A Compact Multiband Antenna for Internet of Things (IoT) and 5G Applications: Design Optimization and Machine Learning (ML)-based Validation

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Manuscript received March 8, 2026; revised April 23, 2026; accepted May 2, 2026
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Abstract—**This paper presents a new, compact, multiband antenna designed for the Internet of Things (IoT) and Fifth Generation (5G) wireless networks to address the growing need for efficient and multi-functional antennas in modern communication systems. The antenna development progresses through four phases to achieve the desired prototype. In the first phase, a single-band antenna utilizing an inverted L-shaped element is designed. The second phase introduces a U-shaped dual-band configuration. The third phase combines a triangular shape with a reversed L structure to attain two distinct resonance frequencies. Finally, the fourth phase culminates in a triple-band antenna resonating at 1.8 GHz, 2.4 GHz, and 5 GHz, showcasing the design's adaptability. The final prototype is implemented on a cost-effective FR-4 dielectric substrate, making the antenna suitable for Wi-Fi, Industrial, Scientific, and Medical (ISM) bands, Wireless Local Area Network (WLAN), and 5G applications. The design has been fabricated and experimentally validated. To further enhance performance evaluation and reduce the computational burden associated with extensive parametric studies, a data-driven machine learning approach is employed for rapid prediction and optimization, using supervised Machine Learning (ML) regression models to validate the antenna gain based on simulated design parameters. The models are evaluated using statistical performance metrics, including the variance score, R-squared, mean squared error, root mean square error, and mean absolute error.**

Index Terms—**multiband antenna; Internet of Things (IoT); Industrial, Scientific, and Medical (ISM) bands; Machine Learning (ML); Fifth Generation (5G)**

I. Introduction

Recently, technology has experienced a significant increase in growth. Many aspects of human life and the world are dependent on the Internet. Smartphones, tablets, and other devices communicate with other devices via the Internet of Things (IoT). As a result, the IoT is considered in observational and sensing applications. Recently, various antenna configurations have been popularized for use in the IoT. In some common devices, single-band antennas are sufficient. However, modern systems require more efficient antennas (e.g., multiband or smart) while remaining compact (low-profile). With the rapid evolution of technology, modern wireless systems have multiple functions and must operate on various frequencies without increasing the antenna size [1–6]. The Fifth Generation (5G) is the most recent wireless communication technology and has had significant benefits over previous generations, such as high data throughput, lower delay, high capacity, and high efficiency [7–13]. The compact size, low profile, broad and multiple frequency spectra, cost-effectiveness, ease of fabrication, directional capabilities, compatibility with modern technology, and other benefits of microstrip antennas make it suitable for limited-space applications, wireless communications, satellite technology, radar systems, wireless power transfer application, and wireless capsule endoscopy system inside the body environment [14–17]. The microstrip multiband antennas can operate in multiple frequency ranges, which is essential for 5G technology, as it employ a broader spectrum of frequencies to enhance capabilities. Designing 5G antennas is complicated by considering factors like frequency higher than 2.5 GHz, beamforming, and compatibility with various cell phones and apps [18–21].

In the literature, multiple types of single-band and multiband monopoles have been constructed, including B, H-type, circular, U-shaped, M-shaped, L-shaped, and D-shaped [22]. Two or more bands of operation can be

doi: 10.18178/ijeetc.15.4.233-242

combined by etching slots into the antenna's radiating element, the ground plane for the antenna, or both [23, 24].

Recent works presented promising multiband microstrip antenna concepts, yet each would entail trade-offs. Al-Hiti *et al.* [25] achieved highly efficient mmWave multiband performance and limit it to very high frequencies that are unsuitable for many IoT scenarios. In addition, the proposed triple-band design was compact but still simulation-based only and had a narrow coverage [26]. Laxman *et al*. [27] concentrated on 28 GHz to 38 GHz operation but absence support for lower and IoT bands. Basha and Umadevi [28] refined the bandwidth using an array approach, at the cost of increased size and structural complexity, which may limit its practical application in compact devices. Pushadapu *et al*. [29] provided wide 5G multiband operation using Defected Ground Structure (DGS), yet this technique adds fabrication difficulty, complexity, and sensitivity which may obstruct its practical implementation in real-world applications. Saeidi *et al.* [30] used a metamaterial to design a dual-polarized Multiple Input Multiple Output (MIMO) antenna for sub-6 GHz applications with high gain and triple bands of operation but with a large size and complex structure.

Machine learning has been employed in various fields for many years. Still, its widespread use and acceptance have increased significantly in recent years due to technological advances and the availability of large datasets like Heart Disease Prediction and Malware detection. Over the past decade, scientists and engineers have dedicated their research to incorporating Machine Learning (ML) methods into different aspects of antenna design, leading to significant advances and practical applications. Recent advances in antenna design have led to a considerable increase in the use of ML. This is because ML can extract information from data gathered from simulated antennas and prototypes with proper training and testing. The production of mistakes increases the probability that the evaluated performance does not accurately represent the result. Machine learning-based predictions can help quickly predict final performance, eliminating the need for manufacturing and measurement tools, thus mitigating the impact of manufacturing-related variability.

In this study, ML is employed as a pre-validation tool to accurately estimate the gain of a single-element antenna prior to fabrication. A supervised regression approach is utilized to model the antenna's gain with high precision, significantly reducing fabrication uncertainty, cost, and time [31–34]. The proposed work presents a compact, partially grounded triple-band antenna designed to address the increasing demands of IoT and 5G applications. Developed through four progressive design stages, the final prototype operates at 1.8 GHz, 2.4 GHz, and 5 GHz, supporting applications such as Wi-Fi, ISM, Wireless Local Area Network (WLAN), and emerging 5G systems. The antenna achieves fractional bandwidths of 9.37%, 7.12%, and 18% across the respective bands, with stable omnidirectional radiation characteristics and realized gains of 1.6 dB, 1.57 dB, and 1.88 dB. To further validate performance, supervised ML regression models are implemented, where K-Nearest Neighbors (KNN) demonstrates over 97% prediction accuracy. A comparative analysis with existing works is provided in Table I.

TABLE I: COMPARISON WITH PREVIOUS WORKS

Ref.	Substrate	Resonance Frequencies (GHz)	Size (mm^2)	Maximum Gain (dB)	Bandwidth (GHz)	Radiation Efficiency
[1]	Rogers 5880	2.4, 2.4 and 2.8, 2.4	41.5 × 38.5 38.5 × 38.5 36.4 × 36.4	3.39, 3.45 and 3.2, 2.45	0.18, 0.02, and 0.22	–
[4]	FR-4	1.8, 2.4, 3.35, and 5.4	32 × 15	1.5, 1.75, 2.5, and 3.7	–	75%
[36]	FR-4	1.8, 2.4, and 5	209 × 260	4.40, 4.75, and 5.25	0.1	80 %
[37]	FR-4	2.4, 3.5, and 5.8	80 × 80	2.33, 3.14, and 2.89	0.14	79 %
[38]	FR-4	2.4	40 × 10	1.35	0.146	–
[39]	FR-4	2.4 and 5	34 × 26	2.2 and 2	0.22	–
[40]	FR-4	1.8 and 2.4	45 × 32	1.6 and 1.8	0.05	–
[41]	Rogers RO4003	3.5	14 × 14	1.42	0.2	42 %
[42]	FR-4	1.73 and 2.53	48 × 48	–3.8, and 1.9	0.03	–
[43]	Rogers 5880	3.08 and 12.16	112 × 26.5	9.97 and 8.45	–	–
[44]	FR-4 (3-layer)	2.64, 5.02, and 6.42	22 × 47	4.2, 3.3, and 3.7	0.4, 1.8, and 1	–
Proposed antenna	FR-4	1.8, 2.4, and 5	43 × 32	1.6, 1.57, and 1.88	0.17, 0.16, and 0.891	>70%

This paper is organized as follows: Section II presents the antenna structure. Section III presents the results and discussion of the proposed antenna. In Section IV, the proposed antenna is experimentally validated. Section V contains ML analysis and verification. Finally, concluding remarks are given in Section VI.

II. ANTENNA STRUCTURE

Four configurations are designed and simulated using a Computer Simulation Technology-Electromagnetic (CST-EM) simulator on an inexpensive FR-4 substrate. The first configuration is a single-band antenna with only one parasitic element, called an inverted I at 4.7 GHz. The second structure is called an L-shaped dual-band antenna at 2.4 and 4.8 GHz. The third structure uses a triangle shape and an I-shaped to get dual resonance frequencies of 1.8 and 5 GHz. The final structure is a triple-band configuration that works at three different resonance frequencies (f_1 = 1.8 GHz, f_2 = 2.4 GHz, and f_3 = 5 GHz). The antenna structure consists of an L-shaped microstrip patch and one triangular patch. Both are connected to the 50 Ω microstrip feeder line. The resonance frequency f_r and effective dielectric constant ε_{eff} for the proposed structure can be calculated using the following Eqs. (1) and (2) [35]:

$$f_r = \frac{c}{4L_{s1}\sqrt{\varepsilon_{\text{eff}}}} \quad (1)$$

$$\varepsilon_{\text{eff}} = \frac{\varepsilon_r + 1}{2} \quad (2)$$

where c is the speed of light, L_{s1} is the physical length of the resonator, ε_{eff} is the effective dielectric constant of the substrate and ε_r is the dielectric constant of the substrate. The proposed antenna has a dimension of 43 mm × 32 mm. Fig. 1 illustrates the proposed antenna, and all parameters used in designing the proposed antenna are summarized in Table II.

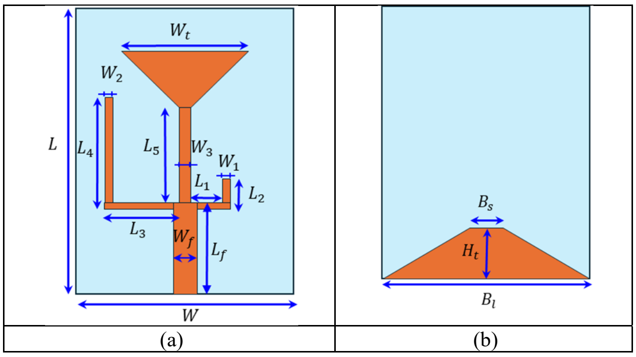


Fig. 1. The proposed multiband antenna: (a) front-side and (b) backside. All parameters' descriptions and dimensions are listed in Table II.

TABLE II: MULTIBAND MICROSTRIP ANTENNA PARAMETERS

Parameter	Description	Value (mm)
L	Total length	43
W	Total width	32
L_f	Feeder length	13.5
W_f	Feeder width	3.15
W_g	Ground width	32
W_1	Element 1 width	1
W_2	Element 2 width	1
W_3	Element 3 width	1.5
h	Substrate thickness	1.6
L_1	Length of horizontal arm for Element 1	5
L_2	Length of vertical arm for Element 1	3.65
L_3	Length of horizontal arm for Element 2	10
L_4	Length of vertical arm for Element 2	16.45
L_5	Length of vertical arm for Element 3	15.2
W_t	Width of triangle shape (Element 3)	18.7
B_s	Shorter base of the trapezoid (back side)	6
B_l	Longer base of the trapezoid (back side)	32
H_t	Height of trapezoid (back side)	7.5

III. RESULTS AND DISCUSSION

First, a single-band microstrip antenna using only 1 antenna element (Element 1) was designed as shown in Fig. 2(a). The simulated S-parameters for a single-band antenna are illustrated in Fig. 3(a). Fig. 2(b) illustrates the second configuration which consists of 2 radiating elements (Element 1 and Element 2), which resonate at two different resonance frequencies, as shown in Fig. 3(b).

In Fig. 2(c), the antenna configuration consists of two radiating elements (Element 1 and Element 3) and resonates at two different resonance frequencies, as shown in Fig. 3(c). In the final structure (Fig. 1), three elements (Element 1, Element 2, and Element 3) are used to get a triple-band antenna.

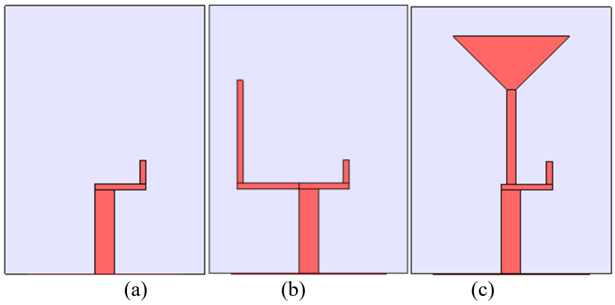


Fig. 2. The geometry of the proposed antenna: (a) Single band antenna, (b) Dual-band antenna (Element 1 and Element 2 are used), and (c) Dual-band antenna (Element 1 and Element 3 are used).

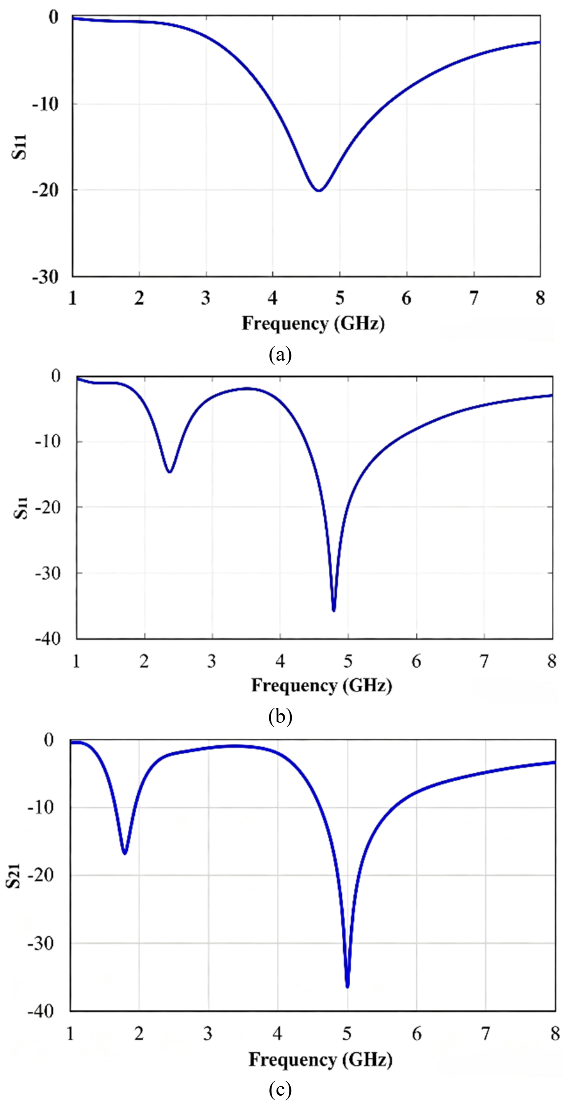


Fig. 3. The simulated S_{11} for the three structures in Fig. 2: (a) Single band antenna, (b) dual-band antenna (Element 1 and Element 2 are used) and (c) dual-band antenna (Element 1 and Element 3 are used).

The simulated return loss (S_{11}) is displayed in Fig. 4. The proposed configuration works at three different resonance frequencies (f_1 = 1.8 GHz, f_2 = 2.4 GHz, and f_3 = 5 GHz). The proposed antenna achieves a total efficiency of more than 70% over a band of operating frequencies, as shown in Fig. 5. All the above structures, as illustrated in Figs. 2–4, have the same ship design on the backside. Fig. 6 presents the radiation pattern for the designed antenna at three distinct frequencies. The simulated 2D far-field radiation pattern for the proposed antenna at $\varphi = 0°$ is demonstrated in Fig. 7. Fig. 8 presents the simulated 2D far-field radiation pattern for the proposed antenna at $\theta = 90°$.

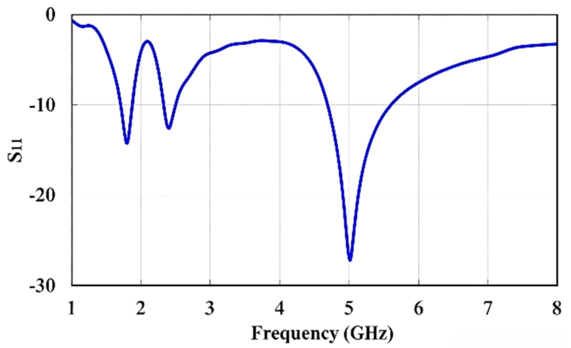


Fig. 4. S-parameter for the proposed multiband microstrip antenna.

The results demonstrate that as the frequency increases, the beamwidth of the main lobe expands, and the side lobes and the radiation pattern become more directional, with the main lobe narrowing and the side lobes becoming less prominent. This is expected because the antenna size increases with frequency, which improves directionality and narrows the beam. As observed from the above figures, the designed antenna offers fractional bandwidths of 9.37% at 1.8 GHz, 7.12% at 2.4 GHz, and 18% at 5 GHz. Additionally, the antenna features an omnidirectional radiation pattern with gains of 1.6 dB at 1.8 GHz, 1.57 dB at 2.4 GHz, and 1.88 dB at 5 GHz.

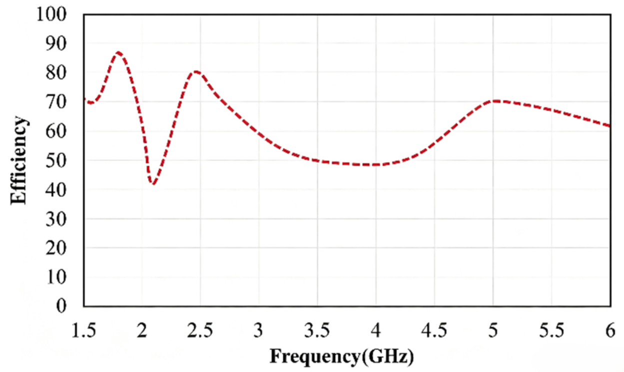
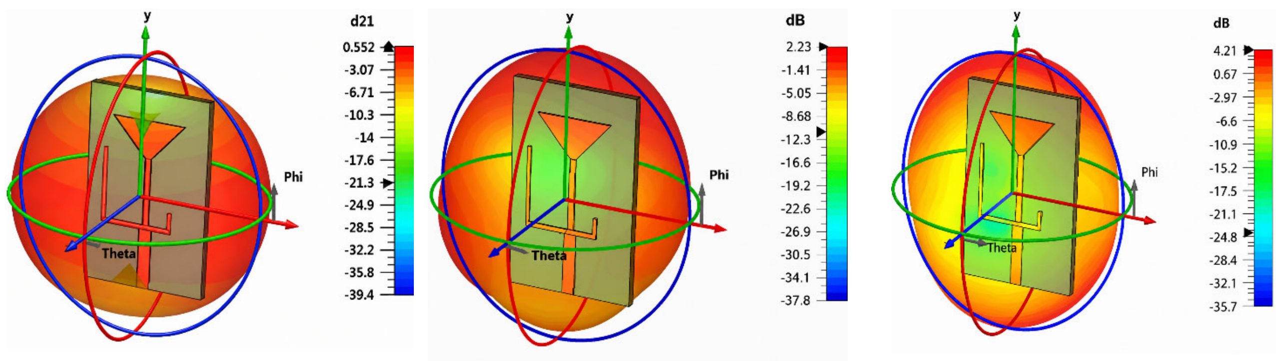


Fig. 5. Total efficiency for the proposed multiband microstrip antenna.

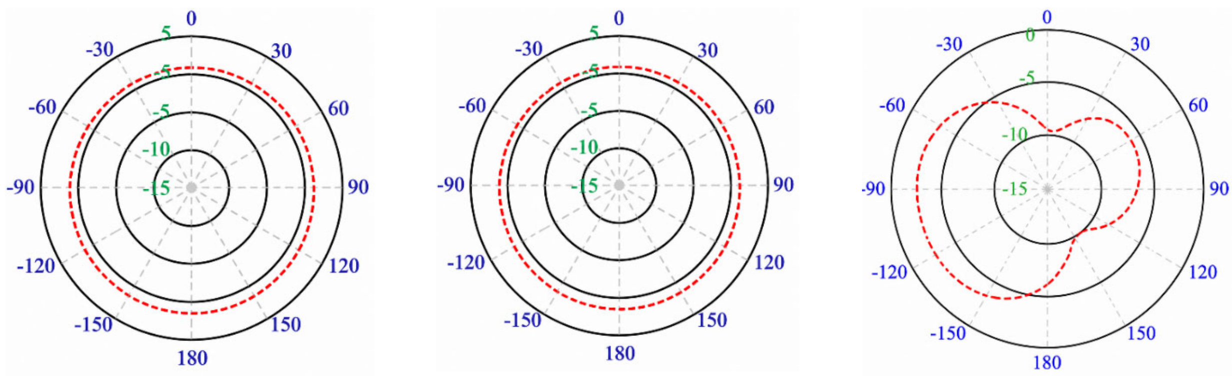
Even though the simulated gains are modest, this is typical for multiband antennas that prioritize compact size, low profile, and low cost while maintaining acceptable gain levels for IoT applications.

Fig. 9 illustrates the surface current distribution at different frequencies; 1.8 GHz, 2.4 GHz, and 5 GHz.



(a) (b) (c)

Fig. 6. 3D radiation pattern of the designed multiband antenna at (a) f_1 = 1.8 GHz, (b) f_2 = 2.4 GHz, and (c) f_3 = 5 GHz.



(a) (b) (c)

Fig. 7. 2D radiation pattern of the designed multiband antenna at $\varphi = 0°$ for (a) f_1 = 1.8 GHz, (b) f_2 = 2.4 GHz, and (c) f_3 = 5 GHz.

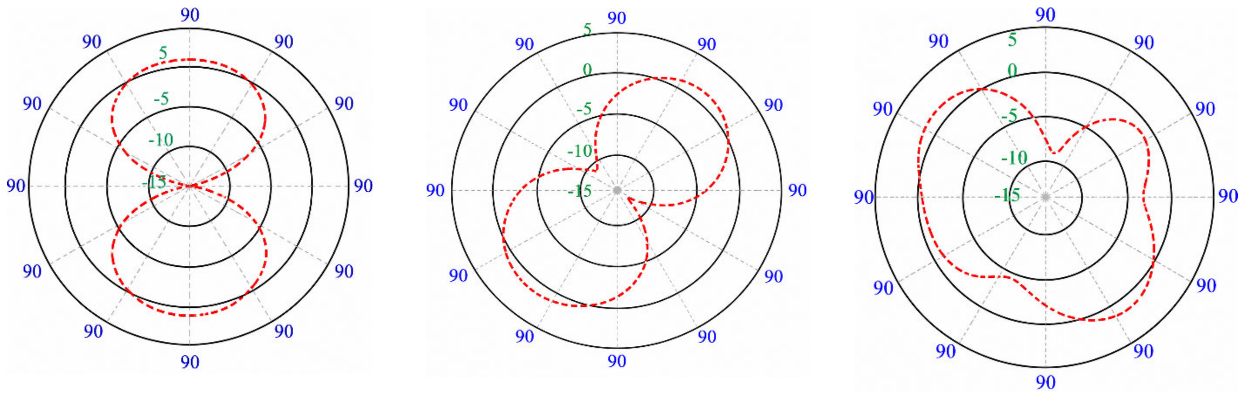


Fig. 8. 2D radiation pattern of the designed multiband antenna at $\theta = 90°$ for (a) $f_1 = 1.8$ GHz, (b) $f_2 = 2.4$ GHz, and (c) $f_3 = 5$ GHz.

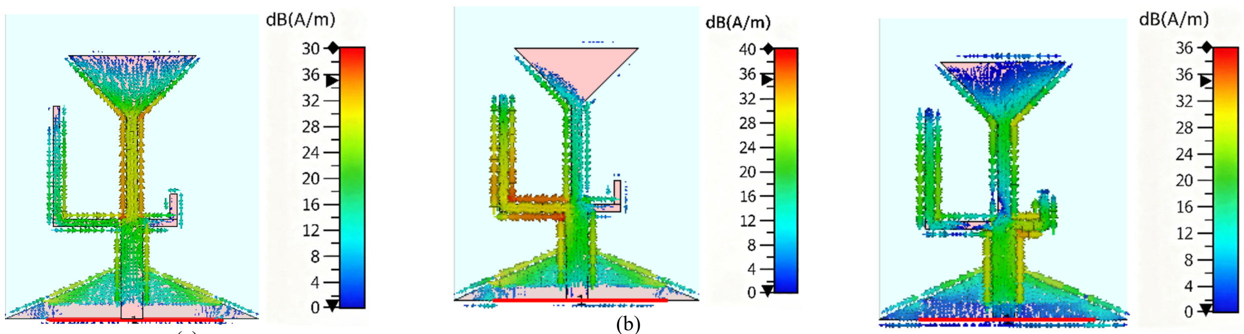


Fig. 9. Surface current distribution of the designed antenna: (a) 1.8 GHz, (b) 2.4 GHz, and (c) 5 GHz.

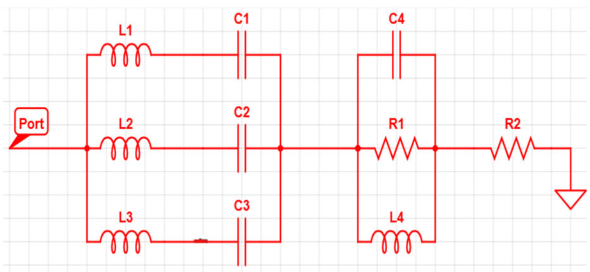


Fig. 10. The equivalent circuit was designed using keysight ADS.

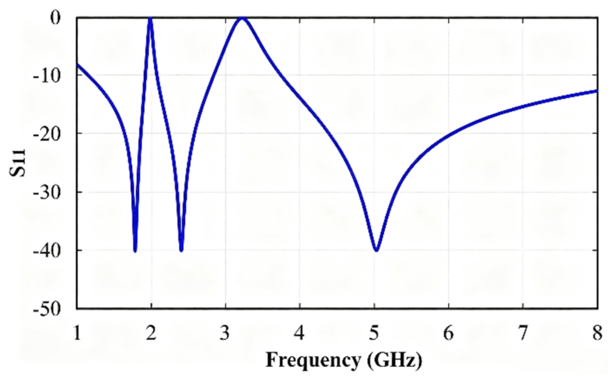
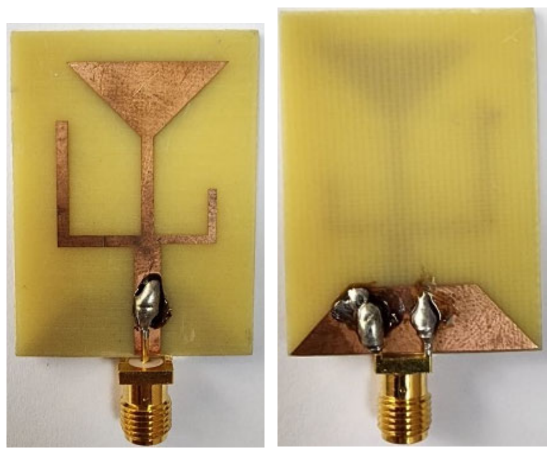


Fig. 11. Simulated and measured reflection coefficient of the designed microstrip rectifier.

The equivalent circuit for the designed antenna has been designed using Keysight ADS software, which can be seen in Fig. 10. The reflection coefficient of the designed schematic triband antenna was simulated to be –32.7 dB, –40.1 dB, and –39.3 dB, at 1.8 GHz, 2.4 GHz, and 5 GHz respectively, as depicted in Fig. 11.

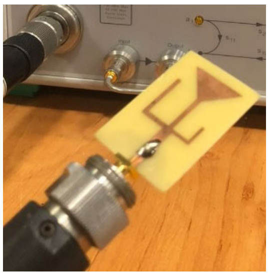
IV. Measurement and Fabrication

The proposed structure is simulated, fabricated, and measured. The design concept and optimization process through simulation are described in the above two sections. In this Section, the fabrication process and subsequent performance characterization of the compact multiband antenna are displayed. The antenna element is printed on the front and back surfaces of an FR4 dielectric substrate. As illustrated in Fig. 12, a 50-Ω connector connects the prototype to the vector network analyzer.

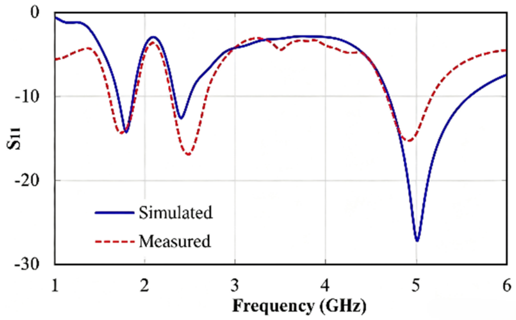


(a) (b)

Fig. 12. The fabricated structure: (a) front side and (b) backside.



(a)



(b)

Fig. 13. Return loss for the proposed structure: (a) Connected to the VNA and (b) Simulated and measured S_{11}.

The suggested antenna was designed using a CST-EM simulator, and the validation was carried out with the Anritsu Vector Network Analyzer (VNA)-37369C. The measured S-parameters (S_{11}) versus the simulated ones are plotted across the operation band in Fig. 13. The results in Fig. 13(b) show that the antenna operates at the three frequencies (1.8 GHz, 2.4 GHz, and 5 GHz) with slight variations in frequency and minor differences in resonance depth, which may have occurred due to the effects of adding an SMA conductor, substrate permittivity variations, and manufacturing tolerance.

Fig. 14 illustrates the radiation patterns measurement setup in an anechoic chamber. However, the simulated and measured radiation patterns at $f = 1.8$ GHz, $f = 2.4$ GHz, and $f = 5$ GHz are shown in Fig. 15. The figures plot the Two-Dimensional (2D) radiation pattern in E- and H-planes.

At high frequencies, FR-4 shows high dielectric loss and major dispersion, which can change the antenna performance and stability. These effects may be more noticeable under differentiated environmental circumstances, including temperature and humidity. Additionally, certain minor deviations in the S-parameters are seen due to fabrication and measurement tolerance.

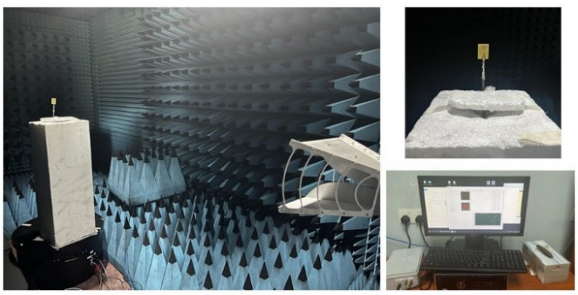
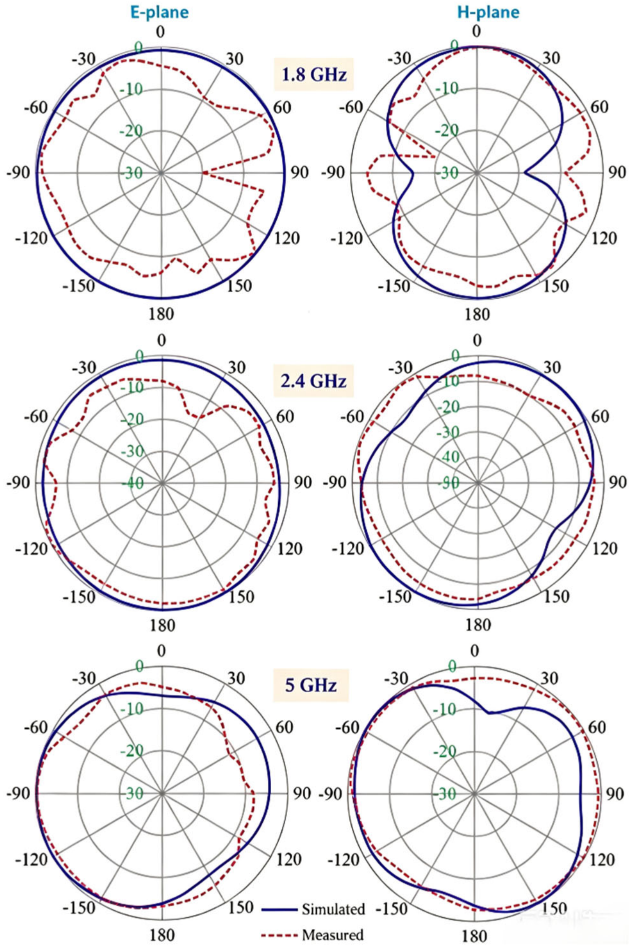


Fig. 14. Photographs of the anechoic chamber measurement setup.



(a) (b)

Fig. 15. Simulated vs measured radiation pattern at: (a) $\varphi = 0°$ and (b) $\theta = 90°$.

V. MACHINE LEARNING (ML) VERIFICATION AND ANALYSIS

Machine learning tools can be used to reduce the time spent on antenna design and performance optimization, thus enabling faster prototyping and modeling. In addition, the manufacturing process inefficiencies and predict outcomes can be addressed without the need for time-consuming and labor-intensive simulations. 2 steps are involved in implementing ML for antenna design. Gathering the relevant data to train ML models effectively is vital. When designing a triple-band antenna, conducting a detailed parametric sweep on key geometric parameters is essential to achieve optimal performance. Critical components such as feeder length 12 mm to 15 mm, feeder width 2 mm to 4 mm, ground width 25 mm to 32 mm, and the vertical arm lengths of Element 1 2.2 mm to 4.1 mm, Element 2 13 mm to 18 mm, and Element 3 12 mm to 15 mm were systematically varied to study their influence on impedance matching, resonance, and bandwidth. Each range was determined carefully through extensive iterative simulations to ensure accurate tuning across all three operating bands. The elements significantly affect the antenna's overall performance.

A comprehensive dataset was generated using parametric sweep simulations in Computer Simulation Technology (CST), Microwave Studio (MWS), resulting in 239 samples, with each sample comprising multiple features, yielding over 1000 data points. During the second phase, various Machine Learning (ML) techniques were employed to evaluate key performance parameters, including antenna efficiency and bandwidth. Following standard statistical practices, the dataset was divided into training and testing subsets, with 80% (191 samples) allocated for training and the remaining 20% (48 samples) reserved for testing. The ML models were trained using the training dataset to learn the underlying relationship between antenna design parameters and performance metrics. Subsequently, the trained models were utilized to predict antenna gain. The predicted results were then systematically compared with the testing dataset to assess model accuracy and generalization capability. This structured approach ensures reliable performance evaluation and validates the effectiveness of the ML-based prediction framework

During the training phase, hyperparameter optimization was employed to fine-tune the models, aiming to minimize prediction errors and enhance overall accuracy. The error and accuracy from this comparison were analyzed to validate the predicted antenna gain, ensuring model reliability. Five different regression models are being assessed: K-Nearest Friends (KNN), Decision Tree Regression (DTR), Random Forest Regression (RFR), Extra Tree Regression (ETR), and Extreme Gradient Boosting (XGBoost). Google Collab is used for ML research. The methodology is depicted in a flowchart in Fig. 16.

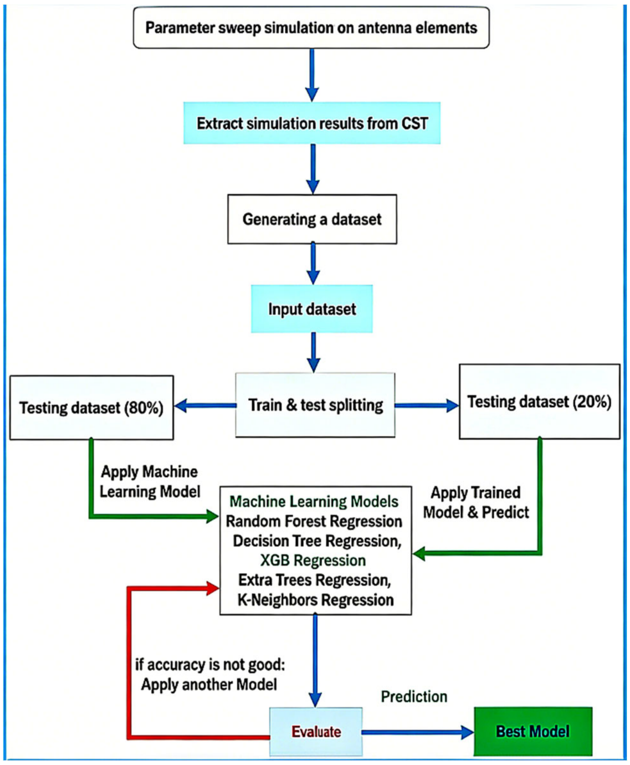


Fig. 16. ML Methodology flowchart.

A. Machine Learning (ML) Algorithms and Metrics for Evaluating ML Performance

ML provides several powerful regression techniques for predicting continuous outcomes, such as antenna gain. In this study, various regression models were employed to achieve accurate predictions based on the dataset generated from the parametric sweep of antenna design parameters. Each model was carefully selected for its ability to handle numerical datasets effectively while ensuring accuracy and minimizing errors. One of the models used is RFR, a technique for ensemble learning that reduces overfitting and increases accuracy by combining the predictions of several decision trees. Random Forest Regression (RFR) enhances predictive performance by randomly selecting subsets of data and attributes for each tree, creating a diverse collection of models that, when combined, provide robust predictions.

KNN regression is another non-parametric technique utilized in this study. KNN estimates relationships between variables by averaging the outcomes of nearby observations in the feature space, making it a simple yet effective method for predicting continuous outcomes. Additionally, DTR constructs a tree-like framework to evaluate the properties of input variables.

The proposed approach systematically splits the dataset based on attribute values, producing outputs that are both interpretable and accurate. It is particularly useful for understanding the impact of individual parameters on antenna gain. The study also employs Extra Trees Regression (ETR), a variant of Random Forest that introduces greater randomness in tree construction and split selection. The algorithm's increased randomness often enhances the model's generalizability and reduces overfitting. Lastly, XGBoost, an efficient and scalable implementation of gradient-boosted decision trees, was used for its exceptional speed and performance. XGBoost is particularly well-suited for large numerical datasets and is known for delivering highly accurate predictions. The models were selected for their complementary strengths in handling numerical data, ensuring reliable and precise predictions of antenna gain while maintaining computational efficiency. This research evaluated various ML methods using a variety of statistical metrics to assess their effectiveness. The fidelity of predictions was measured using R-squared (R^2) and the explained variance score, along with Mean Squared Error (MSE), Mean Absolute Error (MAE), and Root Mean Square Error (RMSE) as the selected error metrics for ML. The error matrices can be determined by utilizing the Eqs. (3–5):

$$\text{MSE} = \frac{1}{n}\sum_{i=1}^{n}(y_i - \hat{y}_i)^2 \tag{3}$$

$$\text{MAE} = \frac{1}{n}\sum_{i=1}^{n}|y_i - \hat{y}_i| \tag{4}$$

$$\text{RMSE} = \sqrt{\sum_{i=1}^{n}\frac{(y_i-\hat{y}_i)^2}{n}} \tag{5}$$

where n is the number of errors, $|y_i - \hat{y}_i|$ is the error absolute, y_i is the real value of the variable of interest for a specific instance i, and $\hat{y}_i$ is the expected value of the variable of interest for the same instance i, as estimated by the ML model. Similarly, y_a is the actual value and y_p is the predicted value.

$$R^2 = 1 - \frac{\sum_{i=1}^{N}(y_i - \hat{y}_i)^2}{\sum_{i=1}^{N}(y_i - \hat{y}_i)^2} \quad (6)$$

$$\text{Explained Varience score } (y, \hat{y}) = 1 - \frac{\text{Var}(y-\hat{y})}{\text{Var}(y)} \quad (7)$$

B. Gain Verification Analysis

The procedures for analyzing and comparing are discussed, including ETR, DTR, RFR, KNN, and XGBoost. Several metrics, such as variance score, R-squared, MAE, RMSE, and MSE, are used to estimate each approach. Furthermore, Fig. 17(a) shows a bar graph that contrasts the fidelity of the models. The most accurate representation of a realized gain in the operation band is KNR. For KNN, the error is less than 6% for all the matrices. The maximum error value (6%) was determined for KNN at the RMSE error matrix. An error margin of 6% is considered acceptable for the proposed application. The most appropriate model has been chosen based on the combination of error and accuracy. However, KNN has the lowest error when the evaluation method at MSE is employed. However, when considering RMSE, all models display the highest error, as shown in Fig. 17(b). Furthermore, the accuracy in all models is more than 97% in R^2 and Var-score, which is very important in verifying the simulated realized gain with the prediction.

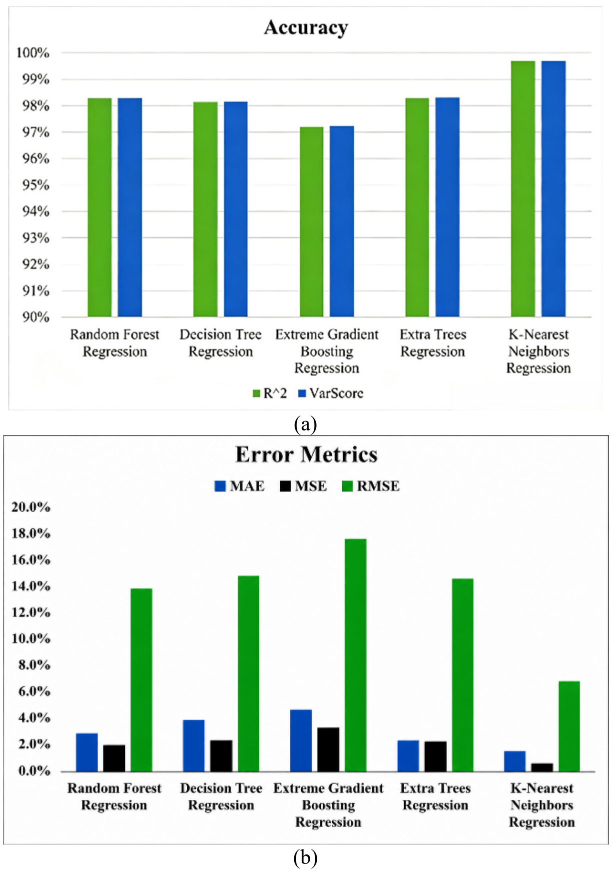


Fig. 17. Performance comparison of ML regressors (gain): (a) Accuracy and (b) Error matrix.

VI. Conclusions

This study introduced a compact and efficient multiband antenna specifically designed for IoT and 5G wireless applications. The development followed a structured four-phase approach, evolving from a single-band configuration to a triple-band prototype. The final design integrates two L-shaped patches and one triangular patch and operates at resonance frequencies of 1.8 GHz, 2.4 GHz, and 5 GHz. Implemented on a cost-effective FR-4 substrate, the prototype demonstrates suitability for Wi-Fi, ISM bands, WLAN, and 5G communication systems. The fractional bandwidths for the proposed antenna are 9.37% at 1.8 GHz, 7.12% at 2.4 GHz, and 18% at 5 GHz, while maintaining an omnidirectional radiation pattern and gain values of 1.6 dB, 1.57 dB, and 1.88 dB, respectively.

To ensure the reliability of the proposed design, an ML-based validation was employed using five different supervised regression models. Among these, the K-Nearest Neighbors (KNN) model outperformed others, achieving prediction accuracy exceeding 97% with minimal error, confirming the precision of the simulated gain values. The antenna was fabricated and experimentally tested, showing strong agreement with simulation outcomes, which verifies its practical viability. The results establish the proposed antenna as a promising solution for next-generation wireless communication systems, offering a balance of performance, compactness, and cost-effectiveness.

In the future, PIN diodes or reconfigurable elements can be added for use in reconfigurable smart surfaces and adaptive IoT systems. Antenna performance could also be enhanced using polarization diversity or MIMO configurations, potentially enabling applications in 5G networks and wearable biomedical devices.

Conflicts of Interest

The authors declare no conflicts of interest to report regarding the present study.

Author Contributions

Wazie M. Abdulkawi: conceptualization, methodology, validation, formal analysis, investigation, resources, writing—review and editing, supervision, project administration, funding acquisition; Abdallah M. Nabil: conceptualization, methodology, software, formal analysis, investigation, data curation, writing—original draft preparation; Md Afzalur Rahman: formal analysis, investigation, data curation, writing—review and editing; Samir Salem Al-Bawri: methodology, validation, formal analysis, investigation, resources, writing—review and editing, supervision; Hassan Yousif Ahmed, methodology, formal analysis, investigation, visualization; Yosef T. Aladadi: methodology, formal analysis, investigation, writing—review and editing, visualization; all authors had approved the final version.

Funding

This research was funded by Prince Sattam bin Abdulaziz University, grant number (PSAU/2025/01/34384).

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