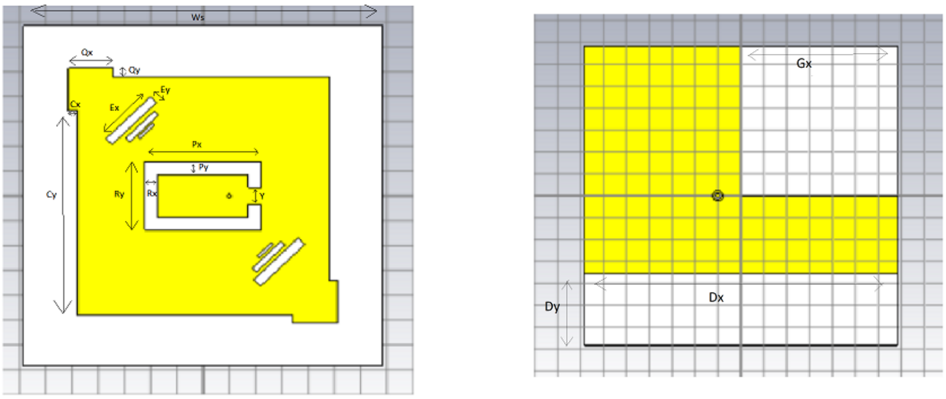
The microstrip antenna was designed to operate within the UHF frequency band of 860-960 MHz using a 3D EM analysis simulation program. In the design of the microstrip antenna, copper was selected for both the antenna patch and the ground plane. Copper is an excellent choice due to its high electrical conductivity, low resistance, and good thermal conductivity, which ensures efficient signal transmission and minimal power loss. The design process began with the ground plane, which initially matched the substrate in a square shape. Then, in the second region, a 68.36 mm square section was removed from the ground plane. Additionally, rectangular sections measuring 136.8 mm by 32.8 mm were removed from the third and fourth regions. The ground plane was given a thickness of 0.035 mm. On top of the ground plane, a substrate in the form of a 136.8 mm square was placed. This substrate was made from FR4, a common PCB material. FR4 features include a dielectric constant of approximately 4.0 to 4.8, good mechanical strength, moderate thermal conductivity, and cost-effectiveness. The substrate thickness was chosen to be 1.6 mm. The patch antenna was then designed on top of the substrate. Initially, the patch was a square, but modifications were made later. The antenna was fed using a coaxial feed, which consists of an inner conductor surrounded by a dielectric insulator, an outer conductor, and an insulating outer jacket. The coaxial feed offers advantages such as minimal radiation loss, good shielding from external interference, and efficient power transfer. The feed point was located within the central part of the patch that had been modified. To determine the optimal position for the feed to achieve better performance, a parameter sweep was conducted. This process involved varying the feed position and analyzing the resulting antenna performance to find the most effective location. Once the best position was identified, the feed was fixed in place.



a) b)

c)

Figure 1: a) Front of the Antenna b) Back of the Antenna c) Feed of the Antenna



a) b)

Figure 2: a) Front b) Back of the antenna with parameters

The above image shows the front and back views of the antenna with the parameters marked. Below is a table that lists the numerical values of these parameters in millimeters. This detailed diagram provides a comprehensive visual representation of the antenna's design, illustrating key dimensions and modifications made to the ground plane and patch. The provided table below the image contains the measurements of these parameters.

Table 1: Parameters of the Antenna

Ex	23.8	Y	10	Gx	68.36
Ey	3.5	Cx	3.4	Dx	136.8
Py	5.13	Cy	82.1	Dy	32.8
Px	44.48	Qx	17.1		
Ry	27.3	Qy	1.4		
Rx	5.1	Ws	136.8		

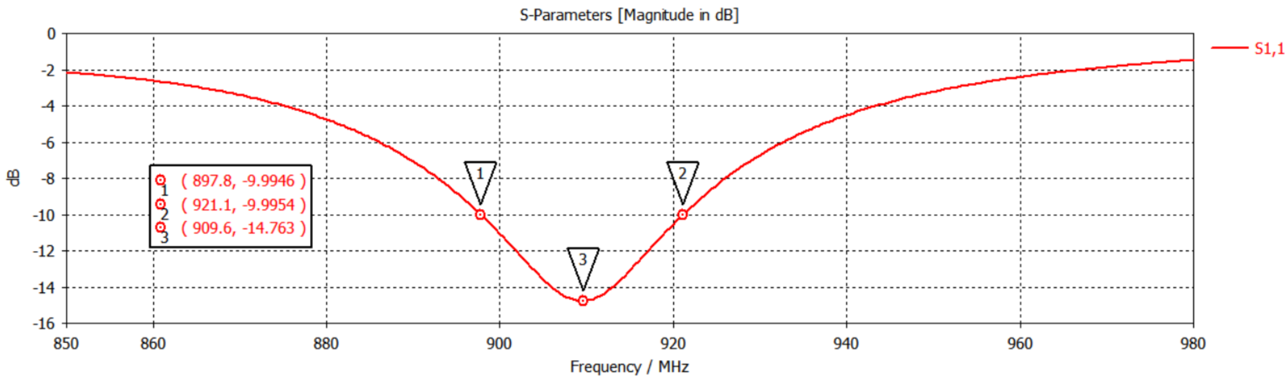


Figure 3: S Parameter of the Antenna

The lowest S_{11} value is at 909.6 MHz with an S_{11} of -14.76 dB, indicating the best resonant frequency of the antenna. The other two points at 897.8 MHz and 921.1 MHz are just at the threshold of -10 dB, marking the bandwidth limits. The bandwidth of the antenna can be inferred from the frequency range over which the S_{11} value remains below -10 dB. From the plot, it appears that the S11 value is below -10 dB from approximately 898 MHz to 921 MHz. This gives a bandwidth of about 23 MHz.

B. *Machine Learning*

After design, some parameters, in this case a = “Ey”, x= “Py” , Xe = “Ex” and Y = “y” are chosen for parameter sweep. 648 data received with this parameter sweep.

Table 2: Parameters for Parameter Sweep

Parameters	*First Value*	*Increasing Amount*	*Last value*
a	*3*	*1*	*8*
x	*1*	*0.5*	*3.5*
Xe	*15*	*5*	*25*
y	*0.5*	*0.34*	*2.2*

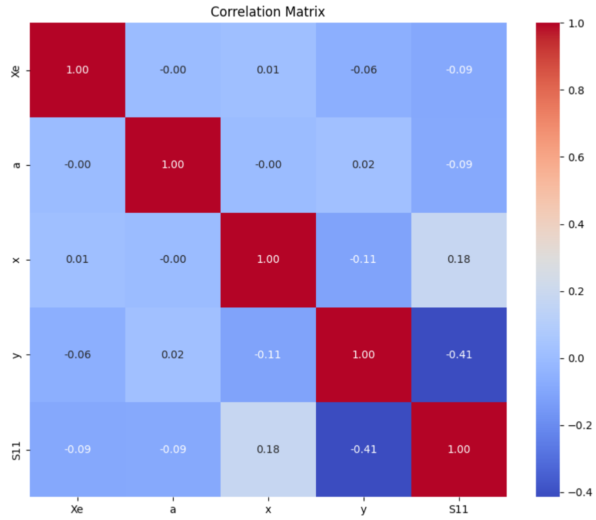


Figure 4: Correlation Matrix for Parameters

This correlation matrix shows that S_{11} is particularly associated with y and to a lesser extent with x. The other parameters do not exhibit significant relationships with S_{11}. These insights provide valuable clues for understanding relationships between variables in the dataset and can guide future analyses.

III. RESULTS

The data received from result of the simulation was entered into various machine learning algorithms and also MSE, MAE, RMSE and R^2 values were examined.

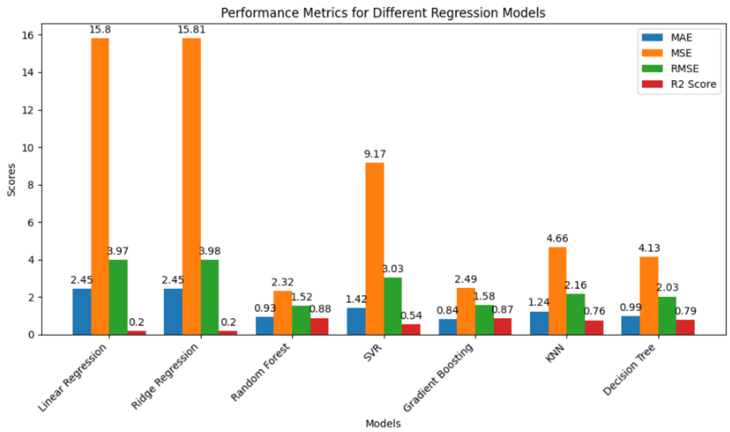


Figure 5: ML Results

For mean absolute error lower values indicate better performance. For mean squared error like MAE, lower values suggest better model accuracy.Root Mean Squared Error being the square root of MSE, also benefits from lower values. R-squared higher values are preferable, indicating a better fit to the data.

Table 3: Predicted S_{11} and parameters

Model	Optimum S_{11} Predicted	Optimum S_{11} Actual	Xe	a	x	y
Lineer R.	-9.29	-5.34	23.92	7.06	1.32	2.10
Random F.	-30.23	-35.89	16.78	7.05	2.00	1.72
SVR	-8.18	-3.13	24.37	6.75	2.21	2.19
Gradient B.	-35.80	-35.89	16.78	7.05	2.00	1.72
Ridge R.	-9.40	-5.34	23.92	7.06	1.32	2.10
KNN	-16.68	-11.51	16.27	7.52	2.11	1.96
Decision T.	-27.10	-29.06	16.78	7.05	2.00	1.72

IV. DISCUSSION

The results of this study highlight the effectiveness of machine learning models in predicting the optimum S_{11} values for UHF RFID antenna design. The performance of various models demonstrates that more complex algorithms, such as Gradient Boosting and Random Forest, are better suited to handle the intricacies of the dataset, yielding lower error metrics and higher R^2 scores. This suggests that the data exhibits non linear relationships that simpler models like Linear Regression and Ridge Regression fail to capture enough. The success of Gradient Boosting and Random Forest models in predicting S_{11} values can be attributed to their ability to manage non linearity and interactions within the data. Gradient Boosting achieved the lowest MAE of 0.84, MSE of 2.49, and RMSE of 1.24, alongside a high R^2 score of 0.87, indicating superior predictive accuracy. Similarly, the Random Forest model demonstrated robust reliability with an MAE of 1.52, MSE of 2.32, RMSE of 1.52, and the highest R^2 score of 0.88. In contrast, SVR exhibited higher error metrics, indicating a limitation in capturing the dataset's complexity effectively. KNN and Decision Tree models performed moderately, offering reasonable predictions but lacking the precision of Gradient Boosting and Random Forest. Accurately predicting S_{11} values is important for optimizing antenna performance, and the demonstrated reliability of Gradient Boosting and

Random Forest models provides a step in this field. This work importance of complex machine learning models in handling the data but also shows practicality in designing efficient UHF RFID antennas.

V. CONCLUSION

This study shows the important role of design of the antenna and machine learning in advancing UHF RFID antenna design. The application of advanced machine learning models, particularly Gradient Boosting and Random Forest, has proven to significantly enhance the accuracy of S_{11} value predictions, a key parameter in antenna performance. Gradient Boosting achieved the highest predictive accuracy, demonstrating its capability to manage the complexities and non linearities inherent in the dataset. The improvement in predicting S_{11} values translates directly to more efficient and optimized antenna designs. These designs are crucial for UHF RFID applications, where performance, reliability, and efficiency are paramount. The evaluation metrics reinforce the effectiveness of these models. Gradient Boosting achieved low error metrics that indicate a high level of predictive accuracy and reliability. Random Forest also performed exceptionally well. These results illustrate the models' ability to accurately capture the relationship between the input parameters and S_{11} values, making them highly suitable for this application. The ability to accurately predict antenna characteristics allows for more effective tuning and optimization, leading to antennas that perform better in real world conditions. By leveraging machine learning, we can streamline the design process, reduce development time, and minimize the need for extensive prototyping and testing. This approach not only saves resources but also fosters innovation in antenna design, enabling the development of more advanced and capable RFID systems.

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