ISSN 1330-3651 (Print), ISSN 1848-6339 (Online) https://doi.org/10.17559/TV-20240611001766
Original scientific paper

Compact Dual-Band Microstrip Patch Antenna Design for 5G Wireless Networks Using Grey Wolf Optimization

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Abstract: The advent of the fifth-generation (5G) wireless technology has revolutionized data transmission, enabling ultra-high-speed communication and enhanced connectivity. However, achieving these advancements requires ultra-low latency, which places stringent demands on antenna design. This study introduces a novel, optimized dual-band microstrip patch antenna tailored for 5G applications. The proposed design employs a nine-patch grid layout to enhance bandwidth and radiation characteristics. The antenna operates efficiently at 24 GHz and 32 GHz, aligning with key 5G frequency bands. The Rogers RO3210 substrate, chosen for its superior properties such as low dielectric loss and high-frequency stability, features a thickness of 1.2 mm. The physical dimensions of the antenna were meticulously optimized using the Grey Wolf Optimizer (GWO) algorithm to achieve superior performance metrics. Simulation results demonstrate wide impedance bandwidth, high gain, and stable radiation patterns. The optimized antenna achieves a peak gain of 9.5 dB with a radiation efficiency of 86%, making it suitable for high-performance 5G networks. The compact size, coupled with the optimized design, ensures easy integration into modern communication devices. This study underscores the potential of advanced optimization techniques and innovative structural layouts in realizing next-generation antennas for 5G applications.

Keywords: dual-band microstrip patch antenna; fifth-generation (5G) networks; grey wolf optimizer (GWO); rogers RO3210 substrate; high-gain antenna design

1 INTRODUCTION

The fifth generation (5G) technology holds various features like higher data rates, reduced latency, increased network capacity, and enhanced connectivity when compared to previous technologies [1]. It supports human interaction through the use of the internet and social media. More specifically, 5G has been applied in self-driving cars, gaming applications and video calls over a high-speed internet connection. Additionally, 5G is used for the advancement of smart cities where interconnected devices and sensors improve urban infrastructure, energy management and public safety.

Microstrip patch antennas have received widespread popularity in modern wireless communication systems [2, 3]. These antennas offer low profile, lightweight, and easy fabrication advantages. The planar structure of patch antennas supports easy integration with other electronic components like mobile phones, wearable devices, and Internet of Things (IoT) applications. Additionally, patch antennas operated at multiple frequency bands.

The 5G applications-based patch antenna's design and optimization are critically based on its requirements. The important requirements include gain, bandwidth, radiation pattern, and efficiency [4]. The antenna design with the constraint of these features makes multi-dimensional optimization problems. The existing approaches need more knowledge about design and require complex design calculations. The Metaheuristic algorithms like Genetic Algorithms (GA), Particle Swarm Optimization (PSO), Hen Maternal Care Optimization [5], (HMCO) Black Widow Optimized (BWO) and the GWO [6, 7] provided powerful support for antenna design. All these methods imitated natural processes effectively to explore the search space.

The primary research gap identified in the existing literature is the limited application of advanced optimization algorithms for the design of compact, high-performance microstrip patch antennas suitable for 5G wireless networks. Many studies have focused on antenna design, the optimization methods used are often outdated or do not fully leverage modern metaheuristic techniques for improving antenna performance. Furthermore, many existing designs fail to address the specific requirements of 5G systems, such as achieving high gain, wide bandwidth, and stable radiation patterns at the high-frequency bands (24 GHz and 32 GHz), which are critical for 5G applications.

In this work, a new design approach for 5G antenna design is proposed. The size of the antenna is optimized using GWO and is motivated by the hunting behaviour of grey. For various engineering issues, GWO is applied to avoid local minima. Here, GWO can optimize the physical dimensions of the antenna to achieve desired performance metrics.

2 RELATED WORK

W.-W. Yang, et al. [8] introduce a dual-band patch antenna for millimetre wave application. The high gain operation is achieved by the formation of a mushroom-shaped array structure that has a gain of 5.64 dB. Also, L. Chang et al. supported a triple-band microstrip patch antenna that has a volume of 33.5 × 32.5 × 4 mm ^{3} with a radiation efficiency of 85.6%.

L. Chang et al. [9] designed a patch antenna with a frequency of 4.8-5.0 GHz 4.8-5.0 GHz. To achieve size minimization, the slots are formed on the ground layer. The proposed antenna shows the highest bandwidth efficiency. Huang, et al. [10] proposed a multi-substrate path antenna for a 5G application. The different substrates are used for the proper functions of radiation, energy coupling, and feeding of the antenna. This antenna shows better cross-polarization discrimination with minimum design complexity.

To achieve a higher selectivity, the antenna with a new feeding approach is introduced by Y. Li, et al. [11]. The radiation nulls are created by a new feeding structure with better differential port isolation capability. J. Seo et al. [12]. presented a miniaturized patch antenna for 5G application operating at dual bands of 28 and 39 GHz in volume 5.8 × 19 × 1.122 mm with a gain of 11.6 dB.

In their article, Y. Cheng et al. [13] presented a circularly polarized planar array antenna that is fed by a substrate with waveguide. The design used semicircle patches and suspended metal posts to achieve circularly polarized operation. Y. Luo et al. [14] developed a dual-polarized high-mode patch antenna using characteristic mode analysis (CMA). This antenna achieved a 9.6 dB gain within the 4.8-5 GHz band for 5G communication networks.

Z. Siddiqui et al. [15] developed a dual-band antenna that is operating at 24 to 40 GHz. The proposed antenna used a ring patch stacked to achieve a dual band with stable gain and a filter-like response including radiation nulls among bands. D. He et al. [16] implemented a double-polarized triple-band antenna for 5G base stations. The array delivered stable radiation patterns with gains of 6.5, 7.6, and 8.2 dB respectively.

R. K. Singh et al. [17] presented a microstrip-fed patch antenna with reconfigurable patterns at two frequency bands. It uses a small additional patch connected via a *p-i-n* diode for frequency reconfigurability and L-shaped cuts for polarization versatility.

L. Wen et al. [18] proposed a dual-polarized 64-element phased-array antenna operating at mm-wave frequencies. The proposed structure is constructed from two stacked multilayer PCBs with 2×2 mm - subarrays The fabricated antenna shows dual-polarized radiation from 3.45 to 3.58 GHz and a ±45° scanning range in both azimuth and elevation from 24.5 to 27 GHz. X.-H. Ding et al. [19] proposed a dual-band shared-aperture antenna design for 3.5 GHz and 28 GHz bands. The fabricated prototype shows operating frequencies from 3.38 to 3.64 GHz and 26.4 to 29.8 GHz with the Peak gains of 6.9 dB.

A low-profile tri-mode antenna is designed by L. Qian et al [20] for 5G applications. The antenna uses two rectangular microstrip patches to excite three orthogonal modes and for polarization diversity. Implementation of the antenna prototype shows a 4.8 to 5.0 GHz impedance bandwidth with a −6 dB reflection coefficient.

B. Cheng et al. [21] developed a MIMO antenna for 5G mobile. It attained a low profile of 0.01 λ_0 for compact 5G mobile applications. Sun et al [22] introduce a dual-band and dual-polarized microstrip antenna that uses a compact multilayer structure with double-layer gridded patches and metallic via-fences. Results show that the prototype shows -10 dB bandwidths from 23.3-31.7 GHz and 42.5-46.5 GHz with average gains of 12 and 13.1 dB.

Z. Wang et al. [23] developed a tri-polarized antenna with a shared aperture meta surface for 5G applications. The antenna operates using TM10, TM20, and TM00 modes to achieve horizontal and vertical polarization with high isolation. The fabricated antenna shows a peak gain of over 10.3 dB and a radiation efficiency of 90.8%.

3 PROPOSED ANTENNA

The proposed approach designed an optimized microstrip patch antenna for dual-frequency operation at 24 GHz and 32 GHz. The radiator of the antenna resembles a grid layout comprising nine microstrip patch elements. The proposed antenna design uses Rogers RO3210 substrate with 1.2 mm thickness for high-frequency performance. The structure of the proposed antenna is given in Fig. 1. The length and width are optimized using the GWO method to achieve the best possible performance metrics. The proposed antenna dimensions are listed in Tab. 1.

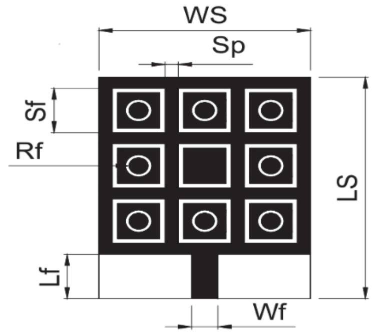

Figure 1 Structure of the antenna with dimensions

Table 1 Dimensions of antenna

Parameter	Value / mm
LS	21.5
WS	15.8
Rf	2.5
SF	4.2
Lf	3.8
Sp	1.1

3.1 GWO Method

The GWO is based on the hunting strategy of wolves that have some specific talents like (1) tracking, chasing and prey approach, (2) chasing and harassing the prey and (3) prey attacking. These strategies are used to explore and exploit the optimal solution in a local search space.

Locating Prey

This phase identified the prey's location and adjusted the search agents' positions. It can be mathematically modelled as follows:

$$\vec{D} = |\vec{C}.\overrightarrow{X_p}(k) - \vec{X}(k)| \tag{1}$$

The Position update of Wolfs is expressed as follows:

$$\vec{X}(k+1) = \overrightarrow{X_p}(k) - \vec{A} \cdot \vec{D} \tag{2}$$

where k indicates a current iteration, $\vec{A}$ and $\vec{C}$ denote coefficient vectors, $\overrightarrow{X_p}$ indicates the prey's position vector, $\vec{X}$ represents position vector, || denotes absolute value.

The vector $\vec{A}$ and $\vec{C}$ are computed as follows:

$$\vec{A} = 2\vec{a} \cdot \vec{r} - \vec{a} \tag{3}$$

$$\vec{C} = 2 \cdot \vec{r} \tag{4}$$

where $\vec{a}$ indicates linear vector from 2 to 0 and $\vec{r}$ represents a random vector in [0, 1]. The search agent location [x, y] is modified using prey's location obtained so far [X*, Y*]. The $\vec{A}$ and $\vec{C}$ are adjusted to achieve the best agent in various places.

Hunting Phase

It is done by alpha wolves with the support of beta and delta wolves. It updated the position using distance vectors that are given in the following.

$$\overrightarrow{D_\alpha} = \left| \overrightarrow{C_1} * \overrightarrow{X_\alpha} - \vec{X} \right| \tag{5}$$

$$\overrightarrow{D_\beta} = \left| \overrightarrow{C_2} * \overrightarrow{X_\beta} - \vec{X} \right| \tag{6}$$

$$\overrightarrow{D_\delta} = \left| \overrightarrow{C_3} * \overrightarrow{X_\delta} - \vec{X} \right| \tag{7}$$

where $\overrightarrow{D_\alpha}$, $\overrightarrow{D_\beta}$ and $\overrightarrow{D_\delta}$ indicate a distance of alpha, beta and delta positions and $\overrightarrow{C_1}$, $\overrightarrow{C_2}$ and $\overrightarrow{C_3}$ denote three coefficient vectors.

The new position vectors are expressed as follows:

$$\vec{X}_1 = \overrightarrow{X_\alpha} - \overrightarrow{A_1} * \left(\overrightarrow{D_\alpha} \right) \tag{8}$$

$$\vec{X}_2 = \overrightarrow{X_\beta} - \overrightarrow{A_2} * \left(\overrightarrow{D_\beta} \right) \tag{9}$$

$$\vec{X}_3 = \overrightarrow{X_\delta} - \overrightarrow{A_3} * \left(\overrightarrow{D_\delta} \right) \tag{10}$$

where $\overrightarrow{X_\alpha}$, $\overrightarrow{X_\beta}$ and $\overrightarrow{X_\delta}$ indicate the position of alpha, beta and gamma wolves, $\vec{X}_1$, $\vec{X}_2$ and $\vec{X}_3$ indicate a new position vector using alpha, beta and gamma wolves, and distance vectors $\overrightarrow{D_\alpha}$, $\overrightarrow{D_\beta}$ and $\overrightarrow{D_\delta}$ denote the distance vector of alpha, beta and gamma and also $\overrightarrow{A_1}$, $\overrightarrow{A_2}$, and $\overrightarrow{A_3}$ represent a coefficient vector. The final position is computed as follows:

$$\vec{X}\left(k+1\right) = \frac{\sum_{i=0}^{n} \overrightarrow{X_i}}{n} \tag{11}$$

where $\vec{X}_1\left(k+1\right)$ denotes a finalized new position vector computed by using alpha, beta and delta wolf and '*n*' represents the three wolf's alpha, beta and delta ($n = 3$).

Attacking Prey Phase

This phase focuses on local search validation and identifying optimal solutions. The Coefficient vector A fluctuates within [−2a, 2a] [−2a, 2a] [−2a, 2a] and decreases linearly from R to 0. When |A| < 1|, search agents perform a local search. When |A| > 1|, search agents diverge to find new prey. Parameter C helps avoid local optima by varying within [0, 2]. The pseudocode for the proposed tuning is given below:

1. Initialize the population of grey wolves (N wolves) in the search space:
- Each wolf's position is represented by a vector of antenna parameters [Ls, Ws, Rf, Sf, Lf, Sp]
- Define the boundaries for each parameter in the search space.
2. Initialize parameters:
- Set a = 2 (decreases linearly to 0 during iterations)
- Initialize coefficient vectors A and C
3. Evaluate the fitness of each wolf:
- Calculate fitness based on antenna performance metrics (e.g., gain, return loss)
- Identify the positions of:
- Alpha wolf (X_alpha): Best solution
- Beta wolf (X_beta): Second-best solution
- Delta wolf (X_delta): Third-best solution
4. While (termination condition not met):
- For each grey wolf i:
a. Calculate distance vectors: D_alpha , D_beta & D_delta
b. Update the wolf's position:X_1, X_2 & X_3
c. Final position update:
- Update parameters A, C, and a:
*- A = 2 * a * r–a, where r is a random vector in [0, 1]*
*- C = 2 * r*
- Decrease linearly from 2 to 0
- Recalculate fitness for each wolf:
- Evaluate the updated positions using the fitness function
- Update the positions of the alpha, beta, and delta wolves
5. Return the position of the alpha wolf (X_alpha) as the optimal solution

The pseudocode describes the process of optimizing the microstrip patch antenna design using the GWO. Initially, a population of grey wolves is randomly initialized within the search space where each wolf represents a potential solution defined by the antenna design parameters, such as length, width, and spacing. The algorithm evaluates the fitness of each wolf based on performance metrics like antenna gain and return loss. The best three solutions are identified as the alpha, beta, and delta wolves, which guide the optimization process. In each iteration, the positions of all wolves are updated based on their distances from the alpha, beta, and delta wolves. This emulates the hunting behavior of grey wolves, where they coordinate to locate and encircle prey. The distance vectors and coefficient parameters are calculated to control the direction and magnitude of movement. The parameter a is decreased linearly to shift the focus from exploration to exploitation. By combining the updated positions, a new location for each wolf is determined. The algorithm recalculates the fitness values for all wolves and updates the roles of alpha, beta, and delta based on their performance. This process continues until the termination condition, such as a maximum number of iterations, is met. The final position of the alpha wolf, representing the best solution, is returned as the optimized antenna design.

4 RESULT AND DISCUSSION

For optimization, the population size is set to 20. The number of iterations is set to 200. The convergence coefficient decreases linearly from 2 to 0. The optimized structure is simulated using HFSS. After GWO, the optimized values are given in Tab. 2. The substrate length (LS) is increased from 20 mm to 21.5 mm to increase resonance. The substrate width (WS) is reduced from 16 mm to 15.8 mm to improve impedance matching. The feed radius (Rf) was increased from 2.3 mm to 2.5 mm for better coupling with the substrate. Additionally, the substrate thickness (SF) and feed length (Lf) were slightly adjusted and the spacing between patches (Sp) was reduced from 1.2 mm to 1.1 mm. These optimizations improve the gain and return loss of the proposed antenna. The Return Loss (RL) behaviour of the proposed antenna is shown in Fig. 2. The RL value of –24 dB is achieved corresponding to the frequencies of 24 GHz and 32 GHz.

Table 2 Antenna design values after optimizations

Parameter	Value / mm (Before Optimization)	Value / mm (After Optimization)
LS	20	21.5
WS	16	15.8
Rf	2.3	2.5
SF	4	4.2
Lf	4	3.8
Sp	1.2	1.1

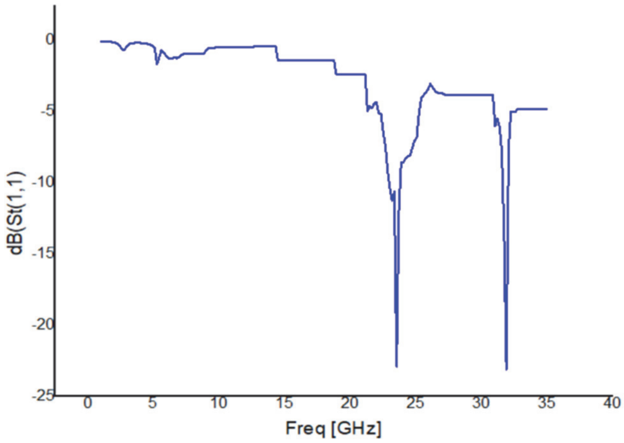

Figure 2 Proposed antenna S11 plot with Sw' of 4.8 mm

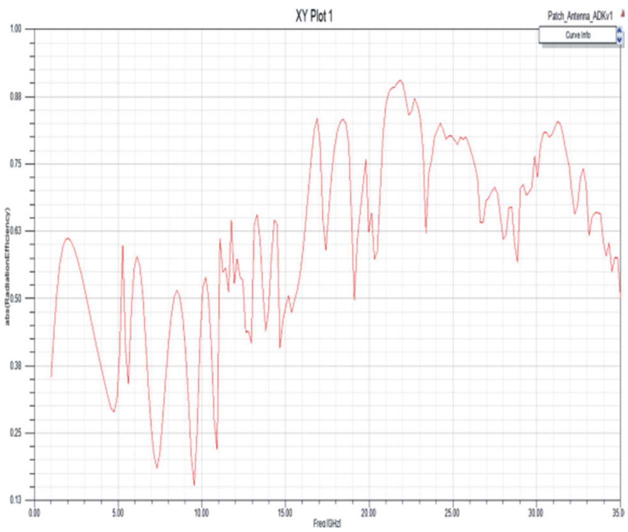

Figure 3 Radiation efficiency

Fig. 3 illustrates the effectiveness of converting input power into radiated energy with robust 80% to 88 % efficiency for the 5G bands.

Fig. 4 shows a radiation pattern that has a directional pattern with multiple lobes and nulls which denotes strong and weak radiation areas. This is best suitable for broad coverage applications. The pattern exhibits a clear directional characteristic with a main lobe centered around the 0-degree mark. This indicates that the antenna radiates most of its power in this direction.

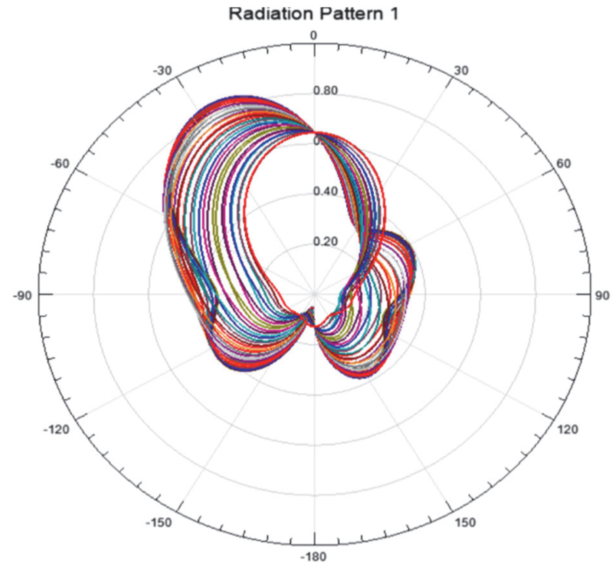

Figure 4 Radiation pattern

Fig. 5 shows a high gain of 9.55 dB that proves an ability to transmit or receive electromagnetic signals efficiently. The color bar on the left indicates the intensity of the radiation with red denoting the highest power density and blue representing the lowest. The pattern shows a clear directional characteristic with the main lobe (pointing in the direction of the *Z*-axis.

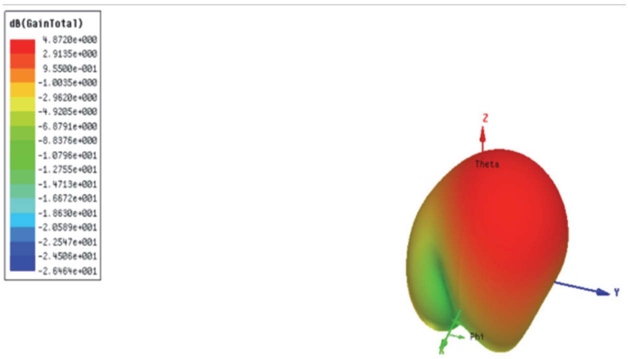

Figure 5 Gain plot

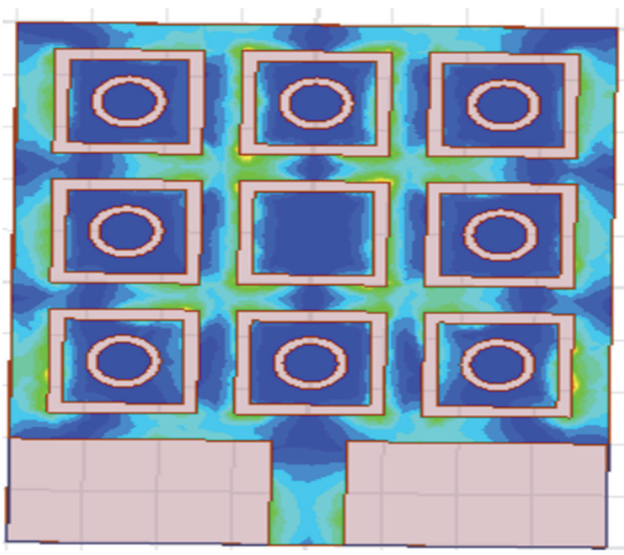

Figure 6 Surface current distribution

The surface currents' internal characteristic is shown in Fig. 6. The figure represents colours various levels of surface current density with red indicating high density and blue indicating low density. It is observed that the slot antenna's performance is significant across different frequency ranges.

Table 3 Performance analysis

Ref.	Frequency	S11 / dB	Volume / mm^3	Gain	RE / %
22	28/28/48	−21, −24 & −30	34.8 × 34.8 × 0.508	8	82
23	27.946 and 37.83	−27.84 & −18.35	55 × 110 × 0.508	7.18 and 9.24	92
24	28	−26	10.2 × 27.8	-	-
25	38	−30	47.4 × 32.5 × 0.51	6.5	86
26	28	−32	26 × 14 × 0.38	1.83	-
27	28	−25	35 × 17 × 0.5	8	-
28	28/38	−19 & −28	15 × 25 × 0.508	5.9	-
Proposed	24 & 32	−24 & −24	16 × 20	9.5	88

The comparison of the proposed antenna is given in Tab. 3. The proposed antenna design shows better performance when compared to existing designs. It operates at 24 GHz and 32 GHz with a Return Loss of −24 dB at both frequencies effectively. This indicates good impedance matching and minimal signal loss. In terms of size, the proposed antenna is relatively compact compared to the previously proposed designs. The radiation efficiency is another critical parameter where the proposed shows an efficiency of 88%. It proves the antenna's ability to effectively radiate the input power and minimise losses. In addition, it achieves a high gain of 9.5 dB higher than compared designs.

5 CONCLUSION

This work introduces a novel patch antenna optimized for 5G applications, designed to address the challenges of compactness, performance, and design complexity. The proposed antenna leverages the capabilities of the Grey Wolf Optimizer (GWO), a metaheuristic optimization algorithm, to refine its volume and ensure optimal performance. By employing GWO, the antenna achieves significant improvements in gain, bandwidth, and overall compactness, demonstrating its potential to meet the stringent requirements of next-generation wireless communication systems. The simulation results confirm the antenna's ability to operate efficiently at dual frequencies of 3.6 GHz and 4.28 GHz, aligning with critical 5G bands for sub-6 GHz applications. These operational frequencies make the antenna suitable for various use cases, including enhanced mobile broadband and IoT connectivity. Furthermore, the optimized design achieves a higher gain, stable radiation patterns, and compact size, which are crucial for seamless integration into modern communication devices. The use of the Rogers substrate enhances the antenna's performance by providing low dielectric loss and excellent frequency stability. These features further validate the design's robustness and its suitability for high-performance wireless applications. Additionally, the incorporation of advanced optimization techniques like GWO paves the way for future antenna designs that can meet evolving industry standards.

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