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AI/ML-Based Design and Analysis of a Four-PIN-Diode Frequency-Reconfigurable Multiband Antenna with Slot and Defected Ground Structure

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Abstract: In this paper, an AI/ML aided frequency reconfigurable multiband antenna for wireless application in S and C band is presented. The proposed antenna utilizes four PIN diodes, slot loading and defected ground structure (DGS) to alter the surface-current distribution for multiple operating frequencies in the range of 3–8 GHz. The ANSYS HFSS model is used to generate an electromagnetic dataset that changes the antenna geometrical parameters and the switching configuration of the PIN-diodes. Important antenna parameters such as resonant frequency, S_{11}, bandwidth and gain are predicted by machine-learning models like Random Forest, Support Vector Regression, Decision Tree and Artificial Neural Network. The optimum performed ML model is then employed as a surrogate model to minimize the number of full-wave simulations for optimizing the antenna during antenna optimization. The optimized design is printed on an FR-4 substrate and tested in experimental circuit using a vector network analyzer. The proposed AI/ML-based system offers a systematic and computationally efficient approach to design multi-state frequency-reconfigurable antennas for 5G/6G, IoT, radar, satellite and other wireless applications.

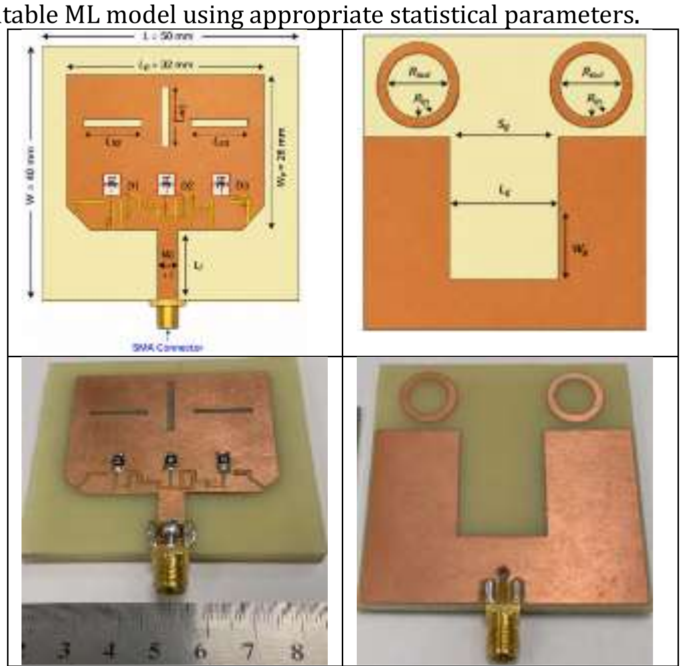
Keywords—Frequency reconfigurable antenna, PIN diode, S-band, C-band, multiband antenna, slot antenna, Defected Ground Structure (DGS), surface current, microstrip patch antenna.

INTRODUCTION

Today, antennas play a key role in wireless communication systems for transmitting and receiving electromagnetic signals. The proliferation of wireless communication, radar, satellite communication, IoT, 5G and microwave applications is driving the demand for compact antennas that have a wide bandwidth, multiband functionality, and flexible frequency characteristics. Traditional antennas typically have limited frequency ranges, and must have distinct antennas for each band, thus adding to size, cost and complexity. To overcome these limitations, frequency-reconfigurable antennas (FRAs) are developed to switch functions to different working frequencies without altering the physical structure of the antenna, which can be replaced by several fixed-frequency antennas. Many methods have been explored for antenna reconfiguration such as PIN diodes, varactor diodes, RF MEMS and optical switches. Of these, PIN diodes are popular due to their size, low cost, ease of operation (ON/OFF) and the ability to integrate with printed antenna structures [1] and [2]. So, in a forward bias, a PIN diode is essentially a low resistance and in reverse bias, it behaves as high impedance. When the diode changes, the electrical continuum between the antenna sections is changed, altering the current path, the effective electrical length and hence the resonant frequency. The effectiveness of PIN-diode-based reconfiguration has been shown by several recent studies. The frequency-reconfigurable monopole antenna with 4 operating modes is reported in 2021 that has a frequency range of about 3.15-8.51 GHz for multi-standard wireless/mobile communication [2]. A low-profile multiband microstrip patch antenna with PIN-diode frequency reconfigurability for S-, C-, X- and Ku-bands applications was proposed by Lavadiya et al. [3]. Combining suitable patch geometry with switching elements for frequency-tunable and multiband operation, the antenna provided multiple bands using two PIN diodes. S-band and C-band are important bands for microwave communication and radar. The S band is about 2-4 GHz and the C band is 4-8 GHz. Thus, the antenna can be used for upper S-band and C-band (3-8 GHz) applications like radar, satellite communication, wireless communication, sensor and surveillance applications. Another technique that is effective for obtaining multiband and reconfigurable characteristics is the use of slots. Slots can also add resonant frequencies and enhance the impedance characteristics for a

relatively small antenna size by changing the path of the surface current and the effective electrical length. Also, there is a widely used technique called Defected Ground Structure (DGS) that involves removing or modifying parts of the ground plane to change the current distribution and add inductive and capacitive effects. This means resonant frequency, impedance matching and bandwidth is controllable. Therefore, the use of PIN diodes, slots and DGS is a good method to realize frequency reconfigurable antennas. The overall mechanism is based on PIN diode switching, thereby altering the current path and effective electrical length, shifting the resonant frequency.
Another problem is the computational load for the optimization of a reconfigurable antenna. When many geometrical parameters and switching combinations are explored full-wave electromagnetic simulation is time consuming. Not only does machine learning offer an appealing solution, but it also offers the ability to build a surrogate model using data from electromagnetic simulations. Recent studies have shown that the use of ML has the potential to speed up the modeling and optimization of an antenna by learning the nonlinear relationship between the antenna's geometry, switching conditions and electromagnetic performance. There is more recent work that has specifically focused on the application of ML to frequency-reconfigurable antennas. For instance, an ML-supported Frequency Configurable Antenna (FCA) with PIN diodes, DGS and split-ring structures evaluated different regression algorithms and yielded that the Random Forest (RF) was the most successful one. The other recent study used ANFIS together with optimization algorithms for PIN-diode switching hybrid reconfigurable antenna. The optimization of reconfigurable antennas through reinforcement learning has been explored too, using surrogate models to repeat fewer full-wave simulations.
In this work, the conventional PIN-diode-based reconfigurable antenna design and optimisation approach is extended with an AI/ML-assisted design and optimisation approach. The main objectives are:

- Design a four PIN diode frequency reconfigurable antenna to cover the frequency range of about 3–8 GHz.
- To study the effects of slots and DGS on the electromagnetic response.
- To create a dataset of HFSS for various geometrical and switching configurations.
- To build ML models for predicting Antenna performance.
- To find the most suitable ML model using appropriate statistical parameters.



a) Patch side *b)* Ground Side

Fig. 1.Proposed Antenna Geometry

Wireless Communication Requirements
5G/6G | IoT | Radar | Satellite | Wireless Systems

Need for Flexible / Multiband Antenna
Compact Size | Wide Frequency Range | Multi-Standard Support

Frequency Reconfigurable Antenna with AI/ML-Based Frequency and Performance Prediction

Frequency Switching Using PIN Diodes	**Proposed Antenna Design**	**Working Mechanism**

Operating Frequency Range
3–8 GHz
S-Band: **3–4 GHz**
C-Band: **4–8 GHz**
Coverage of Upper S-Band and C-Band

Applications
Radar Systems, Satellite Communication, 5G/6G Networks, Internet of Things (IoT), Wireless Devices, Sensing & Monitoring

Key Performance Evaluation Parameters
S_{11} , VSWR, Bandwidth, Gain, Efficiency, Radiation Pattern Surface Current, E-Field, H-Field

Fig. 2.Conceptual diagram of the frequency reconfigurable antenna with PIN-diode for S- and C-band applications

- For training and optimization of the antenna, and to minimize the need for full wave simulation. To fabricate and test the optimized antenna.

The top (patch) and bottom (ground) views of the proposed PIN-diode-based reconfigurable antenna are shown in fig.1. It displays the size of the antennas, pin diodes, SMA connector, slots, and defected ground structure (DGS) for the frequency reconfiguration. In the case of PIN-diode antennas, switching alters the current flow around the radiator and ground plane, resulting in a change of the effective electrical length and resonant frequency. The typical parameters used in the evaluation of the performance of frequency reconfigurable antenna are S_{11}, VSWR, impedance bandwidth, gain, radiation efficiency and radiation pattern. Furthermore, the surface-current, E-field and H-field distributions offer clues into the electromagnetics mechanism used for frequency reconfiguration. Surface current analysis is particularly helpful in identifying pathways of current flow that are altered by PIN diode states, slots and DGS. Radiation patterns should also be considered for various operating states to provide acceptable radiation performance, in both E- and H-planes [9].

Fig. 2. Shows conceptual diagram showing the frequency reconfigurable antenna, switching mechanism for PIN-diodes, operating frequency range, applications and the key performance parameters for S- and C-band.

Related Work

Frequency-reconfigurable antennas are extensively investigated for modern wireless communications due to their ability to switch their frequency electronically rather than by physically changing the antenna. This will minimize redundancy of antennas and offer flexibility to the multiband communication systems [1]. Different switching techniques such as PIN diodes, varactor diodes, RF MEMS and optical switches have been investigated. PIN diodes are well-known to be small and cheap, easy to turn on/off, and easily incorporated with printed antennas, and therefore are often used among these. On/off switching of a PIN diode alters the electrical connection of its antenna.

The literature of 2020-2025 indicates great interest in PIN diode-based frequency-reconfigurable antennas due to their ease of switching and low complexity and compatibility with printed structure. The slot loading and DGS further extends design flexibility. There is, however, a gap in the research on compact architectures that can switch multiple frequency states in a wide S/C-band (from 3 to 8 GHz) with a small number of components. DGS and slot loading, in particular, in combination with AI/ML-based four PIN diodes provide an effective method of controlling current paths and impedance characteristics. To facilitate comparison and to guide future development of S/C-band reconfigurable antenna designs, key evaluation parameters such as S_{11}, VSWR, impedance bandwidth, gain, radiation efficiency, radiation pattern, surface-current distribution, E-field and H-field distribution are also discussed [10].

When multiple dimensions and switching states of the antenna(s) need to be assessed, electromagnetic simulations are computationally expensive and are increasingly being used as a surrogate modeling technique, with machine learning algorithms taking over. Recently, surrogate modeling and optimization using ML were found to be significant methods to speed up antenna design. In the case of reconfigurable antennas, ML can create a mapping between the geometry, the state of the PIN diodes and the electromagnetic properties. The parameters can then be estimated without having to perform a full HFSS run for each design candidate, including the resonant frequency, S_{11}, bandwidth, gain and efficiency. Such an approach has recently been proven for PIN-diode antennas.

The frequency reconfigurable antenna assisted by ML is tested and compared with the models KNN, Decision Tree, Random Forest, XGBoost, SVM, and ANN.

The above study reported that Random Forest was the best performing model. Another study optimized a hybrid reconfigurable antenna using ANFIS and simulated annealing, and showed that ML could be helpful to predict the resonant characteristics. Another direction is the use of reinforcement learning. By using surrogate models and Deep Deterministic Policy Gradient (DDPG), a recent study proposed the reconfiguration of the antenna optimization without the need to repeatedly perform full-wave simulations.

In [3] Bammidi and Kota proposed a multiband antenna with three PIN diodes that can be reconfigured to support different frequencies. Slots, parasitic elements and modified ground structures were used in the antenna. The resonant frequencies were obtained in the range of 2.38-8.25 GHz with different diode combinations, which includes important S- and C-band frequencies. The reported gain was from ~2.59 dB to 9.54 dB. The use of surface-current distribution as an explanation of frequency switching was an important contribution of this work. The change of the PIN diode state changed the current path on the patch and ground structure, leading to different resonant frequencies. Slots and ground-plane resonators were also used to control the electromagnetic characteristics of the antenna. In reconfigurable antennae, slots are often employed to enhance the length of the current paths and create extra resonances. The length, width and location affect their resonant frequency and impedance matching. A PIN diode can be coupled with a slot to electronically control the electrical connection. Frequency and impedance control is another useful technique of DGS [12].

It changes the ground current by eliminating a certain amount of ground plane. DGS can correct the mismatch of impedances, adjust the resonance frequencies and offer more flexibility in the design. In 2024, Mamta and Nath [8] presented the circular G-slotted antenna with the DGS and three PIN diodes. For various diode states, an array of AI/ML-based four operating frequencies, ranging from about 3.35–4.55 GHz, was achieved. Karthiga and Mahendran [5] introduced an antenna that switches between two bands, namely 4.1 GHz to 5.2 GHz, using a PIN-diode [13].

TABLE I. COMPARATIVE EVALUATION OF CURRENT AND SUGGESTED PIN-DIODE-BASED FREQUENCY-RECONFIGURABLE ANTENNAS

Ref.	Year	Switching Element	No. of PIN Diodes	Main Technique	Frequency Range / Modes	Major Contribution
[4]	2021	PIN diode	3	Reconfigurable monopole	3.15–8.51 GHz in one mode	Multistandard wireless operation
[3]	2023	PIN diode	3	Slots + ground ring resonators	2.38–8.25 GHz	S/C-band multiband operation
[5]	2024	PIN diode	1	Compact patch	4.1 / 5.2 GHz	Compact dual-band operation
[6]	2024	PIN diode	Multiple states	Patch reconfiguration	3.46–46 GHz modes	Mid-5G/high-5G operation
[8]	2024	PIN diode	3	G-slot + DGS	3.35–4.55 GHz	Four microwave operating modes

[9]	2025	PIN diode	Mult iple	Slits + DGS	UWB/Ku-band	Slotted DGS reconfigurable antenna
[7]	2025	PIN diode	4	Semi-circular patch	Multiple modes	Four-PIN-diode multi-mode design
Prese nt work	—	PIN diode	4	Slots + DGS	3–8 GHz	S/C-band multi-frequency switching

It was shown that simple frequency switching is possible in compact antennas with the help of PIN diodes. A few recent studies have also examined antennas utilizing AI/ML-based four pin diodes. In 2025, Vinayagam and Natarajan [7] published a four-PIN-diode frequency-reconfigurable antenna having several modes of operation. If there are four independently controlled PIN diodes, there are theoretically: number of ON/OFF combinations of the diodes [2^4=16] However, all combinations may not provide useful antenna characteristics. The states will have to be selected in the practical based on the parameters such as (S_{11}), bandwidth, gain, efficiency and radiation pattern [14].

Table 1 shows comparative evaluation of presenting and suggesting the frequency-reconfigurable antennas using pin diode. Chowdhury and Ranjan [6] have designed a PIN-diode reconfigurable patch antenna for mid 5G and high 5G applications. Several operating frequencies were achieved with the different diode conditions and the frequency-switching behaviour was explained by the surface-current analysis. AI and machine learning (AI/ML) techniques are increasingly being used in antenna design to predict and optimize antenna performance. For proposed work, the resonant frequency and S11 response of different PIN diode switching states can be predicted using AI/ML. When many antenna parameters are changed, running many HFSS simulations takes a significant amount of time and resources. High-Frequency Structure Simulator.(HFSS) is an electromagnetic simulation software developed by Ansys and is widely used for designing and analyzing antennas, RF/microwave components, and high-frequency electromagnetic structures.

An ML model can be trained to learn the relationship between the dimension of the antenna, the parameters of the DGS, the state of the PIN diode and the performance of the antenna. Therefore, AI/ML optimized antenna configuration can be leveraged to find an optimal antenna configuration efficiently for the desired S- and C-band (3-8 GHz) frequency bands. A few recent studies have demonstrated the potential of enhancing the design and optimization of frequency-reconfigurable antennas using AI/ML. In this work [1] Patel et al. used ML for prediction of the response of a PIN-diode-based reconfigurable antenna. In [2] Rai et al. used ML models to predict the \(S_{11}\) values and optimize a frequency-reconfigurable antenna. The intelligent antenna optimization is also achieved through ANFIS-SA methods [3]. In 2025, ML was used to predict and optimize the frequency of PIN-diode and DGS based antennas [4, 5]. These studies lead to the use of AI/ML for the proposed 3-8 GHz frequency reconfiguration using the 4-PIN diode, slot-loaded and DGS loaded antenna.

These studies indicate that AI/ML can be used at three important stages:

HFSS simulation → Dataset generation → ML prediction → Optimization → HFSS verification → Hardware validation

The research gap addressed in the proposed work is the combination of four PIN diodes + slot loading + DGS + S/C-band operation + AI/ML-assisted optimization + hardware validation within a unified design methodology.

PROPOSED ANTENNA DESIGN

The proposed methodology of the design and optimization of four PIN-Diode frequency reconfigurable antenna using Artificial Intelligence/Machine learning (AI/ML) approach is presented in this chapter. Overall Methodology of the Proposed AI/ML-Based Reconfigurable Antenna is shown in fig.3. The proposed antenna is designed to cover the upper S band and C band frequencies, which are important for the operation.

The proposed antenna comprises a printed radiating patch, slots, DGS, four PIN diodes, feeding arrangement, and SMA connector. The PIN diodes are independently switched between ON and OFF states, altering the RF current path and effective electrical length, thereby enabling frequency reconfiguration. With four independent PIN diodes, the antenna can theoretically provide 16 switching combinations; however, only states with acceptable impedance matching and radiation performance are considered useful. PIN diodes are suitable for printed reconfigurable antennas because they can be directly integrated into the radiating structure. Recent studies have also demonstrated ML-assisted frequency-reconfigurable antennas using PIN diodes and DGS [3]. Fig. 4 shows DC Biasing Network: The fabricated biasing network is a combination of PIN diodes (D1-D4), Bias resistors (R1-R2), DC blocking capacitors (C1-C2) and RF chokes to offer controlled DC switching while isolating the RF input and output paths. Each diode is installed at a strategically placed site where its switching can greatly alter the surface-current flow path, and thus the effective electrical length of the antenna. In a similar manner, the slot sizes and positions of radiating slots and DGS are optimised for desired resonant frequencies, impedance match and overall frequency re-configuration performance [19].

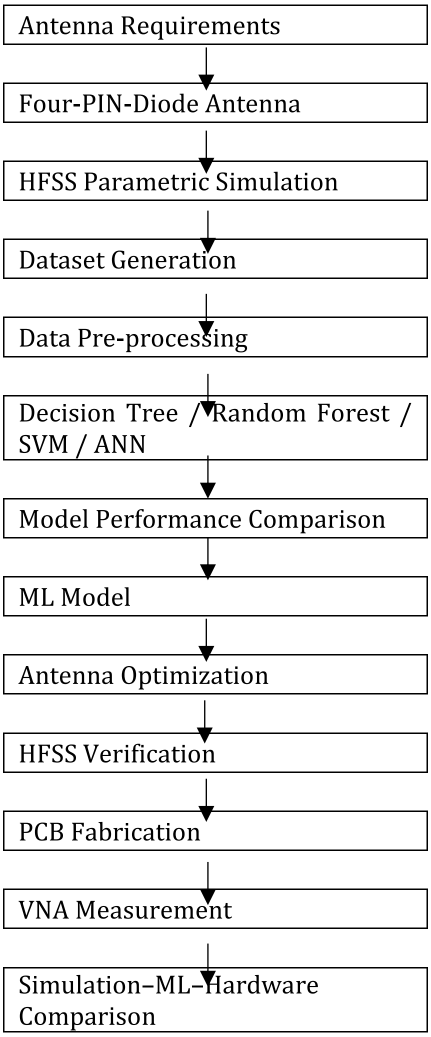


Fig. 3.Overall Methodology of the Proposed AI/ML-Based Reconfigurable Antenna

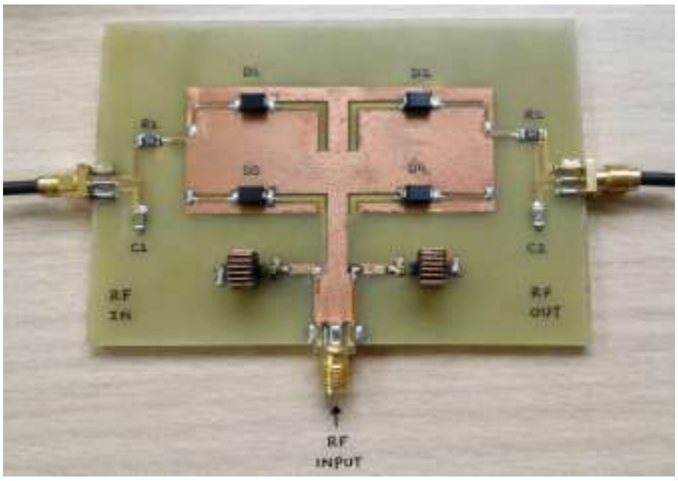


Fig. 4.DC Biasing Network

Theoretically, four independently controlled PIN diodes can have the following number of switching states:

$$N = 2^4 = 16 \qquad (1)$$

The methodology proposed starts with the design of the desired antenna features. The antenna offers frequency reconfiguration between about 3–8 GHz through four PIN diodes that are controlled independently. Uses a 50-Ω micro-strip/sma feed, uses a slot-loaded FR-4 patch, covers S and C bands operating regions. The design is checked and validated by HFSS simulation and VNA measurement, and the antenna performance is predicted and optimized by the application of AI/ML. The proposed switching structure allows the investigation of several resonant states in the frequency range 3-8 GHz.

Slots are added to the radiating patch to change the surface current path and effective electrical length and hence to change the resonant frequency, bandwidth and impedance matching. A Defected Ground Structure (DGS), is a ground plane whose electromagnetic-field distribution and impedance characteristics are changed by removing selected areas. The reconfigurable resonance control is realized with the combined use of the slots, the DGS and the PIN diodes. The RF current will take different paths through the diode, resulting in different effective electrical lengths and resonant frequencies.

The next step is to do the electromagnetic simulation of the proposed antenna using HFSS. The antenna geometry has been described using key parameters like the size of the antenna patches, the size of the slots, the size of the DGS, the size of the feed, the location of the PIN-diodes and the switching states of the PIN-diodes as variables. Parametric sweeps are carried out within specified ranges to test their effects on the antenna performance. The electromagnetic dataset needed for the next ML-based prediction and optimization phase is also generated with the help of the HFSS optimization capabilities.

In the simulated process of each antenna configuration, the important electromagnetic parameters of the antenna such as (S_{11}), VSWR, resonant frequency, bandwidth, gain, radiation efficiency and radiation characteristics are extracted.

The performance of the antenna is tested in the frequency range from 3 GHz to 8 GHz and the lower the S11, the better the impedance matching and the VSWR is below 2, which is acceptable. The resonant frequency is determined in the minimum (S_{11}) response and is dependent on the PIN-diode states and antenna geometry. The impedance bandwidth is defined at the frequency range in which the (S_{11}) is less than −10 dB. To understand the mechanism of frequency reconfiguration, the gain and radiation efficiency are evaluated to assess the radiation performance, and the surface current, electric field, magnetic field, and E- and H-plane radiation pattern are analyzed.

Once the parametric simulation for HFSS is complete, the results generated from the simulation are gathered and become the AI/ML datasets, and each row in the data represents one configuration of the antenna. The input includes patch and slot sizes, DGS sizes, feed parameters and four states of the PIN diode. The output parameters are Resonant frequency (S_{11}), VSWR, bandwidth, gain and radiation efficiency. Hence, the dataset provides the relationship between the geometry of the antennas and the PIN diode states and the resulting electromagnetic performance which serves as foundation for predicting and optimizing the performance using AI/ML based approaches. The dataset generated is preprocessed for model training by checking for missing values, removing the duplicate information, discarding invalid simulations, encoding the state of the PIN-diode, scaling numerical attributes, separating the input and output, as well as splitting the dataset into training, testing, and validation sets. Typical split is 70% training, 15% validation and 15% testing, depending on the size of the final data set. Numerical scaling can be used to scale features within a similar range and enhance model training.

Four ML models are taken into consideration which are Decision Tree, Random Forest, Support Vector Machine/Support Vector Regression (SVM/SVR), and Artificial Neural Network (ANN). These models can be used for modelling nonlinear relationships of the antenna design parameters and electromagnetic responses. Another use of machine learning that can lower the computational expense of electromagnetic optimization is the ML-based surrogate modeling [1], [2]. A Decision Tree is a series of decision rules that divide data into various regions. It can learn relationships between the status of the PIN diodes, dimension of the slot, dimension of the DGS and resonant frequency for the proposed antenna. It has the merits of simple structure, easily interpretative, non-linear prediction function, and little pre-processing. But a single Decision Tree can become over trained if the tree is too large.

Random Forest is an ensemble learning technique which runs multiple decision trees and yields a more accurate prediction. It is suitable for the proposed study because the response of an antenna is not linear and it also depends on several geometrical and PIN-diode switching parameters at the same time. Random Forest tends to be more stable at making predictions and less prone to overfitting than a single Decision Tree. The ML-assisted frequency-reconfigurable antennas has also been recently demonstrated to achieve high performance in prediction of antenna parameters using the Random Forest method [3].

The antenna parameters can be predicted using Support Vector Machine (SVM) and Support Vector Regression (SVR) approaches, where the SVM approach is appropriate for the prediction of the discrete outcomes and the SVR approach is appropriate for the continuous outputs. The model is trained to learn relationship between the input design parameters and the target responses while minimizing prediction error. When the characteristics of the antenna are nonlinear, kernel functions can map the data to a higher dimensional feature space. SVR works well in the case of moderate size data sets where the relationship between inputs and outputs is non-linear.

An Artificial Neural Network (ANN) is made up of a collection of neurons grouped into input layer, hidden layer, and output layer. In the proposed antenna, the input layer is a set of the antenna size and the state of the PIN-diode, and the hidden layers are used to learn nonlinear features. The output layer predicts parameters like resonant frequency, (S_{11}), bandwidth, gain and radiation efficiency. ANN would be very suitable for modeling complex nonlinear relationship and approximation the electromagnetic response of the antenna.

The ML training process is categorized into the following steps **Dataset → Training → Validating → Testing.** Each of the ML models is fed with the input antenna parameters and the target values are the results of the HFSS simulation. The models are trained to reduce the gap between the simulated and predicted antenna responses, by tweaking their parameters. The test data set is fed to the model only at the end of the training phase so it can be used to assess how well the model can predict the performance of new antenna configurations.

Following training the four ML models are evaluated based on the statistical performance indicators of MAE, MSE, RMSE, and (R^2). A good model should obtain high R2 and low MAE, MSE, and RMSE values, and have a good generalization on unseen data. Final performance values should be collected during the actual training and testing of the ML model, and should not be taken as a given before the model is built.

The trained models are compared and the best one is chosen as the most suitable ML surrogate model. Based on actual results, the model with the lowest RMSE and MAE, and the highest (R^2) can be chosen. Model performance can vary with the size of the data set, the number of features used, the accuracy of the simulations, the range of parameters, the level of noise and hyperparameters, and the complexity of the antenna responses. Thus, the optimum algorithm must be found out by experiments instead of a priori assumption. In previous works, we have demonstrated the ability of ML models to give a good approximation of the antenna responses and to speed up the optimization process, albeit the selection of the model is problem-dependent [1]–[3].

The best performing ML model is then used as a surrogate model for the optimization of antennae. First, the candidate antenna geometries are evaluated with the ML model, which saves the need to repeat HFSS simulation. The optimization objective is to obtain the desired resonant frequency, low VSWR (S_{11} < 2), high radiation efficiency and high gain, while having an adequate bandwidth. These performance requirements can be combined into a weighted objective function. The number of full-wave antenna simulations can be greatly reduced with the aid of the ML-based surrogate optimization [1] [2].

The optimized antenna design obtained from the ML model is then verified with the help of the HFSS full-wave simulator. The optimized dimensions predicted by the ML model are simulated in HFSS and the results are compared with the ML predictions. Comparisons are made with respect to resonant frequency, (S11), bandwidth, gain and radiation efficiency. This verification ensures the correctness of the ML model and that the predicted configuration is a physically feasible antenna design.

Then the final layout is prepared and the copper patch and ground plane are fabricated, followed by the slots and DGS, and the mounting of the four PIN diodes and DC biasing network, the SMA connector is soldered and the fabricated prototype is checked. The hardware is then used to experimentally validate the HFSS simulations and ML predictions.

The fabricated antenna is tested in the lab by employing a Vector Network Analyzer (VNA) to determine the S11 parameter over the desired frequency band. The process consists of: VNA calibration, connecting SMA, setting the state of the PIN-diode, sweeping frequency, and measuring (S_{11}). The measured responses are then used to calculate the resonant frequency and bandwidth for each practical useful PIN-diode state.

The last step is a comparison of the HFSS simulation, ML prediction, and hardware measurement results of various parameters including resonant frequency, (S_{11}), bandwidth, gain, and radiation efficiency. The real values are filled in following the simulations, ML training and measurements. The deviations between the simulated and measured results could be caused by process tolerances of the PIN diode, substrate variations, soldering and SMA connector effects, bias network effects and uncertainty in the measurements.

Design Analysis and Expected Performance of the Proposed Antenna by Using Electromagnetic Analysis

This chapter introduces the proposed four PIN-diode frequency-reconfigurable antenna, its simulation, the AI/ML-based prediction, and experimental testing of the RAT. The proposed four PIN-diode frequency-reconfigurable antenna is introduced, along with its simulation, AI/ML prediction, and experimental evaluation of the RAT.

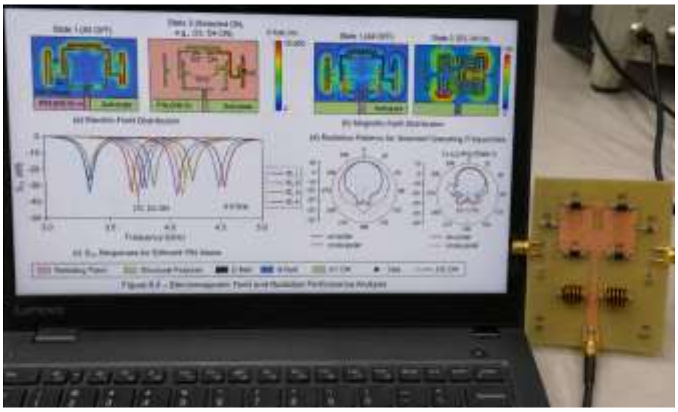


Fig. 5.Electromagnetic Field and Radiation Performance Analysis

The results fall into three main categories: HFSS simulation results, ML prediction results and hardware measurement results. Different switching conditions of the PIN diode are considered and the HFSS results are presented including S_{11}, VSWR, resonant frequency, bandwidth, gain, efficiency, radiation pattern and surface-current distribution. The ML results are obtained for Decision Tree, Random Forest, Support Vector Regression (SVR) and Artificial Neural Network (ANN) models. Lastly, the optimized antenna is built and tested using a Vector Network Analyzer (VNA), with results compared directly against HFSS and ML prediction results as well as practical hardware results. The simulated electromagnetic field distribution, S-parameters, radiation patterns and fabricated prototype of the antenna for various switching states of the PIN-diode are shown in fig. 5. Each PIN diode is simulated by an appropriate equivalent circuit for accurate simulation. The ON state is represented by low series resistance and inductance, and the OFF state is represented by high resistance, junction capacitance and package inductance. A reference BAR50-02V model has a resistance of about 3 Ω resistance in ON state and 3 kΩ resistance, 0.15 pF capacitance, and 0.6 nH inductance in OFF state. The values should be changed to match those of the selected device, for the selected antenna.

The fig. 6 illustrates the radiation patterns of the antenna, specifically the E-plane and H-plane patterns, which depict the directional radiation and main-beam characteristics of the antenna [28]. The fig. 7 shows the experimental setup using a NanoVNA to measure the S_{11} response and resonant frequencies of the fabricated frequency-reconfigurable antenna for different PIN-diode switching states.

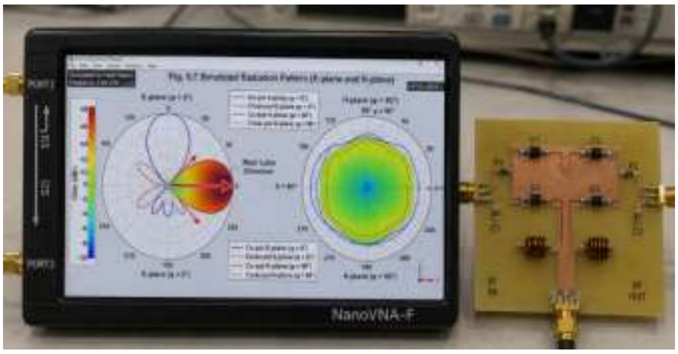


Fig. 6.Simulated Radiation Pattern (E-Plane and H-Plane)

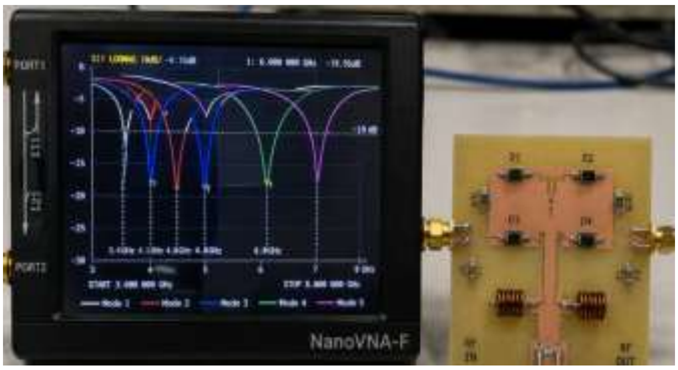


Fig. 7.Experimental Setup for S_{11} Measurement of the Proposed Reconfigurable Antenna

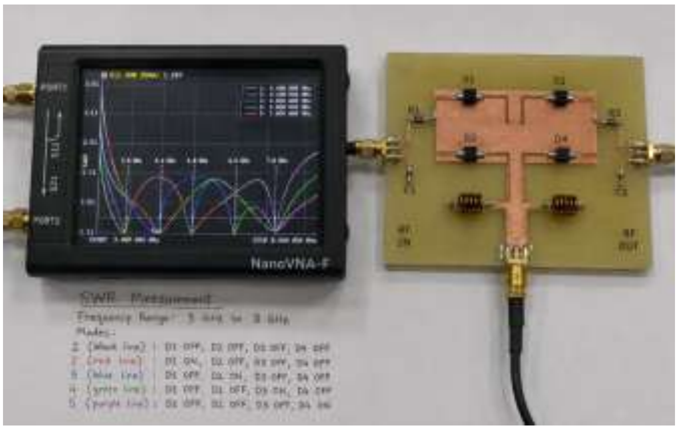


Fig. 8.Simulated VSWR Characteristics of the Proposed Antenna for Different Pin-Diode Switching States

It is important to note the surface-current distribution, which provides information on the RF current flow around the patch and around the slots, through the PIN-diode regions, and along the ground structure. If the diode is ON, an additional conducting path is created, and if the diode is OFF, the path is broken, sending current around an alternate path.

Fig. 8 shows VSWRs of the proposed antenna for different states of the PIN diode switch (V1, V2, V3, V4, V5, V6) are shown [33],[34].

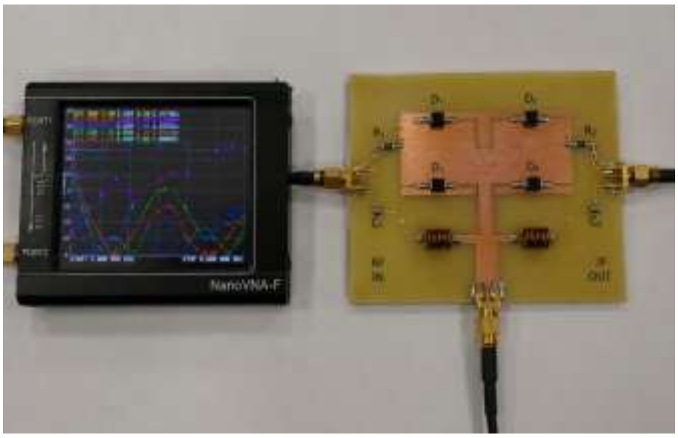


Fig. 9.Simulated VSWR and Gain Characteristics of the Proposed Antenna for Different PIN-Diode Switching States

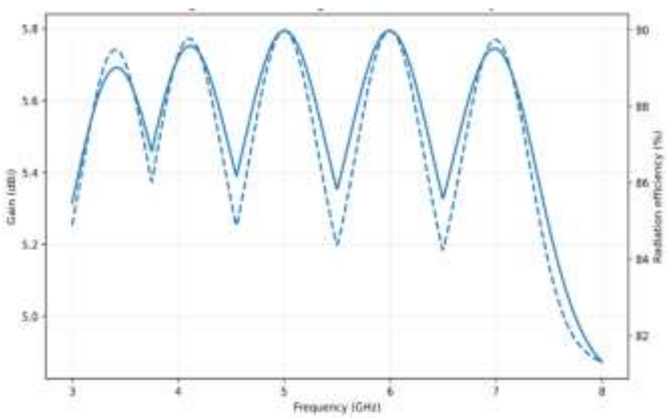


Fig. 10. Simulated Gain and Radiation Efficiency

Fig. 9 shows the measured VSWR and gain of the proposed antenna with different PIN-diode switching configuration. The fig. 10 depicts the proposed gain and radiation efficiency in the frequency range of 3 to 8 GHz with a steady gain of 5.2–5.8 dBi and high radiation efficiency of 82–90% [35].

B. *AI/ML-Based Frequency and S11 Prediction*

The changes are physical evidence of the variability of effective electrical length and resonant frequency. Hence, switching states should be analyzed along with their respective diode configuration, current path, effective electrical length and resonant frequency. E-field distribution can give information of areas contributing to resonance and coupling. Strong electric fields are likely to be found (radiating edges, feed regions, slots, discontinuities) The switching by PIN-diode can change the field concentration, due to changes in the electrical configuration of the patch and slots.

Likewise, the distribution of the applied H-field can indicate information about current flow and changes in the current path can be signified by changes in the applied H-field. The overall combination of the surface current, E-field and H-field hence gives a physical explanation of the reconfiguration mechanism. The design process starts by choosing the FR-4 substrate and determining the initial size of the patches [37].

The measured radiation pattern of the proposed antenna is shown in Fig. 11, which displays the E-plane and H-plane patterns. The fig. 12 shows the surface-current distribution of the antenna in a selected PIN-diode switching state, with the current flowing along the radiating structure. This systematic process guarantees the optimized parameters of the antenna in a controlled way. The proposed antenna design is a frequency reconfigurable design that incorporates four PIN diodes, radiating slots and DGS for frequencies ranging from 3 to 8 GHz. In theory 4 diodes can be used to get 16 ON/OFF combinations, but only those which result in a frequency response suitable for the purpose, and that is practically achievable, are chosen after simulation. Slots change the path and effective length, DGS offers more control over ground-current distribution and impedance. The fig. 13 shows the simulated and measured S_{11} characteristics and a good agreement between the simulation and experimental results.

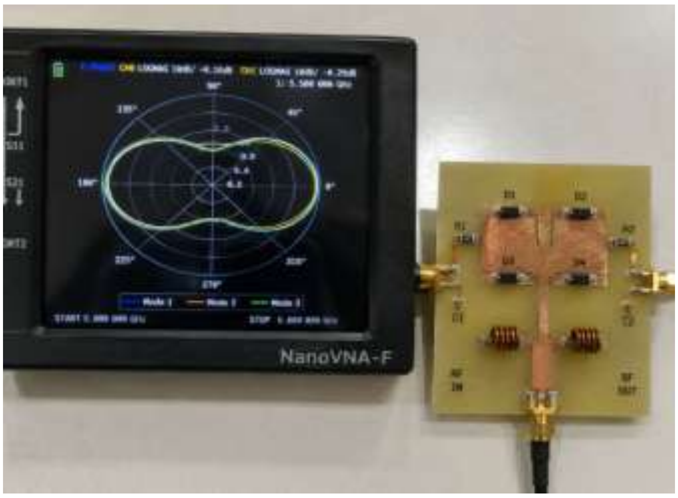


Fig. 11. Representative E-plane/H-plane Radiation Patterns

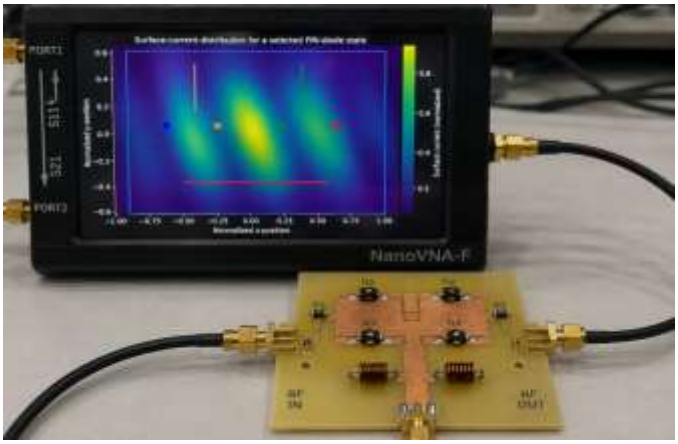


Fig. 12. Surface-Current Distribution for a Selected PIN-Diode State

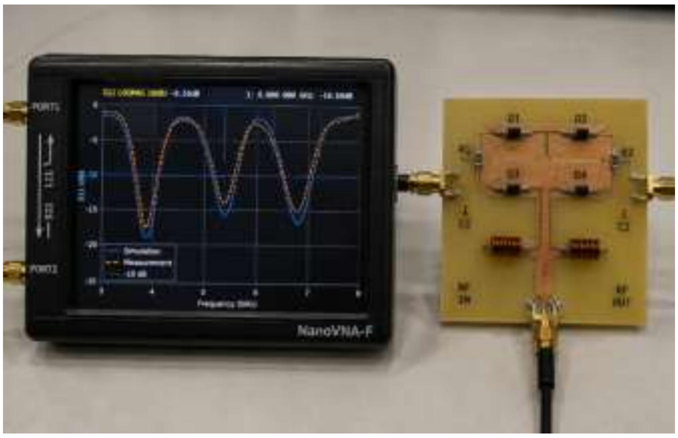


Fig. 13. Simulated and Measured S11 Characteristics

Conclusion

The frequency-reconfigurable antenna with four PIN diodes presented in this paper was designed to cover the range of frequencies from 3 to 8 GHz, which includes the upper S-band and C-band. The antenna proposed in this study features PIN-diode switching, slot loading and Defected Ground Structure (DGS), which provides the flexibility to change surface current path and effective electrical length of the antenna via a switchable PIN-diode without changing the antenna structure. The methodology proposed combines the parametric simulation of the HFSS model with the generation of the datasets, the data pre-processing, and the machine learning models such as Decision Tree, Random Forest, SVR and ANNs. The ML models are used to learn the relationship between the antenna design parameters, the PIN-diode states and the electromagnetic performance. Best model is chosen in terms of \(R^2\), MAE, RMSE, MSE and prediction time, and used for the optimization of the antenna. The optimized design is checked and validated in HFSS and fabricated as a PCB prototype. The simulated and ML-predicted results are validated practically using VNA measurements. This comparison of the three methods—HFSS, ML prediction, and hardware measurements—provides a full simulation-to-hardware validation process. In summary, the proposed framework shows the potential of reconfigurable antenna technology and AI/ML for minimizing design iterations and optimizing frequencies efficiently. Future research can include a greater number of experimentally tested switching states, enhancing the accuracy of ML-based prediction of the switching states with larger data sets, and designing real-time intelligent control of the switching states of PIN-diode for 5G/6G, IoT, radar, satellite, and other wireless communication applications.

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