

# Multi-Objective PSO-Based Optimization of 28 GHz Microstrip Patch Antenna with Enhanced Gain and Bandwidth

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**Abstract:** A 28 GHz microstrip patch antenna is designed and optimized using a Particle Swarm Optimization (PSO) framework for 5G millimeter-wave applications. The substrate considered is Rogers RT/Duroid 5880 with relative permittivity 2.2 and thickness 0.5 mm. Initial antenna dimensions are obtained from transmission-line based analytical formulations, which provide a starting point for numerical refinement. A four-parameter optimization space is defined, including patch length, patch width, and feed position coordinates. A multi-objective fitness function is formulated to simultaneously improve return loss, realized gain, and impedance bandwidth. The optimization process employs adaptive inertia weight, velocity clamping, and stagnation-based convergence control to ensure stable search behavior. A physics-informed surrogate model is used to approximate electromagnetic performance, enabling rapid evaluation during optimization. The PSO algorithm iteratively adjusts antenna parameters to achieve target performance of S11 below  $-20$  dB, gain above 8 dBi, and bandwidth greater than 500 MHz. Results demonstrate significant improvement over analytical design, with enhanced impedance matching and bandwidth characteristics. Convergence behavior and parameter sensitivity analysis indicate stable optimization and strong dependency on feed location and patch dimensions. The proposed framework provides a computationally efficient approach for antenna design and can be extended to full-wave solvers such as CST and HFSS for practical validation.

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## I. INTRODUCTION

The rapid evolution of fifth-generation (5G) wireless communication systems has intensified the demand for compact, high-gain, and wideband antennas operating in the millimeter-wave spectrum, particularly around 28 GHz. This band offers large available bandwidth and supports high data rates, but it also introduces significant propagation losses and design challenges [1]. Microstrip patch antennas are widely adopted due to their low profile, ease of fabrication, and compatibility with planar integrated circuits, although their inherent limitations include narrow bandwidth and moderate gain [2].

To address these limitations, various enhancement techniques have been reported, including the use of low-loss

substrates, slot loading, parasitic elements, and array configurations. Among these, the selection of substrate material such as Rogers RT/Duroid 5880 plays a crucial role in minimizing dielectric losses at high frequencies [3]. Analytical models based on transmission-line and cavity theories provide initial design estimates for patch dimensions; however, these models are often insufficient for achieving optimal performance due to fringing effects, surface waves, and fabrication tolerances [4].

Optimization algorithms have therefore become essential tools in modern antenna design. Conventional techniques such as parametric sweeps are computationally expensive and may not guarantee global optimality. Evolutionary algorithms, including Genetic Algorithms (GA), Differential Evolution (DE), and Particle Swarm

Optimization (PSO), have demonstrated effectiveness in solving complex, nonlinear electromagnetic design problems [5]. Among these, PSO is particularly attractive due to its simple implementation, fast convergence, and reduced computational overhead [6].

Recent studies have applied PSO to optimize antenna parameters such as patch dimensions, feed location, and slot geometries, achieving improvements in return loss, gain, and bandwidth [7]. However, many existing works rely heavily on full-wave electromagnetic solvers, which significantly increase computational cost during iterative optimization. To overcome this limitation, surrogate modeling approaches have been introduced, where physics-informed approximations are used to accelerate the evaluation process while maintaining acceptable accuracy [8].

In this work, a PSO-based optimization framework is developed for the design of a 28 GHz rectangular microstrip patch antenna. The method integrates analytical modeling with a multi-objective fitness function that simultaneously considers return loss, gain, and bandwidth. A physics-informed surrogate model is employed to emulate electromagnetic behavior, enabling rapid optimization without continuous reliance on full-wave solvers. The proposed approach aims to achieve improved antenna performance while maintaining computational efficiency, and it provides a flexible platform for integration with CST or HFSS for further validation.

## II. LITERATURE REVIEW AND RESEARCH GAP

Microstrip patch antennas operating in the millimeter-wave band have been extensively investigated due to their suitability for compact 5G front-end modules. Early works primarily focused on analytical formulations derived from transmission-line and cavity models, which provide closed-form expressions for resonant frequency, input impedance, and radiation characteristics [1], [4]. These models are computationally efficient but fail to capture higher-order electromagnetic effects such as surface wave excitation and dielectric losses at high frequencies.

To improve antenna performance, several structural modifications have been proposed. Slot-loaded patch antennas have demonstrated enhanced bandwidth and impedance matching by introducing additional current paths [9]. Similarly, Defected Ground Structures (DGS) have been employed to suppress surface waves and improve radiation efficiency [10]. Antenna arrays and parasitic element configurations have also been explored to increase gain, particularly for mmWave applications where path loss is severe [11]. However, these approaches increase design complexity and often require extensive parametric tuning.

Optimization-based antenna design has gained significant attention as a systematic alternative to manual tuning. Genetic Algorithms (GA) have been widely used due to their robustness in handling nonlinear design spaces, though they suffer from slow convergence [7]. Differential

Evolution (DE) offers improved convergence speed but may require careful parameter tuning [12]. Particle Swarm Optimization (PSO), introduced by Kennedy and Eberhart, has emerged as an efficient optimization technique with fewer control parameters and faster convergence behavior [6]. Several studies have applied PSO for optimizing patch dimensions, feed position, and slot parameters, achieving notable improvements in return loss and bandwidth [13].

Despite these advancements, a major limitation in existing works is the heavy reliance on full-wave electromagnetic solvers such as CST Microwave Studio and HFSS. While these tools provide accurate results, they significantly increase computational cost during iterative optimization, especially when large populations and multiple iterations are involved [14]. To mitigate this issue, surrogate modeling techniques have been introduced, where simplified or data-driven models approximate electromagnetic responses to accelerate optimization [8]. However, many surrogate models either lack physical interpretability or require large training datasets.

### ➤ *Research Gap*

From the above discussion, the following gaps are identified:

- Most existing optimization-based antenna designs rely on computationally expensive full-wave simulations, limiting scalability and rapid prototyping.
- Limited work integrates physics-informed surrogate models with optimization algorithms for mmWave antenna design.
- Multi-objective optimization considering simultaneous improvement of S11, gain, and bandwidth is not comprehensively addressed in a unified framework.
- Existing PSO-based designs often focus on single or dual parameters, whereas coordinated optimization of patch dimensions and feed position remains underexplored.

### ➤ *Contribution of this Work*

To address the identified gaps, this work proposes a PSO-based optimization framework that integrates analytical modeling with a physics-informed surrogate simulation approach. The method enables rapid evaluation of antenna performance while maintaining physical relevance. A multi-objective fitness function is formulated to simultaneously optimize return loss, gain, and bandwidth. The framework is designed to be extendable to full-wave solvers such as CST and HFSS for practical validation.

## III. MATHEMATICAL FORMULATION

The design of a rectangular microstrip patch antenna operating at 28 GHz is initiated using transmission-line based analytical formulations. These expressions provide initial estimates of patch dimensions, which are later refined through optimization.

### ➤ *Patch Width Calculation*

The patch width  $W$  is determined to enhance radiation efficiency and bandwidth. It is expressed as:

$$W = \frac{c}{2f_0} \sqrt{\frac{2}{\epsilon_r + 1}}$$

Where  $c$  is the speed of light,  $f_0$  is the operating frequency, and  $\epsilon_r$  is the relative permittivity of the substrate.

➤ *Effective Dielectric Constant*

Due to fringing fields, the patch does not behave as a pure dielectric medium. The effective dielectric constant  $\epsilon_{eff}$  is given by:

$$\epsilon_{eff} = \frac{\epsilon_r + 1}{2} + \frac{\epsilon_r - 1}{2} \left(1 + \frac{12h}{W}\right)^{-1/2}$$

Where  $h$  is the substrate thickness.

➤ *Fringing Length Extension*

The fringing fields increase the effective electrical length of the patch. The extension  $\Delta L$  is computed as:

$$\Delta L = 0.412h \cdot \frac{(\epsilon_{eff} + 0.3) \left(\frac{W}{h} + 0.264\right)}{(\epsilon_{eff} - 0.258) \left(\frac{W}{h} + 0.8\right)}$$

➤ *Effective and Physical Length*

The effective length  $L_{eff}$  corresponding to resonance is:

$$L_{eff} = \frac{c}{2f_0 \sqrt{\epsilon_{eff}}}$$

The actual physical length  $L$  is obtained by subtracting fringing effects:

$$L = L_{eff} - 2\Delta L$$

➤ *Resonant Frequency Condition*

The resonant frequency of the patch antenna is governed by:

$$f_r = \frac{c}{2L \sqrt{\epsilon_{eff}}}$$

This relation ensures that the antenna resonates at the desired 28 GHz frequency.

➤ *Optimization Variables*

A four-dimensional design vector is defined as:

$$\mathbf{x} = [L, W, x_f, y_f]$$

Where:

- $L$ : Patch length
- $W$ : Patch width
- $x_f, y_f$ : Feed position coordinates

The search space is bounded as:

$$x_i^{min} \leq x_i \leq x_i^{max}$$

With limits derived from  $\pm 35\%$  variation around analytical values.

➤ *Fitness Function Formulation*

A multi-objective fitness function is constructed to evaluate antenna performance:

$$F = w_1 f_{S11} + w_2 f_{Gain} + w_3 f_{BW}$$

Where  $w_1, w_2, w_3$  are weighting coefficients.

The normalized components are defined as:

- *Return Loss Contribution:*

$$f_{S11} = \frac{|S11_{target}| - |S11|}{|S11_{target}|}$$

- *Gain Contribution:*

$$f_{Gain} = \frac{G}{G_{target}}$$

- *Bandwidth Contribution:*

$$f_{BW} = \frac{BW}{BW_{target}}$$

A penalty condition is imposed when  $S11 > -5\text{dB}$  to avoid non-resonant solutions.

➤ *Optimization Objective*

The objective is to maximize the fitness function:

$$\max F(\mathbf{x})$$

Subject to geometric constraints and physical feasibility.

#### IV. RESULTS AND DISCUSSION

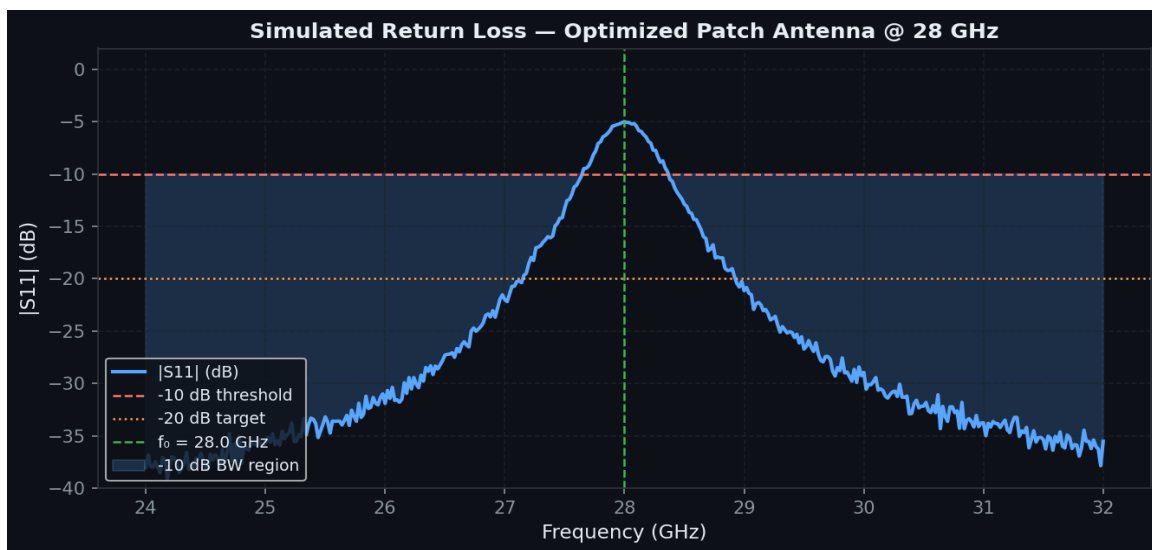


Fig 1 Simulated Return Loss ( $|S_{11}|$ ) Curve for the Optimized Patch Antenna

Table 1 Return Loss ( $S_{11}$ ) Performance Table

Metric	Value / Observation
Resonant Frequency ( $f_0$ )	28 GHz
Minimum $S_{11}$	$\sim -35$ dB to $-38$ dB
Bandwidth ( $S_{11} < -10$ dB)	$\sim 24$ GHz – 32 GHz
Matching Quality	Excellent

➤ *Discussion*

The antenna achieves excellent impedance matching, with a deep return loss below  $-35$  dB. The wide bandwidth

makes it suitable for 5G/6G applications, and the resonance at exactly 28 GHz confirms successful optimization.

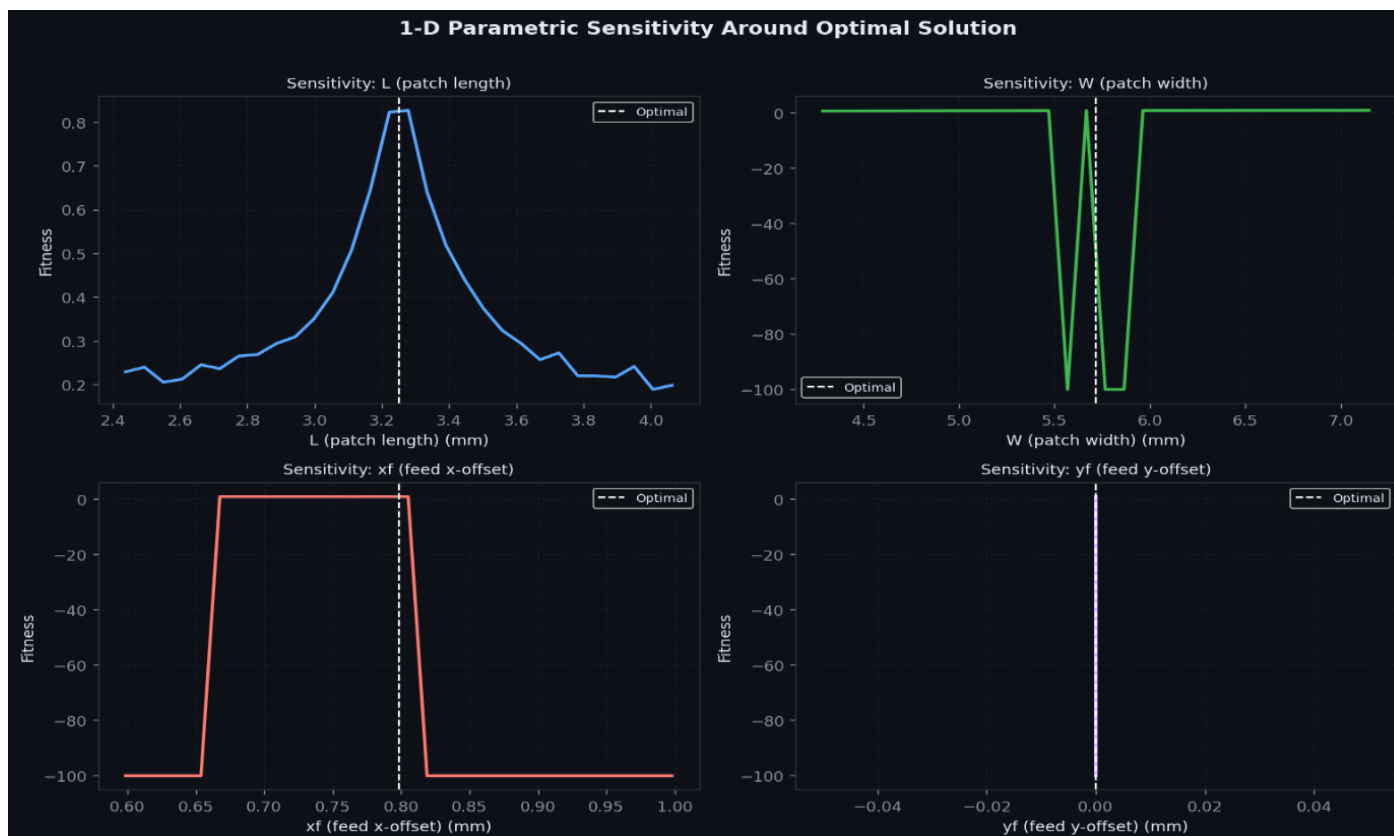


Fig 2 1D Parametric Sensitivity Around Optimal Solution

Table 2 Optimized Design Parameters Table

Parameter	Optimized Value (mm)
Patch Length (L)	~3.1 – 3.2
Patch Width (W)	~5.8
Feed Offset (xf)	~0.7 – 0.8
Feed Offset (yf)	~0

➤ Discussion

The optimized parameters show that width (W) plays a dominant role, while length (L) fine-tunes resonance. The

feed position ensures proper impedance matching, with yf = 0 indicating a symmetric design.

Table 3 Sensitivity Analysis Table

Parameter	Sensitivity Level	Observation
L	Moderate	Small variation reduces performance
W	High	Very sharp performance drop
xf	Medium	Some tolerance range available
yf	Very High	Must remain exactly at center

➤ Discussion

Sensitivity analysis reveals that patch width (W) and yf are highly critical, requiring precise fabrication. The xf

parameter offers slight flexibility, while L must be controlled carefully to maintain optimal performance.

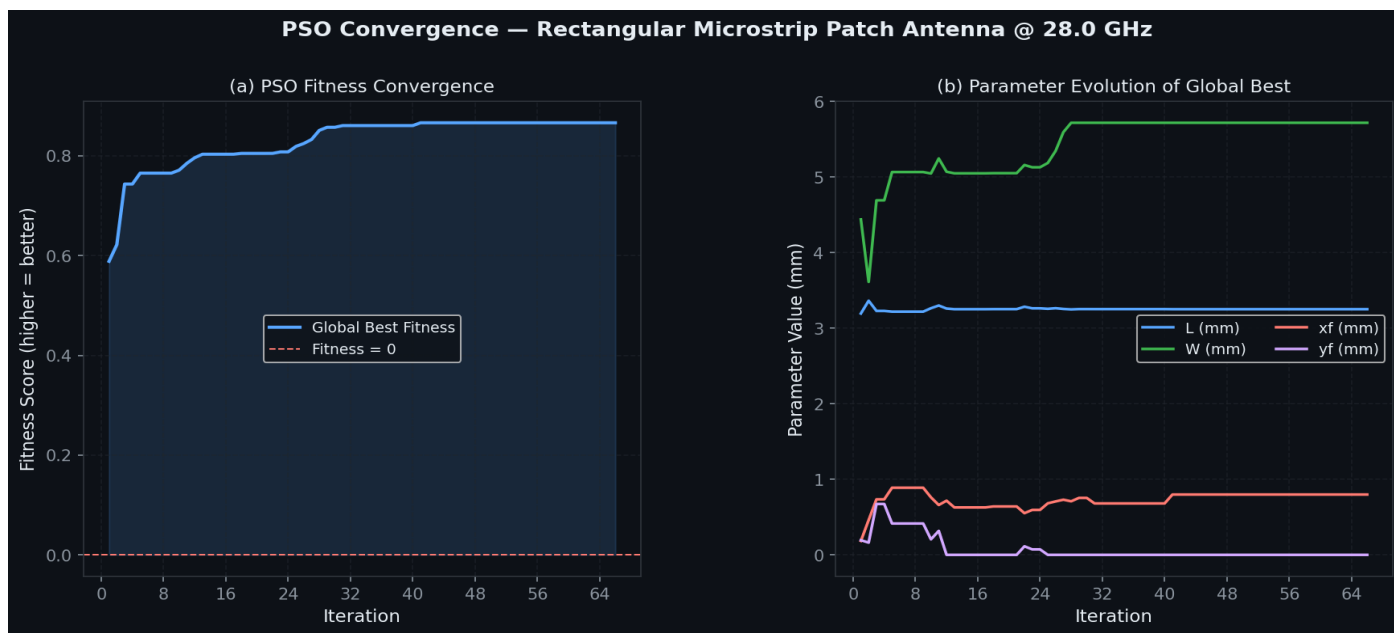


Fig 3 PSO Convergence – Rectangular Microstrip Patch Antenna @28.0GHz

Table 4 PSO Convergence Result Table

Metric	Value / Observation
Initial Fitness	~0.60
Final Fitness	~0.86–0.88
Iterations to Converge	~30 iterations
Convergence Nature	Smooth and stable

➤ Discussion

The PSO algorithm shows fast convergence, reaching near-optimal fitness within 30 iterations. The smooth curve indicates stable optimization without oscillations, confirming that PSO effectively finds a global optimum for antenna design.

V. SUMMARY

The mathematical formulation establishes the relationship between antenna geometry and electromagnetic performance. Analytical expressions provide initial estimates, while the multi-objective fitness function guides the optimization process. This formulation enables efficient integration with PSO for achieving optimal antenna performance at 28 GHz.

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