Dual band antenna design for 4G/5G application and prediction of gain using machine learning approaches

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ABSTRACT

In this research, we disclose our findings from exploring a machine learning (ML) approach to enhancing the antenna's performance in Industrial and Innovation contexts, particularly for4G and 5G (n77, n78) contexts. Methods for evaluating antenna performance utilizing simulation, the resistor, inductor, and capacitor (RLC) equivalent circuit model, and ML are discussed. Gain is a maximum of 6.56 dB and efficiency is about 97% for this antenna. The predicted antenna gain is calculated using an alternative supervised regression ML technique. Multiple measures, including as the variance score, R-square (R2), mean square error (MSE), and mean absolute error (MAE), can be used to assess an ML model's performance. The linear regression (LR) model predicts profit with the fewest errors and highest accuracy of the five ML models. Finally, computer simulation technology (CST) and advanced design system (ADS) modeling findings, along with ML results, show that the proposed antenna is a promising option for 4G and 5G applications.

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1. INTRODUCTION

The demand for antennas capable of operating across a wide range of frequencies has risen sharply as researchers explore methods to enhance the efficiency and versatility of wireless communication systems. The multiband microstrip patch antenna is an exceptional and advanced choice due to its capacity to accommodate multiple communication protocols and frequencies within a single, lightweight package. This makes it an ideal solution for modern communication needs, offering flexibility and high performance in a compact form [1]. Several methods are employed by the multiband microstrip patch antenna to accomplish this goal. These methods include the use of numerous resonators, parasitic elements, and tailored feeding networks. These advancements allow the antenna to resonate at different frequencies, making it suitable for use with a wide range of wireless communication protocols [2]. Microstrip patch antennas have advanced and found new uses in the internet of things (IoT), 5G connectivity, and other areas as wireless technology have expanded [3]. Cellular broadband communication standard, 4th generation long-term evolution (4G LTE). It's a major step forward in mobile network technology that should make it easier to stay online while on the go with gadgets like smartphones, tablets, and even some PCs. The use of the 2.4 GHz frequency range, a critical enabler for reliable IoT connection, is at the center of this revolution [4]. IoT devices can easily connect, communicate, and share data thanks to today's 2.4 GHz wireless communication protocols [5]. The microstrip patch antenna's flat and small form factor makes it a great fit for the IoT, which prioritizes low-profile and space-saving communication solutions [6]. In the 3.5 GHz and 3.7 GHz bands, patch antennas are commonly employed for 5G applications [7]. These stretch from the C-band to the ultra high frequency (UHF) bands and are part of the mid-band spectrum. Coverage and throughput in 5G networks are severely hindered by interference in this frequency range. It strikes a middle ground between the larger data speeds and narrower coverage available in the mm-wave frequencies and the lower frequency bands (sub-6 GHz) [8]. The next generation (5G) of wireless communication technology, 5G new radio (5G NR) is the backbone of 5G networks. To accommodate the growing need for faster data transfer rates, reduced network latency, and enhanced overall network performance, it includes several enhancements over its predecessors [9]. The N77 frequency band is ideal for delivering 5G services in urban and densely populated areas, where extensive coverage and capacity are required to meet the rising demand for fast, dependable wireless internet [10].

In Table 1, we have presented a comprehensive comparison of various processes running simultaneously. Previous literature reports indicated minimum reflection coefficients of -27.5 dB, -20 dB, -34.98 dB, -29.17 dB, -37.42 dB, -19 dB, and -31.2 dB [11]-[18]. However, upon conducting, computer simulation technology (CST) simulations for the suggested antenna, we discovered that the minimum reflection coefficients were measured at -28.132 dB, -32.11 dB, and -28.60 dB at the resonant frequencies of 2.4 GHz, 3.5 GHz, and 3.7 GHz, respectively. Additionally, based on the CST study, we determined that the proposed design demonstrates the highest gain of 6.56 dB, surpassing the gains achieved in the previously referenced studies. Furthermore, the relevant articles [14]-[17] demonstrate radiation efficiencies of 73%, 80-96%, 77.44%, and 80%. However, our suggested microstrip patch antenna recorded radiation efficiencies of 84.15%, 84.27%, and 83.79% in CST. It's important to note that the references do not cover trials involving machine-learning techniques, even though these techniques are extensively used in design. Furthermore, we integrated the resistor, inductor, and capacitor (RLC) equivalent circuit into the suggested antenna, a feature not previously discussed in the cited literature.

Table 1. Performance comparisons with the published state of the art

Parameter	[11]	[13]	[14]	[12]	[15]	[16]	[17]	[18]	This work
Operating frequency (GHz)	2.1, 3.3, 4.1	3.73, 6.73, 9.56	3.3, 3.8	1.8, 3.5, 5.4	3.75, 5.17	2.45, 3.73	_	3.54, 6.72	2.47, 3.5, 3.75
Return loss (dB)	-27.5, -20.5, -24.1	-11.81 -20.15 -13.03	−31.1, −34.98	_	-13.7, -29.17	-35.47, -37.42	-19	-21.4, -31.2	-28.13 -32.11, -28.63
Bandwidth (MHz)	200, 140, 200	10, 29, 19	720 720	140 180 200	400 700	_	867	_	187.5, 387.6
Peak gain (dBi)	4.5,6.1, 4.3	2.8, 2.95, 3.2	2.5	2.34, 5.2, 1.42	4.35	4.74, 3.62	6.21	4.78, 4.65	6.56
Radiation efficiency %	_	_	_	73%, 68%, 59%	80%	77.44%, 58.96%	80%	_	84.1%, 84.2%, 83.7%
Substrate material	Roger RT5880	FR4	FR-4	FR4	RT Duroid 5880	Rogers XT 8100	FR-4	FR-4	FR4
RLC equivalent CKT	No	No	No	No	No	No	No	No	Yes
Machine learning (ML) approach	No	No	No	No	No	No	No	No	Yes

2. METHOD

The proposed antenna has been designed and simulated using CST. This triband microstrip patch antenna is designed to work at three different frequencies: 2.4 GHz, 3.5 GHz, and 3.7 GHz. In Figure 1(a), we see the proposed antenna's frontal geometry. The horizontal slot, which includes slots 1, 2, and 3, has dimensions of 3.55 mm by 39.11 mm. Slot 2 is used between slots 1 and 3, and slot 1 is utilized in the top left corner. Slot 3 is used at the bottom left. There is a 15.15 mm gap between slots 1 and 2, and an 11.85 mm gap between slots 2 and 3. The vertical slot, which includes slots 4, 5, and 6, has the dimensions of 33.32×2.32 mm. The distance between slots 4 and 6 is 8.68 mm, and the slot in the middle, slot 5, is used at the top right. Figure 1(b) shows the patch inverted and used as a ground slot; its thickness is 0.02 mm, and it is constructed of copper annealed material.

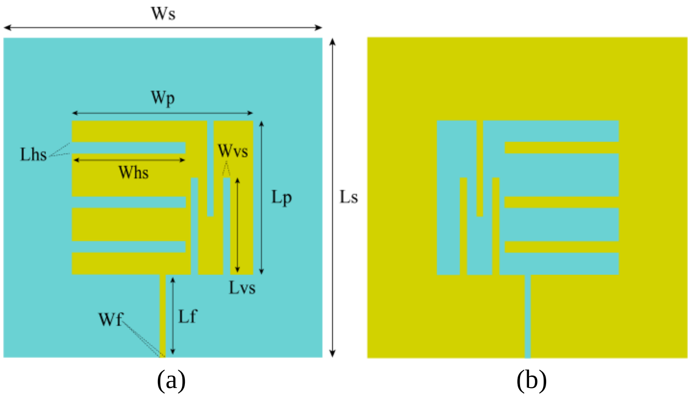


Figure 1. Geometry of proposed antenna; (a) front and (b) back

Here, Ws=110 mm; Ls=110 mm; Wp=62.57 mm; Lp=53.32 mm; Wf=2.45 mm; Lf=28.34 mm; Lvs=33.32 mm; Wvs=2.32 mm; Lhs=3.55 mm; and Whs=39.11 mm.

3. RESULT ANALYSIS

An antenna's particular specifications essentially define its operational ranges and performance characteristics. In the following analysis, we thoroughly examine these crucial factors, emphasizing their importance in determining the antenna's functioning and effectiveness at specific frequencies.

3.1. Reflection coefficient

Reflection coefficient is one of the most important criteria to consider when analyzing the performance of an antenna since it determines the strength of the signal by comparing the total amount of power that is received by the antenna to the total amount of power that is reflected from the antenna. To achieve the appropriate level of performance, the value of the return loss should be lower than -10 dB. Figure 2 depicts the data that shows the frequencies at which the return loss is at its lowest. These frequencies are 2.47 GHz (-28.132 dB), 3.5 GHz (-32.111 dB), and 3.75 GHz (-28.603 dB) demonstrates that the suggested antenna is suitable for 4G/LTE and mid-band 5G (n77 and n78) applications, since the simulated antenna can be operated at three different frequencies.

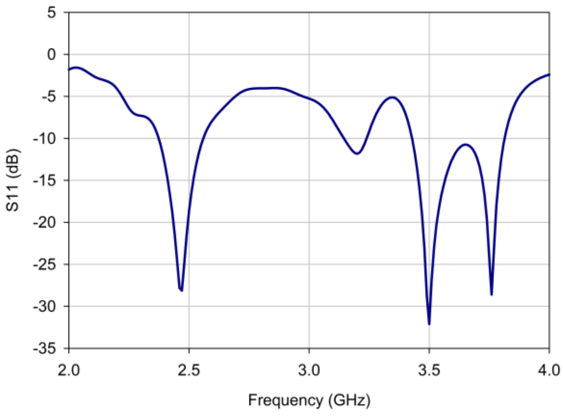


Figure 2. Simulated reflection coefficient of the proposed antenna

3.2. Gain and efficiency

Gain and efficiency are two key indicators of an antenna's quality. The term "gain" refers to the amplification of the primary beam's output power [19]. To determine an antenna's efficiency, we compare the power it emits or receives to the power it uses [20].

The antenna we have proposed has shown impressive performance in terms of gain and efficiency. Throughout our simulating, we have observed that the gain of the antenna ranges from 5 dB to 6.56 dB, while its efficiency spans from 79.16% to 96.66%. These results have been visually represented in Figure 3. It's worth noting that the gain is a critical performance metric for an antenna, and the fact that our antenna achieves a maximum gain of 6.56 dB is particularly noteworthy, especially for a lower-frequency antenna. Furthermore, the efficiency of 96.66% is also remarkable, especially within the context of low-frequency antennas.

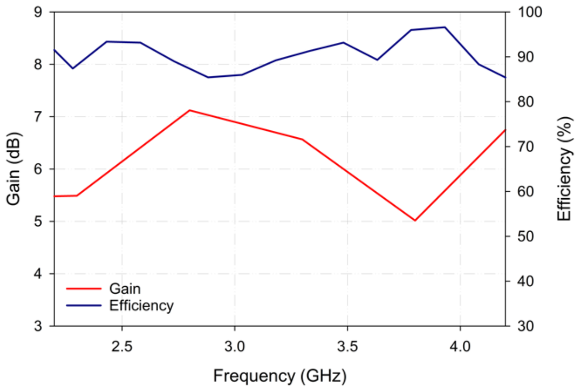


Figure 3. Simulated gain and efficiency of the proposed antenna

3.3. Radiation pattern

Figure 4 is a representation of the fields (both electric and magnetic) at an angle of 0 degrees and 90 degrees [21]. The magnitudes of the magnetic field are -33.3 dBA/m at an angle of 0 degrees and -31.8 dBA/m at an angle of 90 degrees, while the electric field is 18.2 dB V/m at an angle of 0 degrees and 19.7 dB V/m at an angle of 90 degrees. The side lobe level is -1.5 dB, and the half power beamwidth or 3 dB angle beamwidth for 0 degree is 76 degrees. In comparison, at 90 degrees, the side lobe level is only -1.5 dB, and the 3 dB angular beam width is 49.6. At an angle of 0 degrees and 90 degrees, the electric field at a resonance frequency of 3.5 GHz is 16.4 dB V/m and 17.7 dB V/m, whereas the magnetic field is -35.2 dBA/m and -33.8 dBA/m. The side lobe level is -1.3 dB, and the half power beamwidth at 0 degrees is 43,1 degrees. However, at 90 degrees, the side lobe level is -2.2 dB, and the 3 dB angular beam width is 66.9. For a resonant frequency of 3.7 GHz, the magnitudes of the electric field are 16.0 dB V/m at 0 degrees and 17.2 dB V/m at 90 degrees, whereas the magnitudes of the magnetic field are -35.5 dBA/m at 0 degrees and -34.3 dBA/m at 90 degrees. The side lobe level is -1.3 dB and the half power beamwidth at 0 degrees is 38.6 degrees. In comparison, at 90 degrees, the side lobe level is only -1.5 dB, and the 3 dB angular beam width is 52.5.

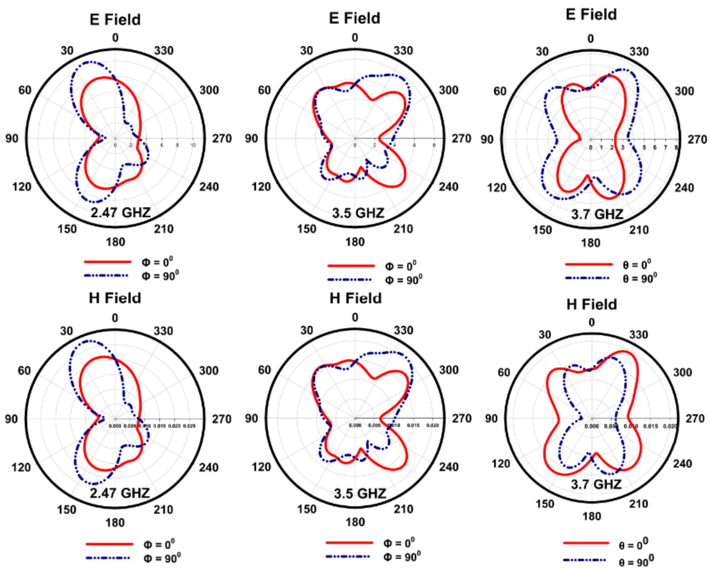


Figure 4. Simulated radiation patterns of the proposed antenna

3.4. ADS-based extraction of rlc lumped elements and equivalent circuit for the suggested MPA

The suggested antenna's RLC template, created with the Agilent advanced design system (ADS) software and displayed in Figure 5, is shown. Appropriate quantities of resistance, inductance, and capacitance have been selected to provide a satisfactory match between the impedance (50 ohm) the transmission line and the equivalent impedance of the proposed antenna [22]. At 2.6 GHz, 3.5 GHz, and 3.7 GHz, the parallel RLC circuit is shown in Figure 4 with the resistance R1=46.58, inductance L1=126.05 pH, capacitance C1=28.18 pF, the resistance R2=52.1, inductance L2=71.32 pH, capacitance C2=1.42 pF, and the resistance R3=54.06, inductance L3=15.16 pH, and capacitance C3=106.54 pF. ADS's S-parameter block monitors impedance-matching operations for optimal efficiency. The expected frequency ranges from (2 to 4) GHz with 10 KHz steps in the S-parameter block. Return loss response (dB (S(1,1) plots graphically illustrate the resonant circuit's output. The CST and ADS may be seen in Figure 6 to have a shared resonance frequency.

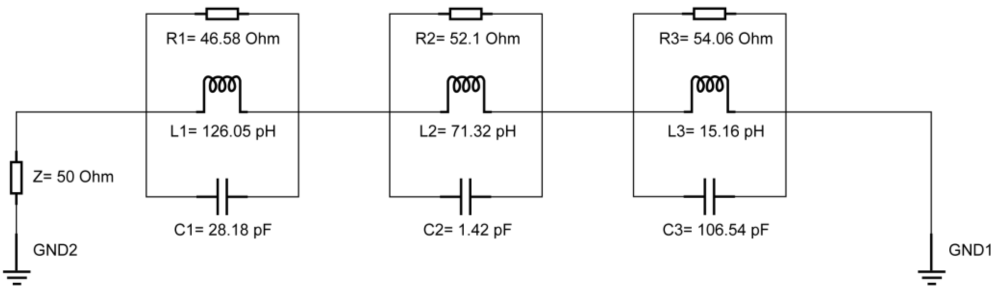


Figure 5. RLC circuit diagram utilizing ADS

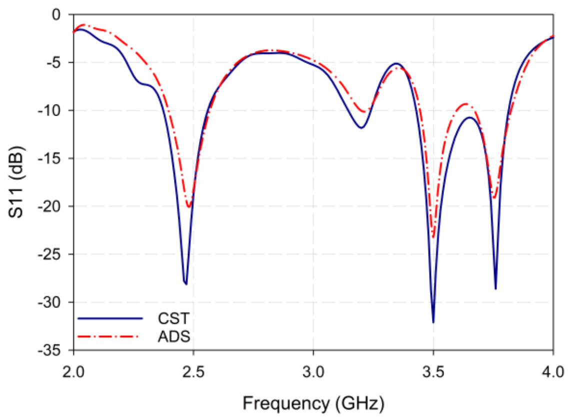


Figure 6. Reflection coefficient comparison between CST and ADS simulation

4. MECHINE LEARNING ANALYSIS

The strategy is two-part. First, build the 5G antenna in CST, a simulation tool, and then extract the parametric sweep dataset. Train a ML model on the dataset to discover the most reliable method. We simulate the proposed antenna using CST MWS, collect 144 data points, and estimate gain using multiple regression ML. We can use 144 data points. Eighty percent is used during learning, whereas twenty percent is kept for assessment. In our dataset, the substrate's length, width, height, and patch thickness are input variables, while the gain parameter is the main output. A ML method that incorporates features and labels is then applied to the training dataset. After training and validation, the model can predict outputs like realized gain from inputs.

4.1. Linear regression

Statistical analysis and ML use linear regression (LR) to estimate the relationship between a dependent (or "target") variable and a set of independent (or "predictors") variables or features. Labeled data is required for accurate predictions as a supervised learning system. The fundamental goal of LR is to find the best-fitting line that minimizes the sum of squared discrepancies between predicted and actual values. This term usually conjures up the regression line or best-fit line [23].

4.2. Gaussian process regression

ML researchers use non-parametric Gaussian process regression to model complex variable interactions. Gaussian processes are used in many ML applications. It is a Bayesian method that predicts non-linear relationships and model uncertainty, like LR is an extension of probabilistic methods. GPR is useful in geo statistics, ML, and Bayesian optimization. This applies mainly to moderate-sized datasets [24].

4.3. Decision tree regression

The supervised ML technique known as decision tree regression is useful for a wide variety of regression problems. When trying to forecast a continuous numeric output variable, decision trees can be utilized for regression even though they are more typically linked with classification difficulties. To forecast the value of the target variable given the values of the input features, a decision tree regression algorithm constructs a tree-like structure [25].

4.4. Poisson regression

Poisson regression is a statistical method for modeling the association between a dependent variable with a Poisson distribution and one or more independent variables. It is also known as Poisson regression analysis or Poisson regression modeling. Data where the outcome of interest is a count of occurrences over a particular period or in a specific location falls under the category of “count data” or “event data,” respectively [26].

4.5. Ransac regression

Random sample consensus (RANSAC) is an iterative technique used for robust regression, particularly in the presence of outliers and noisy data. To estimate model parameters while ignoring or down weighting outliers, RANSAC can be applied to a wide variety of regression tasks. When robust parameter estimate is needed, RANSAC is often employed in computer vision and image processing [27].

4.6. Performance measurement metrics

Error is the most typical regression success indicator. Each strategy was compared using statistical markers. The algorithms’ performance was evaluated using several statistical metrics and compared. We employed five statistics to evaluate our models’ prediction performance: root mean squared error (RMSE), R2, variance score, and mean absolute error (MAE) [28].

The MAE statistic measures how far off the predicted values are from the actual values in a regression problem. A low MAE suggests good dependent variable prediction accuracy. MAE is visually shown in (1).

$$MAE = \frac{1}{n}\sum_{i=1}^{n}|Pi - Oi| \quad (1)$$

Where, n is number of errors and $|Pi\text{-}Oi|$ is error absolute.

Mean squared error is the most typical regression loss function example. The loss is derived by averaging the squared differences between observed and anticipated values over all data points. In (2) shows the intended mean square error (MSE) formulation.

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

RMSE is a frequent statistic used in regression analysis to measure prediction model accuracy. It estimates the typical magnitude of errors or residuals between anticipated and observed values in a dataset.

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(Pi - Oi)^2} \quad (3)$$

One way to describe it is how well the model’s independent variables explain the dependent variable. Regression model fit is usually assessed using R-squared (R2). If R2 is zero, the model’s independent variables don’t explain any of the dependent variable’s variation. The model predicts nothing. The model fully explains all dependent variable variability with an R2 value of 1. A perfect R2 of 1 show that overfitting is unlikely.

$$R^2 = 1 - \frac{\sum_{i=1}^{N}(y_i - \hat{y}_i)^2}{\sum_{i=1}^{N}(y_i - \hat{y}_i)^2} \quad (4)$$

The "variance score" in ML and regression research is R2. R2 measures how much of the dependent variable's variance is due to the model's independent variables. It displays how much of the dependent variable's variation is model-related and how well the model matches the data.

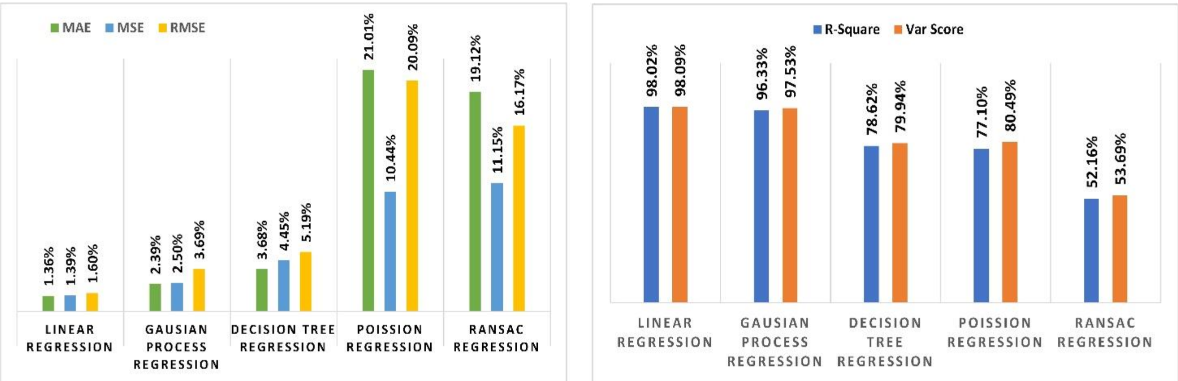
$$explained\ variance\ (y, \hat{y}) = 1 - \frac{Var(y-\hat{y})}{Var(y)} \quad (5)$$

4.7. Result analysis M/L

Table 2 summarizes and compares the predictive abilities of five regression models for directionality, given a set of input parameters. Accuracy performance was measured using measures such as MAE, MSE, and RMSE, with values of 1.36%, 1.39%, and 1.6%, respectively, for each method. The best performance is seen in LR, with an R2 of 98.02% and a variance of 98.09%. Results from several models are compared in Figure 7, where Figure 7(a) shows the error matric bar chart for linear regression (gain) and Figure 7(b) shows the accuracy comparative bar chart for linear regression (gain). Predictability and variation in the directivity difference between simulations are shown graphically in Figure 8. LR was utilized for forecasting purposes.

Table 2. Gain prediction performance

Algorithms	MAE (%)	MSE (%)	RMSE (%)	R-Square (%)	Var score (%)
LR	1.36	1.39	1.60	98.02	98.09
Gausian process regression	2.39	2.50	3.69	96.33	97.53
Decision tree regression	3.68	4.45	5.19	78.62	79.94
Poission regression	21.01	10.44	20.09	77.10	80.49
RANSAC regression	19.12	11.15	16.17	52.16	53.69



(a) (b)

Figure 7. Comparative performance bar chart of ML regression (gain): (a) error matric bar chart for linear regression (gain) and (b) accuracy comparative bar chart for linear regression (gain)

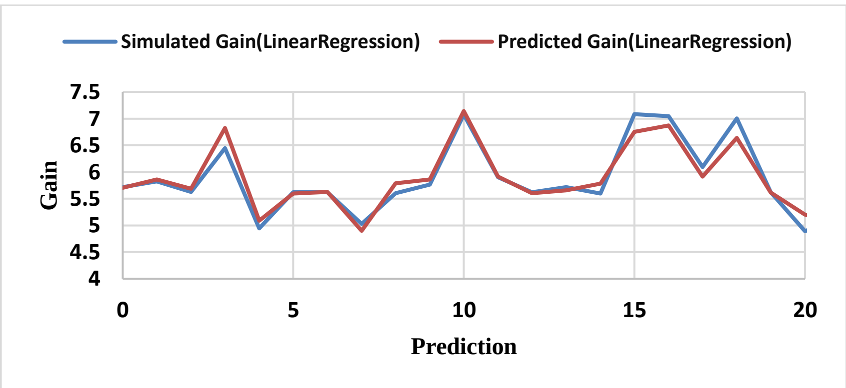


Figure 8. Simulated vs predicted gain using LR

5. CONCLUSION

The suggested antenna is initially designed with the use of the CST modeling tool. It has a maximum gain of 6.56 dB and a maximum efficiency of 97% for cellular communication in the 4G frequency spectrum at 2.47 GHz, in the n78 band at 3.5 GHz, and in the n77 band at 3.7 GHz. The results of CST have also been tested by creating an analogous RLC circuit model and simulating it by using ADS. This is done to check the accuracy of the results. The reflection coefficients that are generated by the CST and ADS simulators are comparable to one another. In addition, to compute the gain of the microstrip patch antenna, five different machine-learning methods were developed. The anticipated findings indicate that the error performances of the LR model are relatively better than those of other models when it comes to forecasting the resonant frequency. This can be seen in comparison to the other models. In conclusion, the modeling findings from CST and ADS, in conjunction with the results from ML, demonstrate that the proposed antenna is a strong contender for both 4G and 5G applications.

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