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Designing and Evaluating THz Antenna using Machine Learning for 6G Network

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Abstract— For improving technology there is a need for High speed internet, sixth generation Technology is becoming more important. To achieve the required performance and capabilities, the development of an ideal antenna is essential. However, the conventional method of simulating electromagnetic fields for antenna design are laborious and computationally demanding, lengthy simulation times and need powerful computers. Terahertz (THz) antenna design and Machine Learning (ML) technology can be applied to address these constrains. The goal of this work is to design an antenna which operate in THz Band and it is a crucial 6G Band for the upcoming infrastructure revolution. Additionally machine learning models such as decision tree, random forest and Mean Square Error (MSE) is used to predict and optimize the return loss of the antenna. The results demonstrate the accuracy of each models with Random forest exhibiting the highest accuracy of 82% in return loss prediction. New development of effective and optimized 6G antenna for High speed communication are provided by machine learning.

Index Terms—Antenna, ML, MSE, THz.

I. INTRODUCTION

Terahertz antenna is a Special antenna for transmission and reception of electromagnetic waves with a terahertz frequency [1]. This electromagnetic spectrum band, which lies between the microwave and infrared regions used for spectroscopy, imaging, communication, and sensing [2]. Information transfer between the source and the target in an important role of THz antenna[3]. On the other side, Terahertz antenna design and fabrication can be difficult and requiring a lot of research into new materials, development methods and antenna topologies. THz antenna has opportunities to transform a verity of industries, including security, wireless communication, environmental monitoring and medical imaging.

Numerous applications including high speed wireless communication, imaging, sensing and spectroscopy uses 1THz to 3 THz frequency range. This frequency range in high speed wireless communication in future 6G networks to achieve a minimal latency and high data transfer rates. THz imaging is helpful for non destructive testing and imaging tasks like food quality monitoring, medical imaging and material defect detection. Applications for THz antenna is sensing environmental monitoring and security. THz spectroscopy applications in material science, chemistry and biology for analyzing structure of the molecules[3],[7]. These antenna performance is greatly impacted by surface roughness at THz frequencies, which increases surface and ohmic losses. Rapid prototyping of THz lenses, horn antennas and waveguides is made possible by 3D printing, which provide accurate and economical miniaturization advantages.

On the other hand, FIB technology overcomes the limitations of classical lithography to enable the production of more complicated antennas, such as spiral antennas and allows for development of smoother antenna surfaces. THz process technologies involves techniques including thick photoresist and electroforming in addition to traditional micro mechanical technique like lithography and laser milling [2]. Electroforming technique that minimizes the effect of antenna surface roughness performance by depositing conductive materials onto antenna components. It is possible to minimize ohmic and surface losses and optimize THz antenna performance by utilizing these manufacturing processes and process technologies. This could lead to the development of high-performance and efficient THz communication systems for a range of applications [2],[7],[8].

For High efficiency and low loss THz antenna for 6G networks via optimized design and materials is implemented. It supports Higher frequencies with minimum size for deployment and device integration. It has directional radiation with high gain enhanced signal strength with minimum interference. Cost Effective in manufacturing for production and commercial viability [2], [6]. From overall technical requirement are mentioned in Fig. 1 is important to develop THz antennas which support for high speed and capacity necessary for 6G systems.

Fig.1 shows Requirements for 6G connectivity.

Antenna Engineers have difficulties in testing and simulation for fine tuning design with iterative process particularly in Terahertz antennas field [4]. In order to achieve the required performance difficult results are need to execute electromagnetic simulations on regular basis. Typically, THz antennas operate at high frequencies with short wavelengths. In order to effectively portray THz behaviors, simulating high frequencies requires a significant amount of processing power, including precise spatial and temporal resolutions. The optimization process frequently involves running simulations, evaluating results, and making small tweaks to antenna settings. To attain the intended outcome, this iterative process might have to be repeated several times, which would lengthen the total time required for design improvement. It is true that machine learning (ML) can provide a useful remedy for the laborious and computationally demanding task of improving THz antennas. The creation of effective THz antennas, minimize the amount of simulations and streamline optimization efforts by incorporating machine learning into terahertz antenna design process [10]. Algorithms for machine learning-based optimization reduce the number of iterations in the process of finding the best antenna layouts. Decision-making for designers is accelerated by predictive machine learning models, which provide real-time assistance [11]. By doing this, you may construct state- of-the-art terahertz communication networks for 6G and beyond while also saving time and computing resources and improving overall design efficiency and performance.

A. Machine Learning in Antenna Design

The improved technology of Artificial Intelligence (AI) has a potential to change the world. As the encompassing domain, AI includes activities like object or sound recognition, natural language comprehension, and complex probabilistic problem solving that have historically required human intelligence [12]. Machine learning (ML) is a main component of artificial intelligence (AI), allowing computers to independently learn from data and experience. The use of machine learning (ML) methods in antenna design and optimization has grown in popularity in recent years.

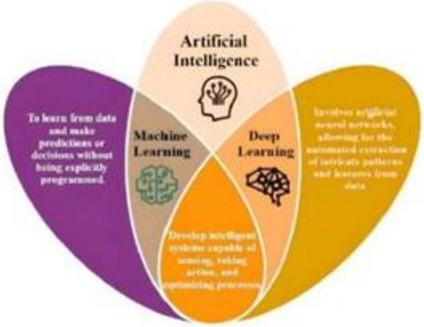


Fig.2.Relationship between artificial intelligence, machine learning and deep learning.

It can assist in automating the design process, cutting expenses and design time, and enhancing antenna performance [13]–[17]. It is capable of being trained to evaluate and decipher information gathered from antenna measurements [18]–[20].]. Deep Learning is the term for machine learning that incorporates neural networks [21]. Figure 2 illustrates the connection between deep learning, machine learning, and artificial intelligence. In supervised learning, an algorithm is trained on labeled data, which entails providing inputs and intended outputs so that it can figure out how to map them [22]. In contrast, unsupervised learning involves an algorithm learning from unlabeled data, which means it has to detect a pattern automatically. Algorithm that uses augmentation learning and gain knowledge by interacting with their surroundings and experiencing rewards or punishments for their behavior [22],[23].

B. Synopsis of Associated Research Using Machine Learning for Antenna Design

A number of researchers looked into using ML algorithm to predict antenna performance. In order to increase the prediction and accuracy and convergence time in antenna Designing, some authors suggested a Multi Objective approach that combines the usage of Multi source Co-Training and second Order Gaussian process with Multi objective learning techniques. This Techniques used for designing complex antenna and practical antenna synthesis because it predict the functional value and a new point with uncertainty using Gaussian process with ML approach. The potential of ML to revolutionize electromagnetic modeling. An independent study [17] examines the use of AI in antenna design, analyzing different AI strategies and promoting more study in this developing area. In [18] The author presents a clever antenna design system built on Machine Learning. It exhibited better categorization and prediction accuracy. Analysis of ML and DL in Antenna design for the range of applications is given in [20], with the focus on effectiveness and for problem solving.

The author put forth a design which streamlines the structural optimization and designing process for the designated frequency of 5G antennas, saving time and making deployment easier. In [25], scientists suggested utilizing Gaussian Process Regression to predict microstrip antenna resonant frequencies efficiently. In, ML models for dielectric resonator antennas were used to achieve dependable return loss (S11) predictions. With the use of a sophisticated machine learning model that combines a decision tree classifier with a fuzzy system, it is possible to predict geometric parameters and classify antennas with an astounding 99% accuracy. In antenna with improved 6db is achieved by the author of reference with the introduction of Machine learning drives optimized technique that uses Auto encoders to make a perfect Multi purpose antenna with separate structure. The author explores beamwidth control with PIN diodes as an affordable substitute for simulations and offers Machine learning related methodology to calculate resonant frequency in antenna.

In recent studies shows how ML based methods can be applied to different types of antennas. Since development of Terahertz antenna is now in its early stages then it has much to learn machine learning approaches might provide fresh perspective and ideas for improving antenna performance at these frequencies. Prior research has not investigated THz antenna optimization with machine learning techniques with the same level of rigor. This works aims to analysis of Machine learning pattern for designing antenna with prediction of return loss.

II.RESEARCHWORK METHODOLOGY

The Aim is to optimize a process of enhancing a Terahertz antenna return loss value by designing an antenna which operate in Terahertz band then utilizing machine learning. Identifying the most accurate and computationally economical algorithm for THz antenna behavior prediction. The goal is to reduce resource intensive simulations, improve antenna performance, and speed up design iteration cycles by using machine learning (ML) techniques to assess data and forecast parameters.

A.Importance of Antenna Domain Return loss

The degree in which the impedence matches with the transmission line or an antenna which is connected is known as return loss. Effective wireless communication depends on the antenna's ability to transfer electricity from the source to empty space efficiently. Return loss is a measurement of the power lost because of impedance mismatch and is commonly expressed in decibels (dB).

$$S_{11} = 10Log_{10}\frac{p_{in}}{p_{ref}}db$$

A low return loss shows the substantial quality of some power is reflected back to the source whereas high return loss shows majority of power is delivered to the load. Return loss is essential in real world applications to guarantee that an antenna operates as best with respect to the gain, radiation, diversity and efficiency. The Return Loss contributing reduction in signal loss, amplified power and improved system work. Return loss is therefore a crucial factor that needs to be taken into account while designing, testing, and optimizing antennas. Figure 3 illustrates the significance of this with regard to the antenna.

Fig.3 Importance of Antenna Return Loss

B.Proposed Methodology

The crucial criterion in analyzing and designing antenna are Return Loss, Efficiency and Signal Quality. This identification draws attention to the particular factors that must be taken into account when optimizing antenna performance for this particular use. Simplifying the model by removing insignificant components can speed up the design process and make analysis and optimization simpler for particular applications or scenarios [24]. A dataset with different dimensions and all of these design factors is constructed in order to use machine learning to estimate return loss. Ansys High Frequency Structure Simulator (HFSS) is used to simulate and design variations in each antenna.

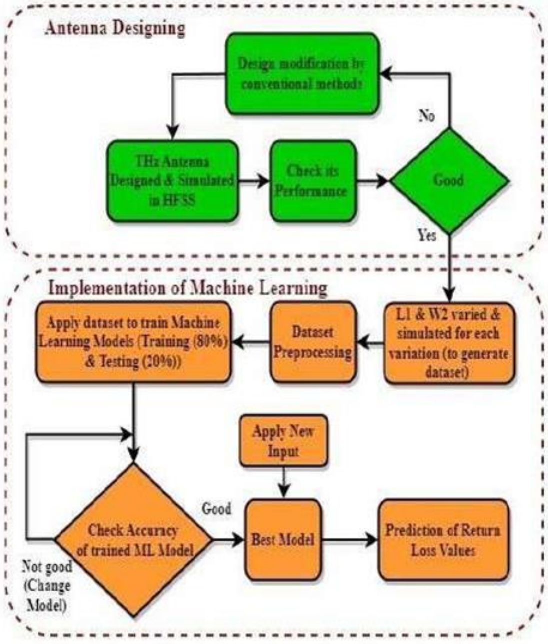


Fig.4.Flowchart for proposed methodology

C. Antenna Dimension and Development

The proposed antenna construction and its design iterations are displayed in Figs. 5 and 6. The antenna is intended to emit radiations at the 1 TeraHertz - 3 TeraHertz frequency band. The antenna's substrate measures 100 micrometer in length, 100micrometer in breath, 10 micrometer in thickness. The suggested antenna uses RT/Duriod6010 (ε_r=10.2) as its substrate, which has a height of 10 µm. As illustrated in Fig. 5, the concentric circular patch has a radius of 40µm, is 10µm broad, and is split into two parts. The micro strip feed line is 10 µm in length and 10 µm in width. A parasitic element measuring 30 µm in length and 4 µm in breadth.

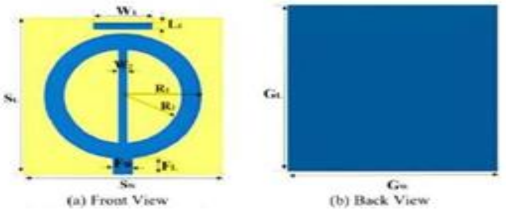
D.Implementing Machine Learning models

Training a model is the first stage in applying machine learning (ML) to forecast the return loss (S11). In order to achieve that a set of data is produced when altering the length W1, L1 and it can act as an input for machine learning rules, in addition to frequency (F), which is another input feature. Return loss, also called a label and shown in (2), is the sole parameter that will be the outcome as

$$F(lL1, W2,F)=S11(values)$$


(a) Design 1 (b) Design 2 (c) Design 3

Fig.5.Iterations in designing Antenna



(a) Front View (b) Back View

Fig.6.Dimensions of Design 4(Proposed Antenna)

Antenna Dimensions

Parameters	Dimensions in um
W_1	30
W_2	4
L_1	4
R_1	40
S_w	100
R_2	20

W2 and L1 is changed from 1 to 9 micrometer. In order to determine the corresponding return loss values of all designed antenna by some adjustments, HFSS software run a simulation from 1 to 6 Terahertz frequency, is examined. The 113,649 values that are produced as a result of this process which is useful for training and evaluate the machine learning model. In following stages the data preparation, an essential machine learning phase that entails organizing raw data, cleaning it, and converting it based on pertinent features so that ML models may be trained on it.

In supervised machine learning, regression is an essential technique, especially for issues involving the prediction of continuous connections with input data and output value. This provides simple method for modeling correlations between variables and forecasting outcomes based on those correlations.

The following is a discussion of the regression analysis-capable machine learning models used in this work: A machine learning approach called Decision Tree presents decisions and their outcomes as a single-tree. It is strong because it can deal with missing data, feature relationships, and nonlinearity. A decision tree method serves as the foundation for the random forest algorithm [25]. The random forest technique uses many trees to produce a forest, but the decision-tree uses single-tree structure. Combining the forecasts from each tree results in the final forecast. The dataset can be subjected to different ML models after it has been loaded. To improve and do experiment, python languages are used because it provides free cloud based GPU/TPU resources, making setup easier and freeing to develop concentrate on designing and to perform an experiment.

III.RESULT

An extensive investigation of the suggested THz antenna opens this section. Subsequently, an assessment of the many machine learning models employed in this study. This part ends with the analysis with educational diagram, which particularly focus on analysis of return loss. This investigation covers a through examination of projected and simulated return-loss for the antenna model variants. This approach offers insightful information on how well machine learning is revolutionizing in Terahertz antennas models.

A. Analysis of proposed Terahertz antenna

In the Fig. 5, shows Design 1 has Terahertz band spanning between 1.5 and 2.67 THz with resonating frequency at 2.1 THz and return-loss of -15dB. It also has a few smaller bands that have separate resonances at 3.50 THz, 4.0 THz, 4.40 THz, 4.80 THz and 5.20 THz with return losses of-16, -17, -19, -17, and -17 dB. The second modification, known as Design 2, is a circular slot with a radius of 30 μm. It features a THz band span from 2.10 to 3.20Terahertz, with resonating frequency 2.70 Terahertz and 3 Terahertz with return loss -17.30dB and -17.7 dB. In concentric circular patch model is again changed by adding a stub vertically in middle of the antenna design producing bands between 1.80THz to2.70THz and 2.80THz to 3.10THz with resonate frequency 2.40THz and 3THz and return-loss of -20.40dB and -16dB, as well as a few small bands with resonating frequency 3.50THz and 4.20THz and return-loss of -33dB and -22dB, respectively.

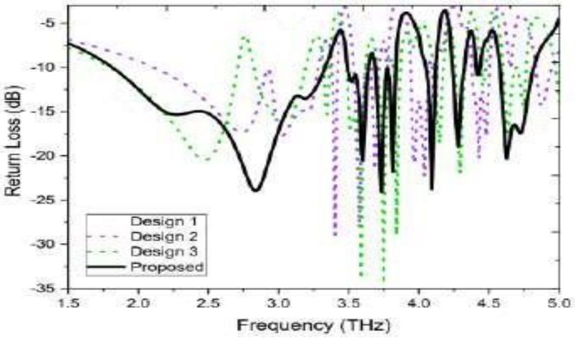


Fig.7.Return Loss Vs Frequency

From the comparison of antenna design 1 and 4 in Fig. 7 the design 4 shows proposed antenna in Fig. 6, which gives wideband between 1,80THz and 3.30THz with resonating frequency at 2.80 Terahertz and return-loss of -24dB. The major electric current generated by the electromagnetic field within the radiating patch is represented by the surface current distribution. By examining the flow of energy through an antenna, approach contributes to our understanding of how electromagnetic waves are distributed across the patch surface. It contributes to the performance optimization of the antenna system by pointing out possible losses and inefficiencies. The suggested design's surface current distribution at 2.7 THz, 3.7THz, 4.2THz and 4.7THz is shown in Fig. 8, which also highlights the precise radiating patch region that is essential for the antenna to resonate at the intended frequency.

Model	R-Square	MaPe	MSE	MAE	T-Predict	T-fit
Decision Tree	0 .716	0.1042	6.2571	0.9871	0.0091	0.3531
Random Forest	.8261	0.0941	3.816	0.861	0.058	0.8911

Fig. 8. Distribution of current on a surface

B. Models of Machine Learning Performance

In Machine learning design to find the performance like Prediction-Time, Mean-Absolute-Error (MAE), Mean-Square- Error (MSE), R Square, Fitting time and Mean-Absolute- Percentage –Error (MAPE), are used.

For Mean Square Error, $MSE = \frac{1}{n}\sum_{i=1}^{n}(y_i - y_l')^2$

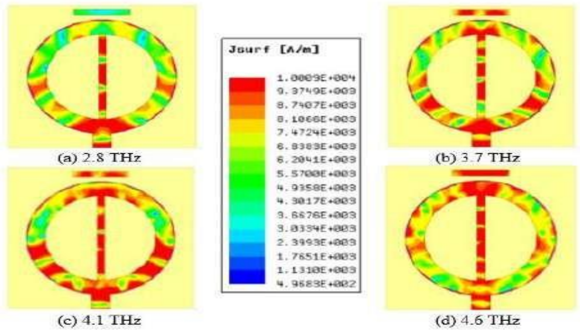
For R-Square value, $R^2 = 1 - \frac{\sum_{i=1}^{n} y_i - y_l')^2}{\sum_{i=1}^{n} y_i - y_l')^2}$

For Mean Absolute Error, $MAE = \frac{1}{n}\sum_{i=1}^{n}|(y_i - \hat{y_l})|$

Here n represents different data points, y_i True data, y^i represents predicted data, and Fitting time represents training time for the model in a provided sheet. Predicted time represents the time to train the design for making prediction. In these models Random-forest achieve better predictive accuracy than decision tree with low mean square error and with high R-Square.

C.Visual Representation with regard to Return Loss Analysis

The graphical display illustrates the actual and predicted values of Return Loss for Decision tree and random forest between 1 to 7 Terahertz frequency range. The graphical proof confirms exact training of models and the amazing agreement between the predicted and actual values. Notably, the Matplotlib module in Google Colab was used to construct these graphs using Python programming, showcasing the tools' adaptability and usefulness for data analysis and visualization.



(a) 2.8 THz (b) 3.7 THz (c) 4.1 THz (d) 4.6 THz

Fig. 9 shows actual data VS predicted values of return-loss on decision-tree.

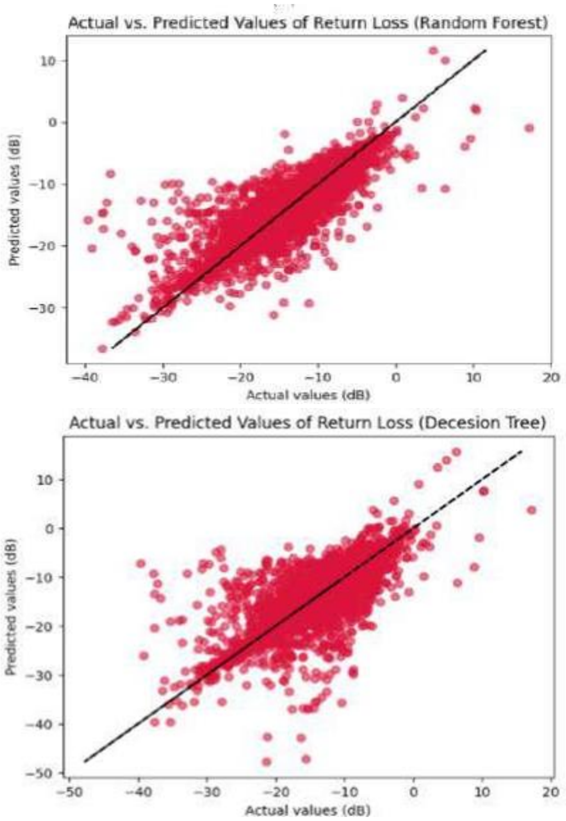


Fig. 10 shows actual value Vs predicted value of return-loss in Random-forest.

D. Return Loss in a random new variation of antenna design was predicted and simulated.

To fine-tune performance, innovative antenna design frequently calls for extensive electromagnetic simulations, which can be a resource- and time intensive procedure. This work presents by using Machine Learning which quickly optimize the working of antenna. In ML model training, an antenna configuration with random variation (L1=3.51 micrometer and W2=5.50micrometer) which is an input data to the design to evaluate prediction capability. In Figure 11 shows the different Machine Learning models like Decision-Tree and Random-Forest predict the Return-Loss values of close alignment with retrieved from the simulations.

This implies that without the need for drawn-out electromagnetic simulations, antenna engineers can quickly optimize antenna parameters by utilizing the predictive potential of machine learning. This Machine Learning models speed up the process of design and also saves computing power by drastically lowering the number of iterative cycles needed for optimization. With less time and effort, this revolutionary method makes it possible to construct state-of-the-art antennas, which eventually increases the capabilities of a variety of applications, including wireless communication and remote sensing.

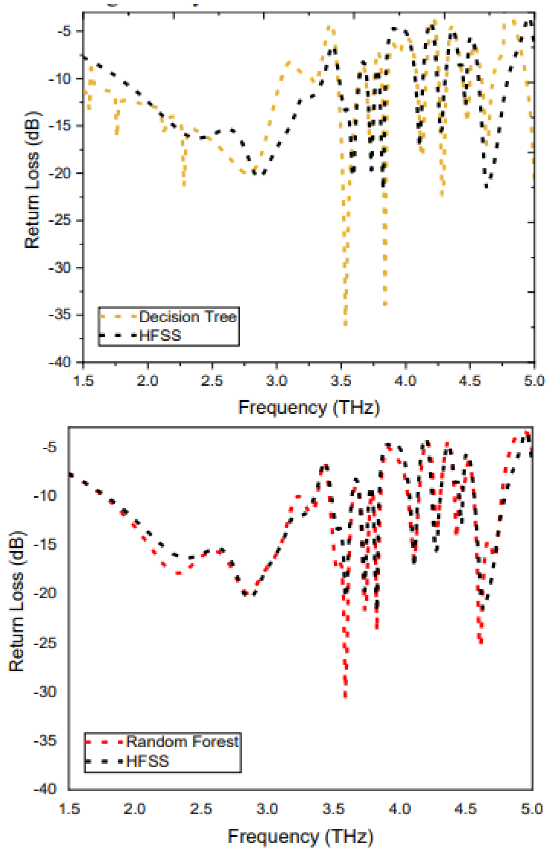


Fig.11 shows simulated and predicted in return-loss (a)Decision-tree (b)Random- fores

IV.CONCLUSION

In conclusion, the multiple design elements needed in creating an ideal THz antenna that satisfies 6G communication standards make it a difficult undertaking. In this work, the designed antenna return-loss functions at Terahertz band a crucial 6G band for future infrastructure was predicted using machine learning models like Decision Tree, and Random Forest. The result shows best performance between the models, Random-Forest algorithm topping this field with accuracy of 82 percent and an accuracy rate of over 71percent. The work is unique to use the ML techniques for the Terahertz antenna's return-loss prediction. This new methodology is better compared to traditional ones which forecast antenna performance through simulation and analytical methods. It is an effective technique for engineers and researchers doing their work in this field of Terahertz technology and it minimize the processing time and processing power for the antenna.

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