Machine Learning-Based Design and Analysis of Antenna Systems: A Comprehensive Investigation

S Rekha[1], Sai Kiran Oruganti[2]
[1,2] Lincoln University College, 47301, Petaling Jaya, Selangor Darul Ehsan, Malaysia;
Email ID: [1]pdf.rekhashanmugam@lincoln.edu.my, [2]saisharma@lincoln.edu.my

Abstract: A major breakthrough in wireless communication has taken place in recent years. Today, individuals depend on cloud computing, the Internet of Things, and applications based on big data analytics. Increased data speeds, quicker send/receive intervals, greater coverage and increased throughputs are essential for such applications. Modern Antennas are among the vital elements of contemporary technology. ML is clearly showing a promising-outlook in optimizing antenna design by accurately predicting antenna performance as well as speeding up the optimization process. This discussion introduces a groundbreaking approach utilizing machine learning to design and optimize multi-band patch antennas primarily targeting advanced IoT applications in beyond-5G and 6G networks. Acknowledging the constraints of conventional antenna design techniques, there are several machine learning algorithms including Decision Tree, Random Forest, Artificial Neural Network (ANN), K-Nearest Neighbors (KNN), Extra Trees, CatBoost, and Gradient Boosting are discussed in terms of significance, merits, and demerits.

Keywords: Wireless Communication, Internet of Things, 5G, Machine Learning techniques, and Antenna design.

Introduction

Ever-increasing requirement for ultra-high-speed communication and data rates has emerged the Sixth-generation communication technology. 5G laid the groundwork for a user-centric paradigm by enabling the deployment of IoT and delivering the internet at scale. By linking a multiple number of devices to the Internet of Things (IoT) network at once, 5G enables large device connectivity. However, a shift to a service-centric approach will result from 6G technology's acceleration of existing technology into a smart integrated digital ecosystem. Due to its reduced latency and increased speed, 6G will primarily facilitate machine-to-machine communication.

Perhaps the most difficult issue is developing a miniaturized and compact antenna for modern gadgets. Video-conferencing, data streaming, AR, drone technology, driverless vehicles, robot technology, smart city and other IoT devices are realizable only due to 5G/6G technology. There are numerous publications discussing on optimization of antenna design using ML techniques and evaluating the antenna performances.

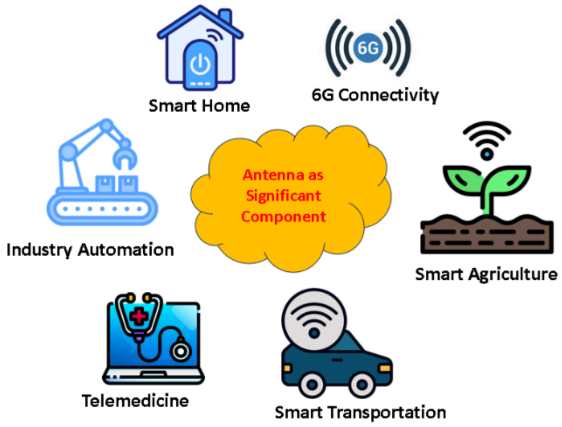

Figure 1. Significant of Antenna in Modern Communication

Literature Review:

I. Decision Trees [8]

A supervised learning system called a Decision Tree uses feature-based splits to represent decisions. By learning from simulation or measured datasets, it aids in the prediction of factors like resonant frequency, gain, and bandwidth in antenna design. It is especially helpful for comprehending how geometric characteristics (such as patch size and substrate thickness) affect antenna performance.

Merits:
data preprocessing is minimal, decision criterion is clear and easy to implement

Demerits:
chances of overfitting are high, minute changes in dataset will influence major changes, and not suitable for nonlinear functions

II. Random Forest [9]

It is a combination of many decision trees and averaging to increase the accuracy. It is used in antenna design to predict design variables and performance parameters. Big datasets can be handled effectively in this method.

Merits:
Immune to overfitting and noise, and huge datasets are handled effectively

Demerits:
High Computing cost, training takes time and reduced transparency.

III. Artificial Neural Network (ANN) [10]

ANN is very good at representing nonlinear relationships and is based on biological neural networks. ANN is frequently used in antenna design to quickly estimate antenna characteristics, taking the place of laborious simulations. It is helpful in inverse design challenges and can approximate complicated electromagnetic phenomena.

Merits:
Excellent for nonlinear modeling, very accurate predictions, and flexible enough to handle challenging issues.

Demerits:
Lacks interpretability (black-box model), requires a lot of training data, and is computationally costly.

IV. K-Nearest Neighbors [11]

K-Nearest Neighbors is transparent learning method which uses the nearest data points to classify or predict values. By contrasting new designs with comparable current ones, antenna performance can be estimated in antenna design. In the early stages of design discovery, it is helpful.

Merits:

Easy to use, requires no training phase, and works well with tiny datasets.

Demerits:

Prediction is computationally costly, performance deteriorates with large datasets, and susceptible towards noise and unimportant factors.

V. Extra Trees [12]

Similar to Random Forest, Extra Trees is a type of ensemble learning which increases node splitting randomness. When modeling highly nonlinear correlations between antenna characteristics and performance measures, it aids in enhancing generality in antenna design.

Merits:

Less variance, faster than Random Forest, and resistant to overfitting.

Demerits:

May need adjustment, poorer interpretability, and occasionally somewhat reduced accuracy.

VI. CatBoost [1]

CatBoost is a gradient boosting technique that minimizes overfitting and effectively manages category features. When datasets contain mixed or encoded parameters, it can be used to accurately forecast antenna properties in antenna design. It is much applicable in tuning of parameters and optimization

Merits:

Better handling of datasets, high accuracy, and less overfitting

Demerits:

High Computation cost, and requires careful tuning

VII. Gradient Boosting [13]

In this technique, a new model will fix the errors of the previous model. It is very useful in increasing the accuracy and optimize antenna parameters. Surrogate model is highly beneficial with this method.

Merits:

High accuracy in prediction, and good for complicate datasets

Demerits:

Takes time to train, can be affected by noise, and overfitting

Table 1. Antenna techniques involving Machine Learning - A Review

Ref No.	Antenna Type	Techniques	Applications	Operating Frequency (in GHz)	Drawbacks
[1]	Multi-band patch antenna;	ML models (CatBoost 77.4% accuracy)	next-generation IoT system	3.5 - 7.8 8.5 - 10.2 11.8 - 15	Only return loss predicted; gain & efficiency not included

[2]	Flexible microstrip patch	iteratively optimized	wearable medical applications	4.143	Performance under bending/flex conditions not detailed
[3]	Rectangular microstrip patch	Modified Ant Colony Optimization	5G Applications	28	Optimization limited to return loss, VSWR, and radiation pattern
[4]	5G Sub- Band Antenna Design	Trained multiple ML models	Wi-Fi & WiMAX Application	3.3	Focused on simulation with no real hardware testing
[5]	Multiband Antenna	Slotted microstrip patch	Full Screen Smartphone	2.7–9.2	Simulation only; integrating ML could further optimize
[6]	Dual Band Antenna Design	Machine Learning Approaches	X band	8.35 – 14.25	ML is only used to find the resonating frequency
[7]	Zig-Zag Antenna Design	Machine Learning	-	0.9 - 1.2 0.8 - 1.1	Limited data for ML training; narrow bandwidth

Conclusion

The efficiency of ML based method for the design optimization of next generation antennas are discussed in this article. This ML algorithms much reduces the time and energy spent on conventional methods of antenna design. There are some ML models which can precisely find the antenna design and performance parameters. This technology is a boon to the contemporary wireless communication which focusses on Smart homes, IoT devices, industry automation and high-speed networks.

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