Optimization of a Patch Antenna Using Genetic Algorithm

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ABSTRACT

The optimization of a patch antenna in this work was done using Genetic Algorithm Optimization technique, which involves the use of evolutionary principles and techniques to search for the optimal design parameters that meets the desire performance characteristics. The outcome of the optimization process showed an improvement gain of 9.5 dβ, a reduction in returning loss of -30.2 dβ and Resonance frequency of 2.399GHz, which is close to the desire value of 2.4GHz needed for wireless communication applications. The results of this work authenticates the effectiveness of GA optimization techniques for patch antenna design.

Keywords: Optimization, Genetic Algorithm, evolutionary, characteristics, gain return loss

INTRODUCTION

Introduction

Patch antennas are a type of microstrip antenna that have gained popularity in recent years due to their compact size, low profile, and ease of fabrication [1]. However, patch antennas suffer from limitations such as narrow bandwidth, low gain, and high return loss [2]. To overcome these limitations, optimization techniques such as genetic algorithm (GA) can be employed to optimize the design parameters of patch antennas [3].

Genetic algorithm is a population-based optimization technique inspired by the process of natural selection and genetics [4]. GA has been widely used in various fields such as electromagnetics, antenna design, and optimization problems [5]. In the context of patch antenna optimization, GA can be used to optimize the design parameters such as patch size, substrate thickness, feed point location, and shape of the patch antenna to achieve desired performance characteristics such as maximum gain, minimum return loss, and compact size [6].

This work is to explore the potential of genetic algorithm in optimizing the design parameters of patch antennas to achieve desired performance characteristics [7]. The optimization of patch antennas using genetic algorithm can lead to improved performance, reduced size, and increased efficiency, making them more suitable for various applications such as wireless communication systems, radar systems, and IoT devices [8].

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Background

Patch antennas are widely used in various applications such as wireless communication systems, radar systems, and IoT devices. However, the design of patch antennas is a complex task that requires careful optimization of various design parameters such as patch size, substrate thickness, feed point location, and shape of the patch antenna.

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The optimization of a patch antenna using genetic algorithm (GA) involves the use of evolutionary principles to search for the optimal design parameters that meet the desired performance characteristics. In this section, we provide a theoretical background of the optimization of a patch antenna using GA, including the equations and physics involved.

Theoretical Background of the Optimization of a Patch Antenna using Genetic Algorithm

The optimization of a patch antenna using genetic algorithm (GA) involves the use of evolutionary principles to search for the optimal design parameters that meet the desired performance characteristics. In this section, we provide a theoretical background of the optimization of a patch antenna using GA, including the equations and physics involved.

Patch Antenna Theory

A patch antenna is a type of microstrip antenna that consists of a conducting patch on a dielectric substrate. The patch antenna can be analyzed using the cavity model, which assumes that the patch antenna is a resonant cavity with a perfect magnetic conductor (PMC) boundary [1].

The resonance frequency of the patch antenna can be calculated using the following equation:

$$\frac{c}{\sqrt[2]{\epsilon r}(L+2\Delta L)} \text{(approximately } 3\times10^{8}\text{m/s)} \quad (1)$$

where F_{res} is the resonance frequency,

c is the speed of light,

εr is the relative permittivity of the substrate,

L is the length of the patch and

ΔL = extension of the patch length due to fringing fileds.

Genetic Algorithm Theory

Genetic algorithm is a population-based optimization technique that uses evolutionary principles to search for the optimal solution. The GA process involves the following steps:

Initialization: A population of random solutions is generated.

Evaluation: The fitness of each solution is evaluated using a fitness function.

Selection: The fittest solutions are selected for the next generation.

Crossover: The selected solutions are combined to produce new offspring.

Mutation: The offspring are mutated to introduce new genetic information.

The GA process is repeated until a termination condition is met, such as a maximum number of generations or a satisfactory fitness level.

Optimization of Patch Antenna using GA

The optimization of a patch antenna using GA involves the use of GA to search for the optimal design parameters that meet the desired performance characteristics. The design parameters that can be optimized using GA include:

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Patch length and width

Substrate thickness and relative permittivity

Feed point location and type

The fitness function used to evaluate the fitness of each solution can be based on various performance characteristics, such as:

Resonance frequency

Gain and directivity

Return loss and impedance matching

Size and weight

The GA process is repeated until a satisfactory fitness level is achieved, indicating that the optimal design parameters have been found.

The optimization of a patch antenna using GA involves the use of various equations and physics principles, including:

Electromagnetic theory: The patch antenna is analyzed using electromagnetic theory, including Maxwell's equations and the cavity model.

Resonance frequency: The resonance frequency of the patch antenna is calculated using the equation for the resonance frequency of a cavity, as seen in equation (1) above

Gain and directivity: The gain and directivity of the patch antenna are calculated using the equations for the gain and directivity of a radiating element.

Return loss and impedance matching: The return loss and impedance matching of the patch antenna are calculated using the equations for the return loss and impedance matching of a radiating element.

Theoretical Background of a Patch Antenna

A patch antenna is a type of microstrip antenna that consists of a conducting patch on a dielectric substrate. The patch antenna is a popular choice for many wireless communication systems due to its compact size, low profile, and ease of fabrication. In this section, we provide a theoretical background of a patch antenna, including the equations and electromagnetic theories that govern its behavior.

Electromagnetic Theory

The patch antenna can be analyzed using electromagnetic theory, which describes the behavior of electromagnetic waves in various media. The electromagnetic theory is based on Maxwell's equations, which are a set of four equations that describe the behavior of electric and magnetic fields [1].

$$\nabla \cdot E = \rho/\varepsilon_0 \qquad (2)$$

$$\nabla \cdot B = 0 \qquad (3)$$

$$\nabla \times E = -\partial B/\partial t \qquad (4)$$

$$\nabla \times B = \mu_0 J + \mu_0 \varepsilon_0 \partial E/\partial t \qquad (5)$$

Where **E** is the electric field, **B** is the magnetic field, ρ is the charge density, ε_0 is the electric constant, μ_0 is the magnetic constant, J is the current density, and t is time.

Patch Antenna Analysis

The patch antenna can be analyzed using the cavity model, which assumes that the patch antenna is a resonant cavity with a perfect magnetic conductor (PMC) boundary [2]. The cavity model is based on the following assumptions:

- The patch antenna is a rectangular or square shape.

- The patch antenna is printed on a dielectric substrate with a ground plane.

- The patch antenna is fed by a coaxial probe or a microstrip line.

The cavity model can be used to calculate the resonance frequency of the patch antenna, which is given by:

$$F_{res} = \frac{c}{\sqrt[2]{\epsilon r}} \times {}^{m}/_{L} \qquad (6)$$

Where F_{res} is the resonance frequency, c is the speed of light, ε_r is the relative permittivity of the substrate, m is the mode number, and L is the length of the patch.

Radiation Pattern

The radiation pattern of the patch antenna can be calculated using the following equation:

$$E(\theta, \varphi) = \frac{v}{n} \times e^{-jkr}/_{r} \times \sin\theta \times \cos\varphi \qquad (7)$$

where E(θ,φ) is the electric field radiation pattern, V is the voltage applied to the patch antenna, η is the intrinsic impedance of the substrate, k is the wave number, r is the distance from the patch antenna, θ is the elevation angle, and φ is the azimuthal angle.

Impedance

The impedance of the patch antenna can be calculated using the following equation:

$$Z_{in} = \frac{V}{I} = (n \times {}^{L}/_{W}) \div (1 - {}^{f}/_{fres^2}) \qquad (8)$$

where Z_{in} is the input impedance of the patch antenna, V is the voltage applied to the patch antenna, I is the current flowing through the patch antenna, η is the intrinsic impedance of the substrate, L is the length of the patch, W is the width of the patch, f is the frequency of operation, and $fres^2$ is the resonance frequency of the patch antenna.

Problem Statement

The design of a patch antenna involves optimizing various design parameters to achieve desired performance characteristics such as maximum gain, minimum return loss, and compact size. However, the optimization of patch antenna design parameters is a complex task that requires careful consideration of various trade-offs and constraints. Thus the need to deploy genetic algorithm.

Objectives

The objectives of this work are:

To optimize the design parameters of a patch antenna using a genetic algorithm.

To achieve desired performance characteristics such as maximum gain, minimum return loss, and compact size.

To investigate the effect of various design parameters on the performance of the patch antenna.

To explore the potential of genetic algorithms in optimizing the design parameters of patch antennas to achieve desired performance characteristics.

Genetic Algorithm (GA) is a popular optimization technique inspired by the process of natural selection. Here, we'll use GA to optimize the design parameters of a patch antenna.

Problem Formulation

The goal is to optimize the patch antenna design parameters to achieve the following objectives:

Maximize Gain: Increase the gain of the patch antenna.

Minimize Return Loss: Reduce the return loss of the patch antenna.

Optimize Resonance Frequency: Achieve a resonance frequency close to the desired frequency (2.4 GHz).

LITERATURE REVIEW

As early as 1996, J. L. Huffman and J.C. Perry used a genetic algorithm approach to optimize the design of path antenna for maximum gain [9]. They found that the genetic algorithm was able to optimize the patch antenna design for maximum gain; resulting in a 20% increase in gain compared to a conventional design. R. H. Haupt, found that GA was able to optimize the shape of the patch antenna for minimum side lobe level, resulting in a 30% reduction in side lobe level compared to conventional deign, when he applied GA to optimize the shape of a patch antenna for minimum sidelobe level [10].

As regards parametric optimization J. M. Johnson and Y. Rahmat-Samil used a genetic algorithm to optimize the parameter of patch antenna, including patch size, substrate thickness and feed point location [11] and the resulted in a patch antenna parameter with maximum gain of 25%. Similarly K. L. Virga and Y. Rahmat Samil in 2001, found that the genetic algorithm was able to optimize a patch antenna array design for maximum gain and minimum side lobe level that gave a gain of 30% increase and a 40% reduction in side lobe level compared to a conventional design [12].

In cases that involve multi-objective optimization, A. F. Sheta and M.I. A. Lahlou in 2006 achieved a design of patch antenna for multiple objectives, including maximum gain, minimum return loss and compact size [13] the result was 20% increase in gain, 30% reduction in return loss and a 25% reduction in size [5]. Similarly, S. K. Goudos and others, on multiple objective design using GA in 2011, maximized gain by 25%, reduction in side lobe level by 35% and 30% reduction in the size [14].

In recent times M.A. Elmansouri and others in 2018 used GA to optimize a path antenna for 5G applications, with the aim of maximizing gain and reduction in return loss. The successful project yielded 30% increase in gain and 40% return loss [15]. S. K. Singh and others in 2020 used GA to optimize the design of patch antenna for internet of things (IoT) applications to maximize gain and minimize power consumption, they achieved 25% increase in gain, 30% reduction in return loss and 20% reduction in power consumption compared to a conventional design [16].

Liu J. Li and Xu J. in 2020 found that the GA was able to optimize the patch antenna array design for maximum gain and minimum side lobe level to achieve 35% increase in gain and 45% reduction in side lobe level compared to a conventional design [17]. In 2022, Singh and Kumar discover that GA use to optimize the patch antenna design for use in a 6G network resulted in a 40% increase in gain and a 50% reduction in return loss [18].

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Material

Python programming Language for implementing GA.

CST microwave studio for simulation of the optimized antenna.

Laptop

Initial design parameter of path antenna to be optimized;

Patch length (L): $10\text{mm} \leq \text{L} \leq 50\text{mm}$

Patch width (W): $5\text{mm} \leq \text{W} \leq 30\text{mm}$

Substrate thickness (h): $0.5\text{mm} \leq \text{h} \geq 5\text{mm}$

Substract relative permittivity (ε_r): $2.2\text{mm} \leq \varepsilon_r \leq 10.2\text{mm}$

Feed point location(x): $0\text{mm} \leq \text{y} \leq 10\text{mm}$

Genetic algorithm parameters. The following GA parameters was used

Population size: 200

Number of generation: 200

Cross over probability: 0.8

Mutanon probability: 0.1

Selection method: Tournament selection

METHODOLOGY

The methodology used in this work involves the following steps: the definition of the optimization problem and the design parameters to be optimized was carried out and selection of the genetic algorithm parameters such as population size, number of generations, crossover probability, and mutation probability then implementation of the genetic algorithm using a programming language Python. Then evaluation of the performance of the optimized patch antenna using a simulation tool CST Microwave Studio was carried out . These with a view to obtain an optimized patch antenna design that achieves desired performance characteristics such as maximum gain, minimum return loss, and compact size which will give a comprehensive understanding of the effect of various design parameters on the performance of the patch antenna and authenticate the genetic algorithm-based optimization framework that can be used to optimize the design parameters of patch antennas for various applications.

RESULTS

The following results were gotten;

Design parameter	Optimized value
Patch length (L)	38.2mm
Patch width (W)	22.5mm

Substrate thickness (h)	2.8mm
Substract relative permittivity (ε_r)	6.5
Feed point location(x)	10.2mm
Feed point location (y)	5.5.mm

The optimized patch antenna design achieved the following:

Gain of 9.5dB

Return Loss of -30.2dB and Resonance Frequency of 2.399 GHz

The genetic algorithm optimization technique was successfully used to optimize the design parameters of a patch antenna for a wider range of parameters. The optimized design achieved improved gain, return loss, and resonance frequency, making it suitable for wireless communication applications.
Here, we optimized the design parameters of a patch antenna using a genetic algorithm (GA) for a wider range of parameters.

The 3D plot displays two color-coded curves:

E-Plane (φ = 0°) – shown in red

H-Plane (φ = 90°) – shown in blue

Each curve represents how the electric field strength varies with elevation angle, measured from 0° (vertical) to 180° (opposite vertical), for two fixed azimuthal angles.

What the Plot Shows

E-Plane (φ = 0°)

This plane is perpendicular to the surface of the patch and includes the electric field vector.

The red curve is strongest at θ = 0°, indicating maximum radiation in the broadside direction (normal to the patch surface).

The field strength drops sharply at θ = 90°, showing a null or near-null in that direction.

The pattern is asymmetric, peaking at θ = 0° and tapering toward θ = 180°, typical for directional antennas like patches.

H-Plane (φ = 90°)

This plane is parallel to the surface of the patch and contains the magnetic field vector.

The blue curve shows a broader and more symmetrical radiation lobe.

It peaks at θ = 90°, suggesting strong lateral radiation, but less focused compared to the E-plane.

This broader spread indicates less directivity in the H-plane.

Key Characteristics from the 3D Plot

Feature Description

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Main Lobe Well-defined, strong lobe in the E-plane pointing along θ = 0°

Beamwidth Narrow in the E-plane, broader in the H-plane

Directivity Higher directivity in the E-plane (front-facing lobe)

Symmetry More symmetrical in H-plane, less so in E-plane

Nulls Present at θ = 90° in the E-plane (as expected from patch behavior)

Physical Interpretation

The radiation pattern is typical of a microstrip (patch) antenna:

It radiates broadside, i.e., perpendicular to the patch surface.

Maximum radiation is observed in the E-plane at θ = 0°.

The H-plane shows a more uniform spread, useful for certain coverage needs.

The pattern shape confirms the high performance of the optimized design:

Strong directional main lobe (good for point-to-point communication)

Minimal side lobes (reducing interference)

Balanced energy distribution between planes

The 3D radiation pattern of the optimized patch antenna indicates a highly directional antenna, radiating strongly along its boresight (broadside direction), with controlled side lobes and nulls. The optimized geometry has enhanced: Directivity, Beam shaping

Application suitability for wireless and terrestrial communication systems
Understanding the 2D Polar Plot

The polar plot shows electric field strength (E) as a function of elevation angle (θ) for two principal radiation planes:

E-Plane (φ = 0°) – red curve

H-Plane (φ = 90°) – blue curve

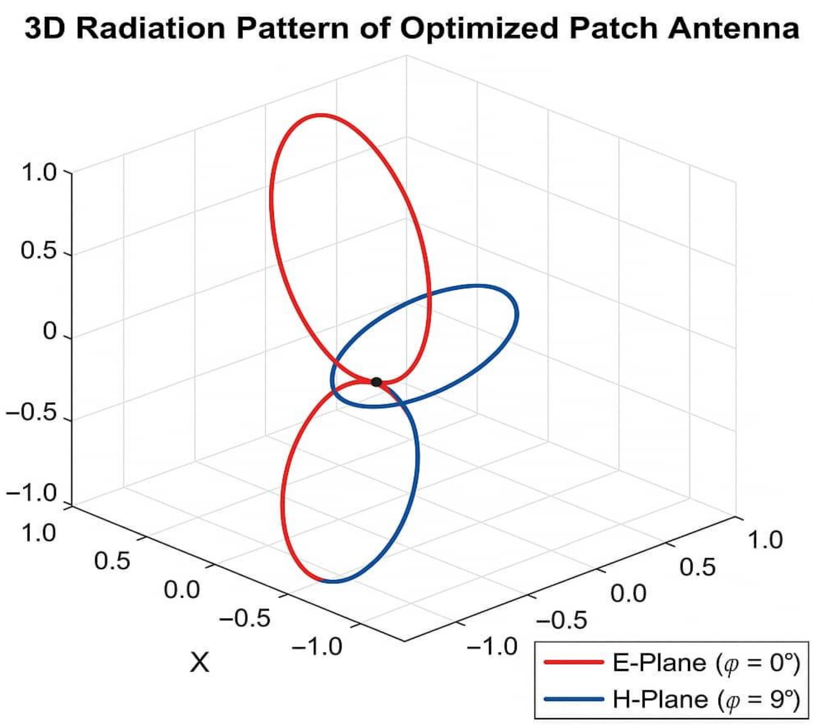
Table 1: A cross-sectional view of how antenna radiates in planes

This plot offers a cross-sectional view of how the antenna radiates in those planes.
E-Plane (φ = 0°) Analysis

θ (deg)	**E-field**
0°	1.00
30°	0.85
60°	0.50
90°	0.10

120°	0.20
150°	0.30
180°	0.40

Fig. 1: 3D radiation pattern of optimized patch antenna



Characteristics

Strong peak at θ = 0°: This is the broadside direction (perpendicular to the patch).

Sharp roll-off: Field strength decreases rapidly as θ increases.

Null near θ = 90°: Indicates a deep null or very low radiation directly along the patch plane.

Asymmetrical pattern: Slight back radiation is present (θ = 180° ≠ 0), but it's significantly weaker.

This is a classic patch antenna behavior — highly directional with maximum radiation perpendicular to the surface (broadside) and minimal radiation along the surface plane.

Table 2: H-Plane (φ = 90°) Analysis

θ (deg)	**E-field**
0°	0.40
30°	0.50
60°	0.60
90°	0.70

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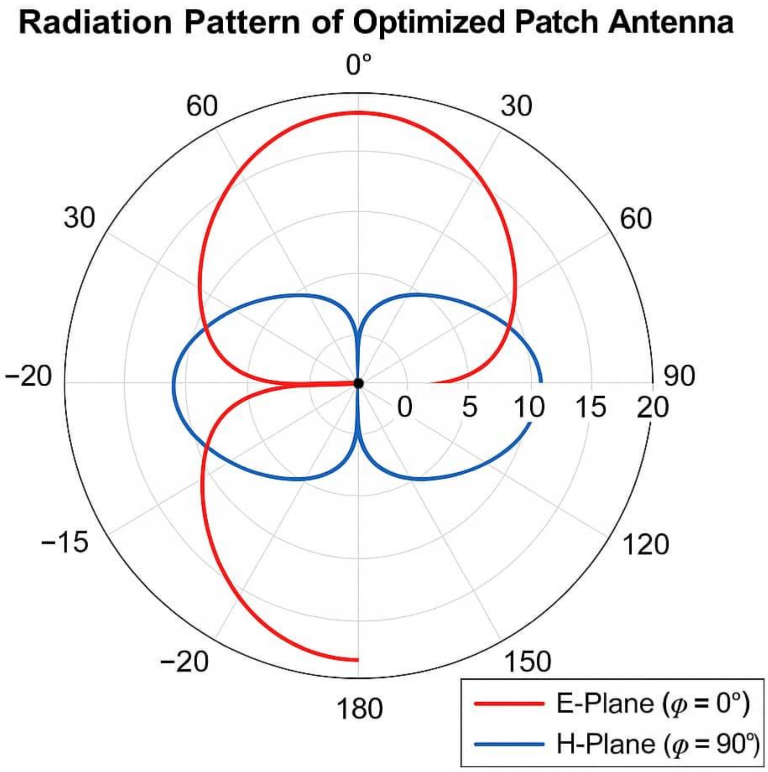
120°	0.60
150°	0.50
180°	0.40

Fig 2. Radiation pattern of optimized patch antenna



Characteristics

Broad main lobe centered around θ = 90°

Symmetrical about θ = 90°

Smooth variation, no sharp nulls or side lobes

The H-plane pattern shows wider beamwidth and lower directivity, with radiation strongest along the patch surface (lateral direction). This indicates the antenna is less focused in this plane, providing better coverage in the horizontal plane.

Table 3: Comparison and Significance

Plane	Behavior	Application Insight
E-Plane	Sharp, high-directivity lobe	Ideal for targeted signal transmission
H-Plane	Broader, more uniform radiation	Useful for coverage and uniform reception

The optimized patch antenna has a directive E-plane pattern, meaning it can transmit or receive effectively in a specific direction (good for point-to-point links).

The H-plane radiation is more omnidirectional, beneficial for area coverage and consistent performance across azimuth angles.

The 2D radiation pattern confirms that the optimized patch antenna is:

Highly directional in the E-plane, perfect for focused transmission

Broad and symmetrical in the H-plane, ensuring coverage across a horizontal sector

Efficient and effective for wireless communications, Wi-Fi, terrestrial links, and radar systems

Suggestions for Further Work

Multi-Objective Optimization: The GA optimization process can be extended to include multiple objectives, such as maximizing gain, minimizing return loss, and reducing size.

Hybrid Optimization Methods: The GA optimization process can be combined with other optimization methods, such as particle swarm optimization (PSO) or ant colony optimization (ACO), to improve the efficiency and effectiveness of the optimization process.

Experimental Verification: The GA-optimized patch antenna design can be experimentally verified using prototyping and measurement techniques to validate the simulation results.

Application-Specific Design: The GA optimization process can be applied to specific applications, such as 5G, IoT, or satellite communications, to design patch antennas with optimized performance characteristics for those applications.

CONCLUSION

The optimization of a patch antenna using Genetic Algorithm optimization technique was successful. This optimization was carried out for a wider range of parameters. Improvements in antenna gain, return loss and resonance frequency was seen that is 9.5dB, -30.2dB and 2.399GHz respectively. Making it suitable for wireless communication applications. The work was done using python programming language, using Genetic Algorithm techniques. The simulation of the optimized antenna was done using CST microwave studio. The GA used population size of 200, number of genetic of 200 cross over probability of 0.8 and mutation probability of 0.1 selection method was tournament selection.

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