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Advanced Miniaturized Microstrip Patch Antenna Design for High-Efficiency 5G Applications

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Abstract: This work presents a compact microstrip patch antenna design for 5G applications, which operates in 25 GHz, 28 GHz, and 32 GHz frequency bands and provides triple-band functionality. The proposed antenna has a compact volume of 15.4 × 12.8 × 1 mm, contributing to its miniaturization, which is crucial for 5G communication systems. To optimize return loss characteristics, a line slot is introduced on the patch. The slot width is optimized using an XGBoost prediction model, which serves as an objective function for a Coati optimization technique. This optimization aims to achieve an optimal slot length that results in a superior return loss of -30 dB. The proposed antenna shows a peak gain of 7.3 dB at 28 GHz and exhibits an exceptional radiation efficiency of 98 %. The design and manufacture of this antenna validates its high gain and superior return loss in the specified triple bands, making it suitable for reliable and efficient 5G communication systems. The combination of compact size, high gain, and efficient return loss optimization ensures that this antenna meets the demanding requirements of modern 5G technology. The use of advanced optimization techniques, such as the XGBoost prediction model and Coati optimization, highlights the innovative approach of this design. This methodology not only improves the antenna's performance but also ensures that it can be effectively integrated into compact 5G devices, providing robust and high-quality communication capabilities. The success of this design underlines its potential for widespread application in the rapidly evolving field of 5G communications and offers a promising solution for future wireless technologies.

Keywords: Microstrip antenna, 5G communication, triple-band operation, miniaturization, optimization techniques.

1. INTRODUCTION

In wireless communications, there is a huge demand for 5G technology, which offers unprecedented connectivity and ultra-fast data transfer rates [1]. 5G technology operates at higher radio frequencies with lower latency and also connects to multiple devices simultaneously [2]. This communication allows for a more reliable and consistent connection even in crowded urban areas.

Recently, patch antennas have gained more significance in modern wireless communication systems due to their compactness, low profile, ease of integration and versatility multiband operation [3]. Patch antennas are developed on dielectric substrates, which offer multiple merits due to their structure. The min advantages of patch antennas include minimum cost, ease of manufacturing and compatibility with different form factors. These antennas are ideal candidates for use in compact electronic devices such as internet of things (IoT) devices, mobile phones and other wireless systems [4].

The 5G networks are subject to several performance constrains, namely higher gain, improved radiation efficiency and precise frequency band coverage. The previous antenna model had to overcome several challenges to meet these criteria. Finding an antenna for a particular resonant frequency with improved return loss behavior requires optimal dimensional values with a better result. Patch antennas, on the other hand, pose a challenge as there are no systematic procedures or exact mathematical formulas that guarantee exact solutions. This model includes machine learning (ML) and optimization methods to implement an antenna design to achieve an effective and optimal solution [5], [6]. In addition, it enables fine-tuning of antenna parameters and achieving optimized performance metrics that would be difficult to achieve through conventional design iterations.

Conventional microstrip patch antennas for 5G applications may be larger and therefore less suitable for integration into compact devices. In addition, traditional design approaches may rely on manual or semi-automated optimization methods, which can be time-consuming. The optimal performance metrics such as return loss and gain cannot be achieved without advanced optimization algorithms, resulting in a delayed design. In this work, an ML-based metaheuristic optimization algorithm is developed to design an optimized patch antenna. The trained XGBoost model is used in the objective function of the Coati optimization model to find the optimal length of the slot for the proposed patch antenna with the aim of achieving better return loss values at 25 GHz, 28 GHz, and 32 GHz.

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2. LITERATURE REVIEW

Alieldin et al. [7] have proposed a triple-band patch antenna for 5G applications. The proposed antenna has a higher bandwidth of 32% with high polarization purity. A microstrip patch antenna suitable for 5G applications is presented by Kalaiarasi et al. [8]. The proposed antenna is manufactured on an FR4 substrate. The operating frequency of the antenna is 0.9 GHz (WiMAX), 2.7 GHz (WLAN), and 4 GHz (Wi-Fi). Ramasamy et al. [9] also proposed a patch antenna for a 5G application on an FR4 substrate. The proposed antenna operated in the WLAN (5.2 GHz), Wi-max (5.5 GHz), and 5G n34 bands.

A novel millimeter-wave antenna array designed by Ramasamy et al. [10] operates at 28 GHz for 5G mobile communication systems. It is a redesigned patch antenna with dual U-shaped etched slots on an RT Rogers 5880 substrate. The developed antenna achieves a radiation efficiency of 93 % with an improved gain of 12 dB. In their study [11], a 28 GHz microstrip patch antenna featuring a rectangular slot was developed. The developed antenna was printed on a Rogers Rt-duroid substrate with a height of 0.4 mm. The analysis has shown that the gap-coupled feeding technique is optimal and meets the specific requirements for 5G applications [12]-[16].

Various studies have explored antennas for 5G communication, but many encountered challenges such as larger dimensions, lower impedance bandwidths, or lower gains, which affects the quality of wireless communication. Further research is needed to improve high-speed data transmission capabilities. This work aims to develop an antenna that is optimized for cellular wireless communication, focusing on minimizing the return loss and maximizing the gain by using ML models.

3. PROPOSED ANTENNA MODEL

The proposed structure of the square triple-band microstrip patch antenna is shown in Fig. 1. It consists of a radiating layer, a substrate layer, and a grounding layer. The proposed antenna is mounted on a Rogers RO3210 substrate. The dielectric constant of the RO3210 substrate is 10.2, the loss tangent is 0.003 and the substrate thickness is 1 mm. The high permittivity and low dielectric loss tangent of Rogers RO3210 in patch antenna design increase its efficiency and reliability, making it a favorable choice for 5G communication systems, and the substrate also has excellent thermal stability. It maintains its electrical properties over a wide temperature range. In addition, RO3210 offers good mechanical strength, making it suitable for complex circuit designs that may involve bending or flexing. The top surface of the patch antenna consists of a single line slot with a thickness of 0.36 mm to enable triple-band operation.

By forming a slot on the radiating patch with a length of 2.5 mm, the desired frequencies for the three operating bands 25 GHz, 28 GHz, and 32 GHz are achieved with return loss values of -26, -19, and -20.9 dB, respectively. The proposed antenna dimensions are listed in Table 1. To improve these return loss values, an optimization algorithm based on XGBoost is used in combination with the Coati algorithm to determine the optimal slot length.

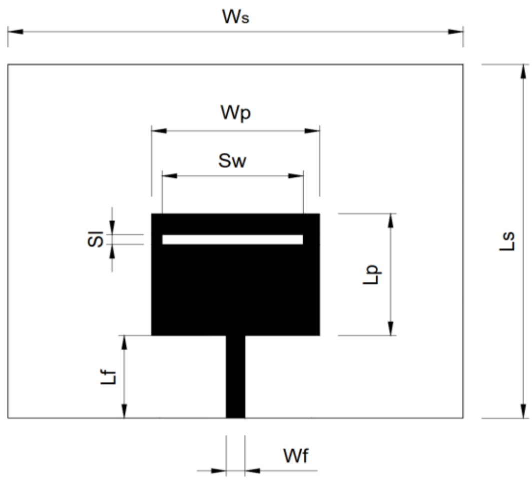

Fig. 1. Microstrip patch antenna structure.

Table 1. Dimensions of antenna.

Parameter	Value [mm]
Ws	15.48
Wp	5.72
Wf	0.64
Ls	12.84
Lp	4.42
Lf	3
Sw	4.8
Sl	0.36

Development of the COA-XGBoost Model

The Coati optimization algorithm (COA) mimics natural behaviors such as hunting and foraging to efficiently explore and exploit the search space. The process of achieving the best solution is divided into two phases:

I. Attack strategy on prey and escape strategy from predators:

This process is mathematically modeled like coatis on a tree as follows:

$$X_{\mathrm{P1\,i,j}} = x_{\mathrm{i,j}} + rand \cdot \left(I_{\mathrm{guana\ j}} - I \cdot x_{\mathrm{i,j}}\right),\ i = 1,2,\ldots N \quad (1)$$

where $X_{P1i,j}$ refers to the updated position of the i^{th} coati (or candidate solution) in the j^{th} dimension during the first phase of the COA. i usually refers to the index of a coati or a candidate solution in the population. j refers to the index of a decision variable within a solution vector. N typically represents the number of coatis in the population. $x_{i,j}$ is the current position of the coati in the population. $rand$ is the random number, which varies from zero to one. I represents an influence factor determining the weight of the coati's movement towards the 'prey' or away from it. $I_{\mathrm{guana_j}}$ represents the position of the 'prey' or best solution. $I_{\mathrm{guana}}Gj$ represents a random position generated during the simulation for the 'prey' on the ground. The position of the iguanas on the ground can be mathematically modeled as follows:

$$I_{guana_j} Gj = lb_{i,j} + rand \cdot (ub_j - lb_j) \tag{2}$$

where, lb_j stands for the lower bound and ub_j for the upper bound of the j^{th} decision variable. Similarly, the coatis on the ground can be modeled mathematically as follows:

$$X_{P1i,j} = \begin{cases} x_{i,j} + rand \cdot (I_{guana} Gj - I \cdot x_{i,j}) & if\ F(I_{guana} Gj) < F_i \\ x_{i,j} + rand \cdot (x_{i,j} - I_{guana} Gj) & else \end{cases} \tag{3}$$

where, F is the objective function and F_i is the fitness value of the i^{th} candidate solution.

II. Escape strategy from predators (exploitation phase):

Coatis evade predators by moving quickly to find a safer position nearby. This represents the exploitation phase in COA for local search. The local bounds can be calculated as follows:

$$lb_{local_j} = \frac{lb_j}{t}, \quad ub_{local_j} = \frac{ub_j}{t} \tag{4}$$

where t stands for an iteration counter that is used to control specific operations. In addition, the local bounds are specifically adjusted during the exploitation phase to explore the solution space more effectively. The new position of the coatis is expressed mathematically as follows:

$$X_{P2\,i,j} = x_{i,j} + (1 - 2 \cdot rand) \cdot \left(lb_{\mathrm{local}_j} + rand \cdot \left(ub_{\mathrm{local}_j} - lb_{\mathrm{local}_j}\right)\right) \tag{5}$$

where lb_{local_j} and ub_{local_j} are modified bounds to explore nearby solutions. The COA initializes the positions of the coatis as candidate solutions in the search space and forms a population matrix. The population matrix of the problem is represented as $X = [X_1, X_1, \ldots X_N]$ with the objective function $F_i = F(X_i)$. The value of the objective function linked to the i^{th} candidate solution is X_i.

The updating of the population in all phases can be expressed as follows:

$$X_i = \begin{cases} X_{P1i} & if\ F_{P1i} < F_i \\ X_{P2i} & if\ F_{P2i} < F_i \\ X_i & else \end{cases} \tag{6}$$

where X_{P1i} denotes the updated position in the first phase (attack strategy on 'prey') and X_{P2i} denotes the updated position in the second phase (escape from predators). F_{P1i} is the fitness value of the position X_{P1i}, F_{P2i} is the fitness value of the position X_{P2i}.

The COA iteratively updates the positions of the coatis based on the above strategies until the algorithm reaches convergence. The COA uses the innate behaviors of the coatis to strike a balance between exploration and exploitation as they traverse the solution space, facilitating an effective search for optimal solutions in different problem domains.

XGBoost or eXtreme Gradient Boosting is an ML model used for accurate prediction of tabular data. The concept of XGBoost belongs to the family of ensemble learning, which iteratively combines weak learners to create a robust predictive model, as shown in Fig. 2. This iterative process involves minimizing the loss function by adding new models that complement the deficiencies of the existing models.

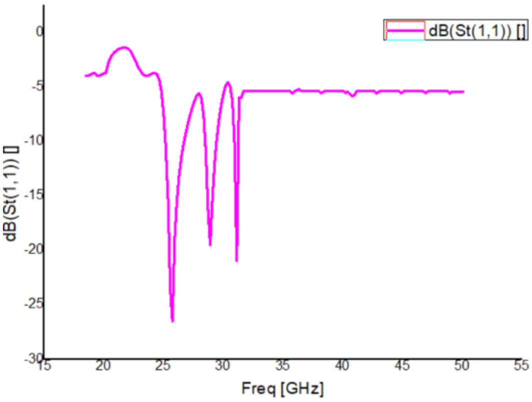

Fig. 2. S11 plot for the proposed antenna with *Sw* of 2.5 mm.

4. RESULTS AND DISCUSSION

For COA, initialize the number of coatis as 50. The total number of iterations is set to one hundred for the optimization. The antenna reaches the required resonant frequency with a slot width of 2.5 mm. To achieve a better RL performance, the parameters converge to fitness values. The exact value of *Sw* of the antenna obtained by the COA-XGBoost is 4.798 mm, which is considered to be 4.8 mm. The S11 plots for the proposed antenna corresponding to *Sw* of 2.5 mm and 4.8 mm are shown in Fig. 2 and Fig. 3.

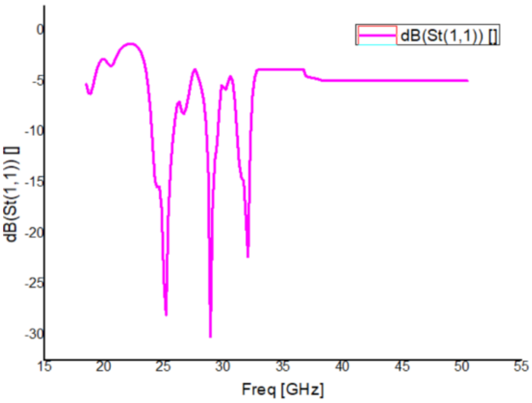

Fig. 3. S11 plot for the proposed antenna with *Sw* of 4.8 mm.

After completing the performance analysis with ANSYS HFSS, the proposed antenna prototype (Fig. 4) is manufactured and tested. The process involves photolithography for precise etching and slot cutting with challenges such as maintaining tolerances, substrate fragility, and minimizing surface roughness to avoid performance degradation.

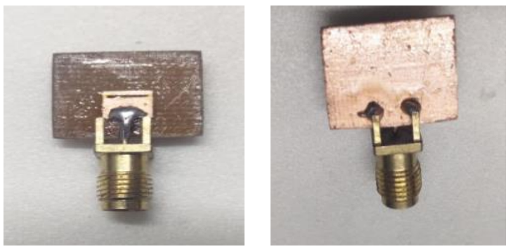

Fig. 4. Manufactured prototype (front and back view).

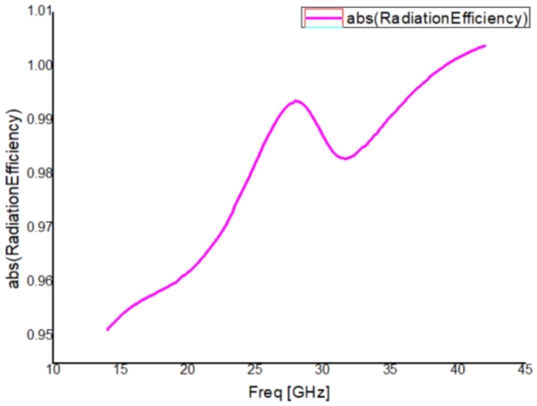

Fig. 5. Radiation efficiency plot.

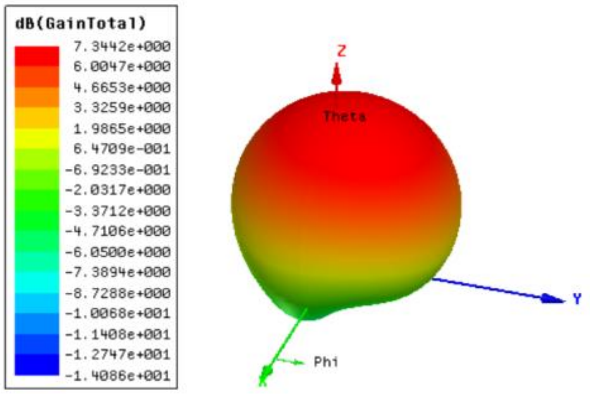

Fig. 6. Gain plot.

The radiation efficiency plot in Fig. 5 illustrates the antenna's effectiveness at 25 GHz. It shows a 98 % efficiency, which reaches 99 % at 28 GHz, and maintains a robust 98 % efficiency even at 32 GHz.

The proposed antenna exhibits a commendably high gain of 7.4 dB, a favorable attribute that is particularly valued in microstrip patch antennas. This gain characteristic is shown in Fig. 6 and demonstrates the antenna's ability to transmit or receive electromagnetic signals efficiently.

The comparison of the proposed antenna design with other design approaches is shown in Table 2. The proposed tri-band antenna achieves exceptional performance with low return loss values (S11) of -28 dB (25 GHz), -30 dB (28 GHz), and -22 dB (32 GHz), which ensures efficient power transfer. Its compact size of 15.4 × 12.8 × 1 mm does not compromise its impressive gain of 7.3 dBi. It shows considerable radiation efficiency of 99 %, which ensures minimal power loss during operation.

Table 2. Comparison of the proposed antenna design.

Reference	Frequency of operation [GHz]	S11 [dB]	Size [mm]	Gain [dBi]	Radiation efficiency [%]
[12]	28 / 28 / 48	-21, -24 & -30	34.8×34.8×0.508	8	82
[15]	27.946 / 37.83	-27.84 & -18.35	55×110×0.508	7.18 and 9.24	92
[9]	5.2 / 5.5 / 28	-32	26×14×0.38	1.83	-
[8]	0.9 / 2.7 / 4	-28	18×16×0.285	4.41	-
[7]	0.7–0.96 / 1.7–3 / 3.3–3.8	-30, -15 & -15	30×30×0.23	5	-
Proposed	25 / 28 / 32	-28, -30 & -22	15.4×12.8×1	7.3	99

The prediction accuracy is compared with other models such as random forest, Gaussian process regression, and neural networks. The accuracy values are shown in Table 3 and in the diagram in Fig. 7. Random forest achieved an accuracy of 89.5 %, while Gaussian process regression achieved an accuracy of 91.6 %. Neural networks achieved an accuracy of 93.5 %. The XGBoost model outperformed all others, achieving the highest accuracy of 96.4 %. The XGBoost model emphasizes its superior predictive ability in estimating RL values at different slot widths.

Table 3. Performance analysis of the proposed model.

Model	Prediction accuracy [%]
Random forests	89.5
Gaussian process regression	91.6
Neural networks	93.5
XGBoost	96.4

XGBoost adds complexity to hyperparameter tuning and can be less interpretable than traditional methods. It also struggles with noise sensitivity and scalability for large, complex design spaces. Future work could focus on integrating advanced optimization techniques or AutoML for automated hyperparameter tuning, along with methods for noise reduction.

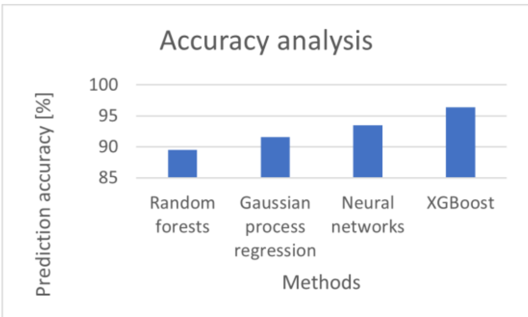

Fig. 7. Performance analysis.

5. Conclusion

The development and optimization of microstrip patch antennas is key to achieving high performance in 5G wireless connectivity. In this work, a new hybrid algorithm based on ML and a metaheuristic optimizer is developed to design a patch antenna for improved performance. The XGBoost model is found to be suitable compared to the other ML techniques. The antenna resonates at the frequencies of 25 GHz, 28 GHz, and 32 GHz with a return loss of -28 dB, -30 dB, and -22 dB, respectively. The antenna achieves a high gain of 7.4 dB and a radiation efficiency of 98 %. The simulated results show a better result in terms of field distribution, radiation pattern, VSWR, etc. The antenna design is a preferred choice for 5G applications, especially in scenarios requiring high gain. The results of the manufactured antenna are very satisfactory and are well suited for 5G communication.

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