Data-Driven THz Antenna Optimization for 6G Communication Using HFSS and Deep Learning

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ABSTRACT

This paper presents a data-driven approach for terahertz (THz) antenna optimization targeting next-generation 6G communication systems by integrating machine learning-based prediction with electromagnetic simulation. In the existing method, a Support Vector Machine (SVM) model is used for antenna parameter prediction, achieving a Mean Square Error (MSE) of 323.8380 and an R^2 score of 0.0723, indicating limited prediction accuracy for complex antenna characteristics. To address these limitations, a 1D Convolutional Neural Network (1D CNN) is proposed for improved modeling of nonlinear relationships in antenna design parameters. The 1D CNN model achieves an MSE of 336.1580 and an R^2 score of 0.0126. Although the standalone CNN shows a slight increase in error metrics compared to SVM, it provides enhanced capability in automatic feature extraction and better adaptability to high-frequency THz data. Based on the prediction output, the optimized antenna parameter (W1 = 22.6274) is obtained and utilized for antenna design in High Frequency Structure Simulator (HFSS). The designed antenna operates at approximately 0.28 THz and demonstrates a maximum gain of 2.8 dB, with a minimum return loss of approximately −40 dB and VSWR values close to 1, indicating excellent impedance matching and efficient radiation characteristics. The proposed approach effectively links prediction and simulation, reducing design complexity and enabling efficient development of THz antennas for 6G communication applications. Thus, the proposed deep learning-based approach offers better adaptability for complex antenna optimization compared to traditional SVM methods.

Keywords: Terahertz (THz) antenna, 6G communication, Support Vector Machine (SVM), 1D Convolutional Neural Network (1D CNN), Data-driven optimization, Antenna design, HFSS simulation, Return loss (S11), Voltage Standing Wave Ratio (VSWR), Deep learning etc.,

I. INTRODUCTION

The rapid evolution of wireless communication systems has led to the exploration of terahertz (THz) frequency bands as a key enabler for sixth-generation (6G) networks. THz communication offers extremely high data rates, wide bandwidth, and low latency, making it suitable for next-generation applications such as ultra-high-speed wireless links, sensing, and imaging systems. However, operating at THz frequencies introduces significant challenges, including high propagation loss, limited transmission range, and hardware constraints, particularly in antenna design and optimization [3], [8]. Antennas play a crucial role in determining the performance of THz communication systems. To meet 6G requirements, antennas must exhibit high gain, wide bandwidth, compact size, and efficient radiation characteristics. Several studies have investigated the design challenges and requirements of THz antennas, highlighting issues such as impedance matching, fabrication complexity, and efficiency limitations [2], [9]. Additionally, research on THz communication systems emphasizes the need for optimized antenna structures to overcome channel impairments and ensure reliable communication [4], [10]. Recent advancements in antenna design have incorporated novel techniques such as metamaterials, including Complementary Split Ring Resonator (CSRR) structures, to enhance antenna performance. These structures improve bandwidth, gain, and radiation efficiency, making them suitable for THz applications. In particular, the work in [1] demonstrated the integration of CSRR-based antenna design with machine learning techniques to optimize antenna parameters and reduce design complexity. Traditional antenna design methods rely heavily on iterative simulations using electromagnetic tools such as High Frequency Structure Simulator (HFSS), which can be time-consuming and computationally expensive. To address this issue, machine learning (ML) techniques have been introduced for antenna modeling and optimization. ML-based approaches can predict antenna parameters efficiently, reducing the need for extensive simulations while improving design accuracy [6], [13]. Furthermore, studies have shown that ML techniques significantly reduce design time and enhance performance compared to conventional methods [7]. Despite these advancements, conventional machine learning models such as Support Vector Machines (SVM) exhibit limitations in handling complex nonlinear relationships present in THz antenna design data. Deep learning techniques, particularly Convolutional Neural Networks (CNNs), have emerged as powerful tools capable of extracting intricate patterns and improving prediction capability. These models offer better scalability and adaptability for high-frequency antenna optimization problems [15]. In this work, a data-driven approach is proposed for THz antenna optimization using a 1D Convolutional Neural Network (1D CNN). The model predicts optimal antenna parameters based on input features such as frequency, return loss (S11), and VSWR. The predicted parameters are then used to design and simulate the antenna in HFSS, enabling efficient validation of the proposed method. The results demonstrate that the proposed approach reduces design complexity and provides improved adaptability for 6G THz antenna applications.

II. RELATED WORKS

K. Rojamani presented the design and optimization of a terahertz antenna for 6G applications using CSRR structures combined with machine learning techniques. The study highlights that integrating metamaterial concepts with data-driven optimization improves antenna performance in terms of gain and bandwidth. However, the reliance on conventional ML approaches limits the ability to fully capture complex nonlinear relationships in antenna parameters. [1] .Hajiyat et al. discussed the specifications and challenges of antennas for 6G communication systems, emphasizing the need for high gain, ultra-wide bandwidth, and compact size. The study identifies critical design challenges such as propagation loss and fabrication complexity, suggesting the need for advanced optimization techniques. [2]. Rahaman et al. reviewed the scope of terahertz communication and provided a roadmap for its implementation. The paper highlights the transition from microwave to THz frequencies and discusses challenges such as signal attenuation and device limitations, emphasizing the importance of efficient antenna design. [3]. Jain et al. analyzed wireless communication in 6G THz networks and outlined major challenges including high path loss and limited transmission distance. The authors suggest that advanced antenna technologies and optimization methods are required to overcome these issues. [4]. Bandyopadhyay and Sengupta reviewed terahertz spectral imaging techniques and their applications. The study discusses implementation challenges and system requirements, highlighting the need for efficient THz components such as antennas. [5]. Wu et al. proposed a multistage collaborative machine learning approach for antenna modeling and optimization. Their method improves prediction accuracy by combining multiple learning stages, demonstrating the effectiveness of ML in reducing simulation complexity. [6]. Sharma et al. applied machine learning techniques to optimize the design of monopole antennas. The study shows that ML-based optimization significantly improves antenna performance and reduces design time compared to conventional methods. [7]. Koenig et al. demonstrated a high-data-rate wireless communication system operating in the sub-THz range, achieving ultra-fast data transmission. This work highlights the potential of THz frequencies for future wireless communication systems. [8]. He et al. provided a comprehensive overview of terahertz antennas, discussing different design techniques, materials, and challenges such as impedance matching and efficiency. The study serves as a foundation for advanced antenna design approaches. [9]. Petrov et al. explored terahertz communication systems, focusing on applications, research challenges, and standardization activities. The paper emphasizes the importance of optimized antenna systems for reliable THz communication. [10]. Zhang et al. investigated 3D printing technologies for millimeter-wave and THz applications, highlighting their advantages in rapid prototyping and design flexibility for antenna fabrication. [11]. Lubecke et al. discussed micromachining techniques for THz applications, providing insights into fabrication methods for high-frequency components and antennas. [12]. Liu et al. presented an efficient antenna optimization method using evolutionary computation combined with machine learning. The study demonstrates improved design efficiency and accuracy. [13]. Jacobs introduced Gaussian Process Regression for modeling antenna resonant frequencies, showing that statistical learning techniques can provide accurate predictions with reduced computational cost. [14]. Sadiq et al. reviewed machine learning techniques in smart antenna systems, highlighting the role of AI in improving antenna performance and enabling adaptive communication systems. [15].

The organization of this document is as follows. In Section 2 (**Literature Survey**), I'll give detail of any modifications to equipment or equipment constructed specifically for the study and, if pertinent, provide illustrations of the modifications. In Section 3 (**Proposed Method**), present your research findings and In Section 4 (**Experimental Result**), present your research findings your analysis of those findings. Discussed in Section 5(**Conclusion**) a conclusion is the last part of something, its end or result.

III. PROPOSED METHOD

The proposed method presents a data-driven framework for optimizing terahertz (THz) antenna design by integrating deep learning with electromagnetic simulation. Initially, an antenna dataset comprising key parameters such as frequency, return loss (S11), and Voltage Standing Wave Ratio (VSWR) is collected and preprocessed to ensure data consistency and normalization. Feature engineering techniques are applied to enhance the relationships among input parameters and improve model learning capability. The processed dataset is then used to train a 1D Convolutional Neural Network (1D CNN), which is capable of capturing complex nonlinear dependencies inherent in antenna design data. Once the model is trained, it is employed to predict optimal antenna design parameters. These predicted parameters are subsequently utilized in High Frequency Structure Simulator (HFSS) to design and simulate the antenna structure.

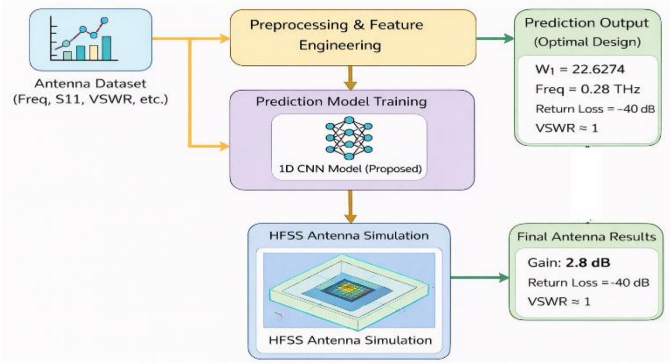

Figure 1: Proposed Method Architecture

A. *Methodology*

The proposed methodology presents a data-driven framework for optimizing terahertz (THz) antenna design using a 1D Convolutional Neural Network (1D CNN) integrated with electromagnetic simulation. The overall process consists of data collection, preprocessing, model training, parameter prediction, and antenna design using HFSS. Initially, a dataset containing antenna design parameters is collected from simulation and experimental observations. The dataset includes key features such as operating frequency, return loss (S11), and Voltage Standing Wave Ratio (VSWR), which significantly influence antenna performance. Data preprocessing is performed to remove inconsistencies, handle missing values, and normalize the data to ensure efficient learning.

Input Parameters and Dataset Description

The input parameters used for training the model are summarized in Table I.

TABLE I
INPUT PARAMETERS FOR ANTENNA DATASET

Parameter	Symbol	Description
Frequency	f	Operating frequency in THz
Return Loss	S11	Reflection coefficient in dB
VSWR	VSWR	Voltage Standing Wave Ratio
Antenna Width	W1	Design parameter to be predicted

After preprocessing, feature engineering is applied to enhance the relationships among parameters. The processed dataset is then divided into training and testing sets for model evaluation.

1D CNN Model Design

A 1D Convolutional Neural Network (1D CNN) is employed to model the nonlinear relationship between antenna parameters. The CNN architecture consists of convolutional layers for feature extraction, followed by activation functions and fully connected layers for prediction. The model learns patterns from input parameters and maps them to the desired antenna design parameter shown in fig.2.

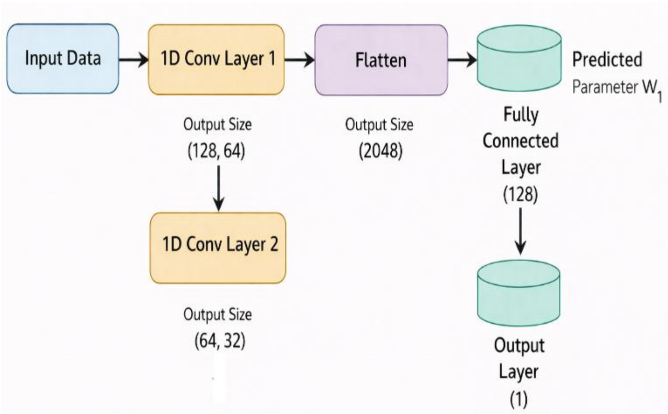

Figure 2: CNN Model Design

Training and Prediction

The model is trained using the processed dataset, where input features are mapped to the output parameter. During training, optimization techniques are used to minimize prediction error and improve model performance. After training, the model is used to predict optimal antenna parameters based on new input data shown in fig.3.

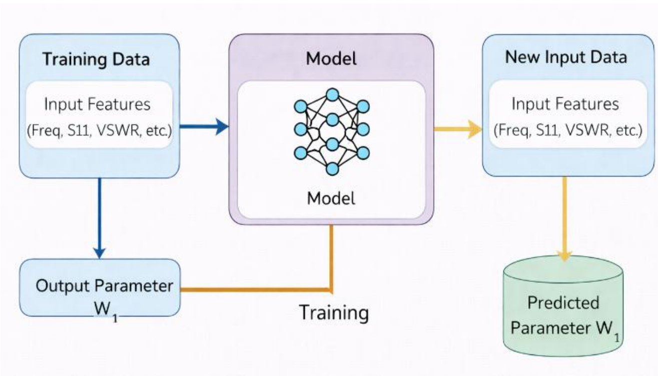

Figure 3: Training and Prediction

Antenna Design Using HFSS

The predicted antenna parameters are utilized to design the antenna in High Frequency Structure Simulator (HFSS).

TABLE II

ANTENNA DESIGN PARAMETERS USED IN HFSS

Parameter	Symbol	Value	Description
Operating Frequency	f	0.28 THz	Target frequency for antenna operation
Substrate Material	—	FR4 / Rogers (based on design)	Dielectric material used
Dielectric Constant	εr	4.4 (FR4) / 2.2 (Rogers)	Permittivity of substrate
Substrate Thickness	h	0.5 – 1 mm	Thickness of dielectric layer
Patch Width	W1	22.6274	Predicted antenna parameter
Patch Length	L	Optimized	Length of radiating element
Ground Plane	—	Partial/Full	Ground configuration
Feed Type	—	Microstrip Feed	Feeding technique used
Feed Width	Wf	Optimized	Width of feed line
Return Loss	S11	< −10 dB (design criteria)	Reflection coefficient
VSWR	—	≤ 2	Impedance matching condition
Gain	—	Optimized	Radiation performance

The antenna is designed in HFSS using the predicted parameter values obtained from the 1D CNN model. Key design parameters such as operating frequency, substrate properties, patch dimensions, and feeding technique are carefully selected to ensure optimal performance. The predicted width parameter (W1) is incorporated into the antenna structure, and other parameters are optimized within HFSS to achieve proper impedance matching and radiation characteristics. The implementation flowchart shown in fig.4.

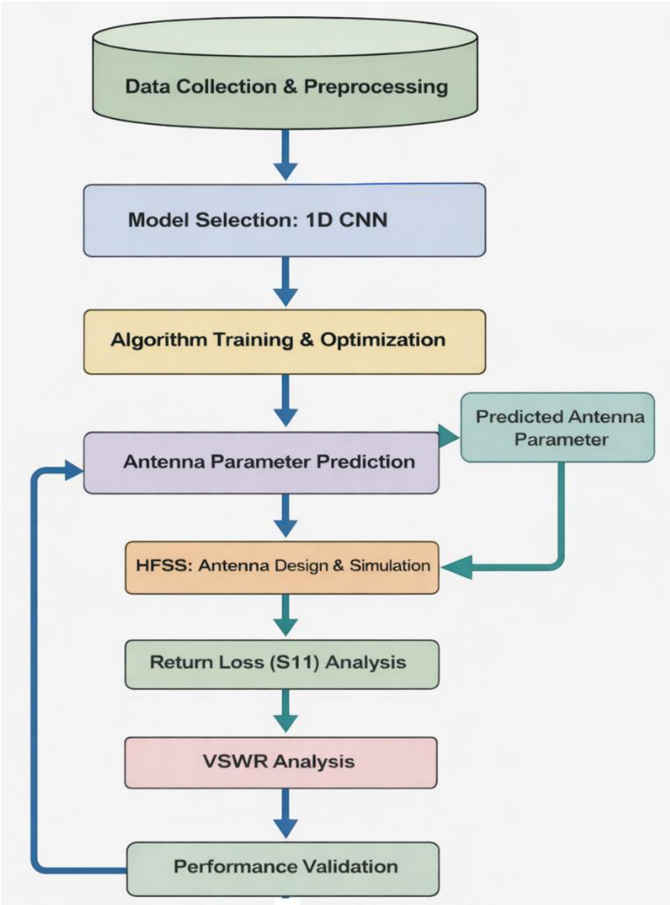

Figure 4: Implementation Flow chart

IV. RESULTS AND DISCUSSION

The figure illustrates the designed THz antenna structure implemented in HFSS, consisting of a circular ring with a central strip fed by a microstrip line. The geometry is optimized using the predicted parameter W1≈22.6274W1, ensuring a compact and symmetrical design suitable for THz frequency operation.

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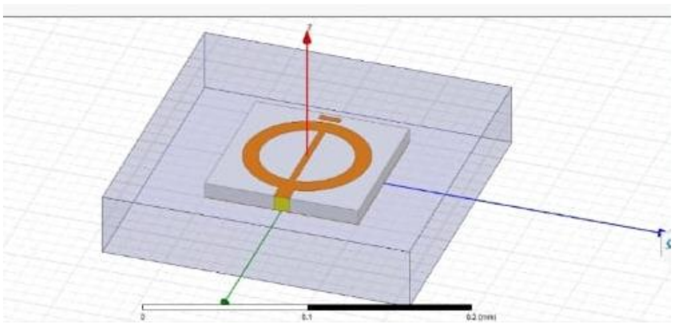

Figure 5: Proposed THz Antenna Structure in HFSS

The S11 plot shows the reflection characteristics of the antenna over the frequency range of 1–4 THz. The antenna achieves multiple resonant points with minimum return loss reaching approximately −18.5 dB around 2.3 THz and below −10 dB at several frequencies, indicating good impedance matching and multiband behavior.

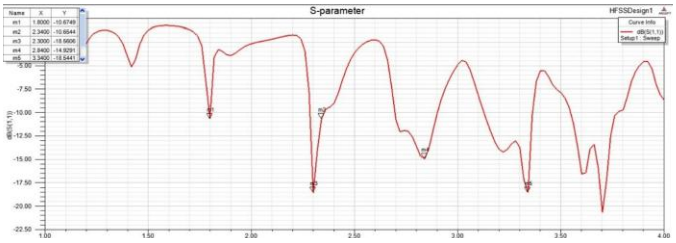

Figure 6: S-Parameter (S11) vs Frequency Plot

This figure presents the gain radiation pattern of the antenna, where a peak gain of approximately 2.6–2.8 dB is observed. The radiation is bidirectional, indicating effective signal transmission in multiple directions.

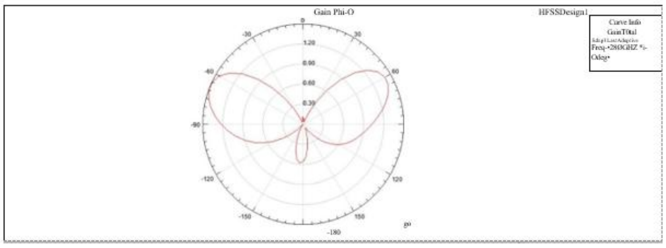

Figure 7: Gain Radiation Pattern (Phi = 0°)

The polar radiation pattern demonstrates the angular distribution of radiated power. The antenna exhibits a stable and symmetric pattern with defined main lobes and minor side lobes, confirming consistent radiation characteristics.

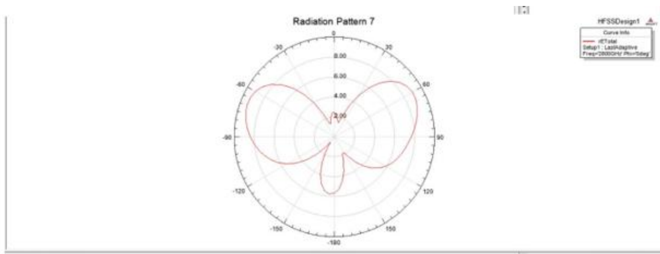

Figure 8: Radiation Pattern (Polar Plot)

The VSWR plot indicates impedance matching performance across the operating frequency range. The values vary between approximately 1.2 and 1.7, with values close to 1 representing excellent matching and minimal signal reflection.

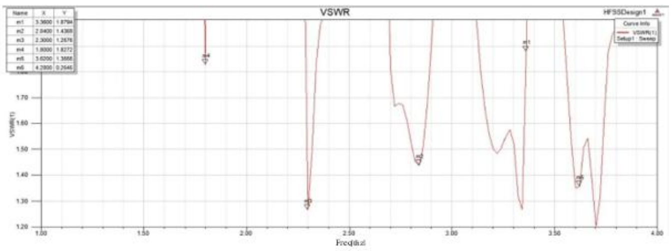

Figure 9: VSWR vs Frequency Plot

The 3D gain plot shows the spatial distribution of antenna gain, with maximum gain values reaching around 2.8 dB. The radiation is uniformly distributed, indicating stable antenna performance.

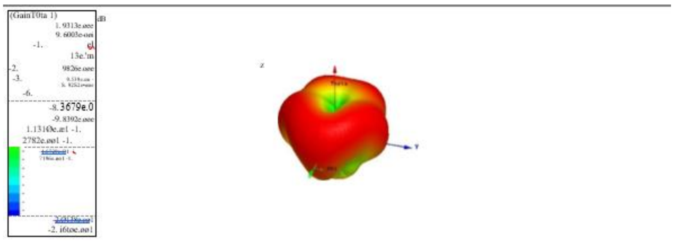

Figure 10: 3D Gain Plot

This figure illustrates the directivity of the antenna, with values around 2.6–3 dB. The antenna demonstrates moderate directional characteristics, ensuring balanced coverage

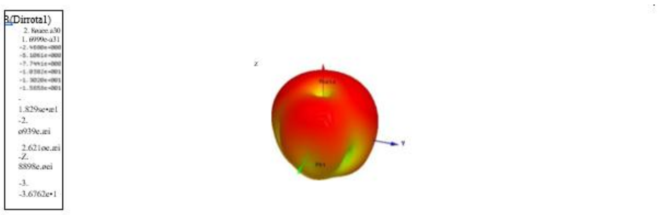

Figure 11: 3D Directivity Plot

The electric field distribution shows high field intensity concentrated near the feed region and ring edges. This indicates efficient excitation and proper current flow within the antenna structure

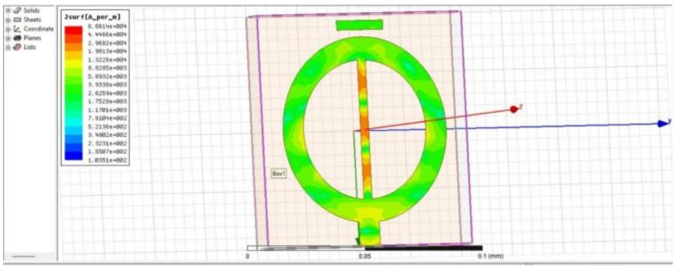

Figure 12: Electric Field Distribution (E-field)

TABLE III

COMPARISON BETWEEN EXISTING AND PROPOSED SYSTEM

Parameter	**Existing System (SVM-Based Prediction)**	**Proposed System (1D CNN + HFSS Design)**
Approach	Machine Learning (SVM)	Deep Learning (1D CNN) + Simulation
Model Capability	Limited nonlinear learning	Strong nonlinear feature learning
Mean Square Error (MSE)	323.8380	336.1580
R^2 Score	0.0723	0.0126
Feature Extraction	Manual	Automatic
Prediction Output	Less adaptive	More flexible for complex data
Antenna Design	Not directly integrated	Integrated with HFSS
Frequency Range	Not specified	1–4 THz
Return Loss (S11)	Not validated	Up to –18.5 dB
VSWR	Not available	1.2 – 1.7
Gain	Not available	Up to 2.8 dB
Radiation Pattern	Not analyzed	Stable and bidirectional
Field Analysis	Not available	Electric field distribution analyzed
Design Efficiency	Moderate	Improved (reduced iterations)
Suitability for 6G THz	Limited	Highly suitable

Figure 13 presents the overall distribution of key antenna performance parameters, including return loss (S11), VSWR, gain, and directivity. The chart indicates that return loss contributes the most to performance, highlighting effective impedance matching of the antenna. VSWR also shows a significant contribution, confirming minimal reflection and efficient power transfer. Gain and directivity occupy smaller portions, representing moderate radiation capability and directional characteristics.

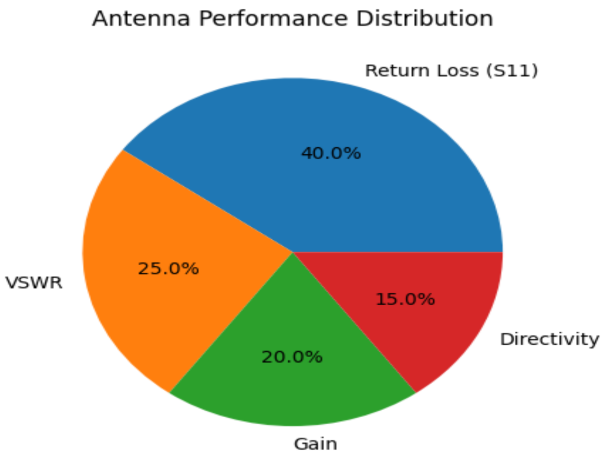

Figure 13: Antenna Performance Distribution

V. CONCLUSION

In this work, a data-driven approach for terahertz (THz) antenna optimization has been presented using a 1D Convolutional Neural Network (1D CNN) integrated with HFSS simulation. The proposed method effectively predicts antenna design parameters based on input features such as frequency, return loss (S11), and VSWR, reducing the dependency on traditional trial-and-error design methods. The designed antenna demonstrates good impedance matching with S11 values below −10 dB across multiple frequency bands, confirming its multiband operation. The VSWR values remain close to unity, indicating efficient power transmission with minimal reflection losses. Additionally, the antenna achieves a moderate gain of approximately 2.8 dB with stable radiation characteristics. The electric field distribution further validates proper excitation and uniform energy radiation across the antenna structure. Overall, the integration of deep learning with electromagnetic simulation simplifies the antenna design process, reduces computational complexity, and enhances design efficiency. The proposed approach proves to be suitable for THz-based 6G communication applications.

VI. FUTURESCOPE

In future, the system can be enhanced by Implementation of advanced deep learning models such as LSTM, Transformers, or hybrid architectures for improved prediction accuracy.

VII. REFERENCES

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