ITM Web of Conferences **69**, 04011 (2024) https://doi.org/10.1051/itmconf/20246904011
MAIH2024

Optimization and Performance Enhancement of a Miniaturized Rectangular Patch Antenna with Slotted Ground Plane Using Ant Colony Algorithm

Ibtissam BAHLAOUANE[1*], *Abdelfettah BELHABIB*[2], *Saida IBNYAICH*[1], *and Abdelouhab ZEROUAL*[1]

[1]Department of Physics, I2SP Research Team, Faculty of Sciences Semlalia, Marrakesh, Morocco
[2]Department of Electrical Engineering, SIGER Laboratory, Faculty of Sciences and Technologies, Fez, Morocco

Abstract. This paper introduces a new approach for miniaturizing a rectangular patch antenna to achieve a resonant frequency of 2.45 GHz using the Ant Colony Optimization (ACO) algorithm. Initially, the antenna is designed using conventional methods and then the ground plane structure is optimized by introducing slots using ACO algorithm. The targeted resonant frequency of 2.45 GHz is achieved through an appropriate fitness function. The ACO algorithm is employed to design the optimal shape of the ground plane, resulting in a 50.9% miniaturization rate. The proposed antenna, with dimension of 37.6×33.04×1.6 mm^3, will be useful for wireless applications such as Wi-Fi and Bluetooth.

1 Introduction

Antennas are a crucial element in wireless communication systems. They are used in various applications, including mobile and satellite communications, wireless technologies, and radar systems. Traditionally, antennas were designed using trial-and-error methods, which involved iterative adjustments of dimensions and configurations to achieve the desired performance. While sometimes effective, this approach can be time-consuming and resource-intensive. With the emergence of artificial intelligence (AI), new optimization methods have been introduced, greatly improving the efficiency of antenna design.

Several methodologies have been applied to increase the reflection coefficient at the resonant frequency, such as implementing an inset feeding technique in a Microstrip Patch Antenna (MPA) [1]. The Ant Colony Optimization (ACO) algorithm has been employed to enhance antenna performance by optimizing the shape of the radiating element, thereby improving the reflection coefficient, gain, and bandwidth [2]. Additionally, the Genetic Algorithm (GA) has been used to the miniaturization of MPAs. In [3], an initial antenna design is created to resonate at a specific frequency, and by applying GA while maintaining the antenna's dimensions, the antenna is optimized to resonate at a lower frequency, effectively reducing its conventional size.

In [4], the design and simulation of double-layer and slotted coupled microstrip patch antennas for Wi-Fi and Bluetooth applications were explored. To improve the performance of miniaturized antennas, GA is employed to identify the optimal parameters for the radiating element and the ground plane [5-8]. Bandwidth enhancement is achieved through the implementation of a partial ground plane in [9].

In this paper, the purpose is to achieve the miniaturization of a rectangular patch antenna at a desired frequency using an improved ACO algorithm, specifically aiming to minimize the reflection coefficient at 2.45 GHz. This is accomplished by modifying the ground plane structure, where slots are introduced through the ACO algorithm. Initially, a microstrip patch antenna is designed to resonate at a higher frequency of 3.5 GHz using conventional methods. The ACO algorithm is then applied to optimize the ground plane structure and shift the antenna's resonant frequency to a lower value of 2.45 GHz, while maintaining the antenna's physical dimensions. This approach effectively reduces the antenna's size compared to traditional designs.

This study is organized as follows: after the introduction, in section 2, the antenna structure and the optimization methodology are detailed. Section 3 presents the simulation results, analyzing the performance improvements achieved through the proposed design. Finally, Section 4 concludes the paper.

2 Antenna structure and methodology

2.1 Patch Antenna Configuration

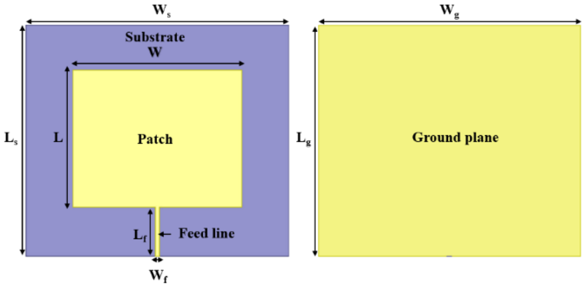
Patch antennas consist of a radiating element placed on the top of a dielectric substrate with a ground plane on the opposite side. These antennas are typically used in applications such as Wi-Fi, Bluetooth, and satellite

---

[*] Corresponding author: bahlaouane.ibtissam@gmail.com

communication due to their ability to be easily integrated into devices and systems.

Fig. 1 presents the geometry of the proposed patch antenna, which consists of a rectangular radiating patch made of copper. The feed is provided through a microstrip transmission line with an impedance of 50 Ω. The substrate is an FR4 epoxy material with a relative dielectric constant (ε_r) of 4.4 and a thickness of 2 mm. The ground plane is placed on the opposite side of the substrate. This antenna is designed to operate at the resonant frequency of 2.45 GHz.



(a) Front view (b) Back view

Fig. 1. Patch antenna structure.

Initially, the 3.5 GHz antenna is designed using conventional methods, and then the ACO algorithm will be implemented to optimize the ground plane structure by introducing slots, in order to shift the antenna's resonant frequency to a lower value of 2.45 GHz, which is the desired frequency, while keeping the original dimensions unchanged. This approach ensures that the antenna operates at the desired frequency while maintaining its compact size, offering an efficient and optimized design solution.

Table 1 summarizes the key dimensions of the proposed antenna design for both 2.45 GHz and 3.5 GHz operating frequencies. The table highlights the patch, substrate, ground plane, and feed line dimensions. The Table 2 compares the performance and dimensions of the patch antenna at 2.45 GHz and at 3.5 GHz.

Table 1. Antenna Dimensions.

Antenna Components	**Dimension (mm^2)**	
	2.45 GHz	**3.5 GHz**
Patch (L × W)	28 × 34.5	19.6 × 24.15
Substrate (Ls × Ws)	47.2 × 53.7	33.04 × 37.6
Ground plane (Lg × Wg)	47.2 × 53.7	33.04 × 37.6
Feed line (Lf × Wf)	10 × 0.765	10 × 0.765

Table 2. Characteristics of the Antenna at 2.45 GHz and at3.5 GHz.

	Antenna 2.45 GHz	**Antenna 3.5 GHz**
Dimension (mm^3)	53.7 × 47.2 × 2	37.6 × 33.04 × 1.6
Resonant frequency (GHz)	2.45	3.5
Bandwidth (−10 dB) (MHz)	58	113
Reflection coefficient (dB)	−16.4	−20.28

Fig. 2 presents the simulated reflection coefficient S_{11} for the two antennas designed for different resonant frequencies. The first antenna resonates at around 2.45 GHz, with a minimum reflection coefficient of approximately -16 dB. The second antenna resonates at around 3.5 GHz, with an improved reflection coefficient of nearly -20 dB.

This comparison highlights the difference in performance between the two designs, with the second antenna exhibiting better reflection characteristics at its resonant frequency.

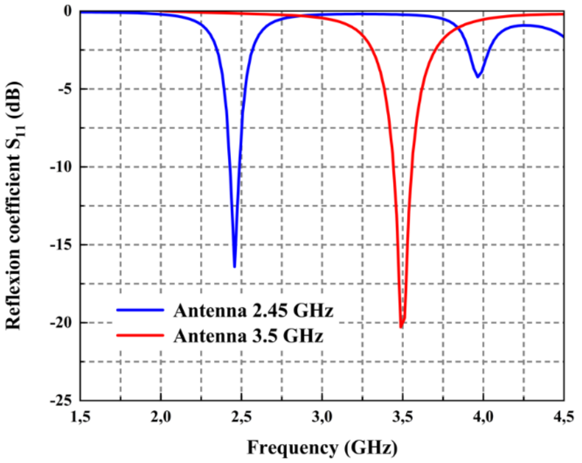


Fig. 2. Simulated reflection coefficient for the antennas at 2.45 GHz and 3.5 GHz.

2.2 Ant Colony Optimization Overview

The ACO algorithm draws inspiration from the behavior of ants. It is a powerful metaheuristic technique used in optimization problems. Despite having limited individual cognitive abilities, ants can collectively find the shortest route between a food source and their nest. This approach was first introduced by Marco Dorigo and Thomas Stützle in the 1990s, initially to tackle the traveling salesman problem by finding the shortest route between multiple cities [10] [11]. The ACO algorithm continues to be a widely used technique for solving complex optimization problems due to its balance between exploration and exploitation. The trade-off between exploration, where ants discover new paths, and exploitation, where they reinforce known good solutions, is crucial to the algorithm's success. Ants rely on pheromones to communicate and explore the solution space, meanwhile reinforcing promising paths. Recent improvements have focused on enhancing these mechanisms, optimizing pheromone update strategies, and introducing dynamic balancing between the two phases to prevent premature convergence. Due to its effectiveness, ACO has been applied across various fields, including patch antenna design, where it is used to optimize antenna structures for enhanced performance [2].

Fig. 3 illustrates the integration of the ACO algorithm for optimizing the patch antenna. This flowchart outlines the step-by-step process of how ACO is applied.

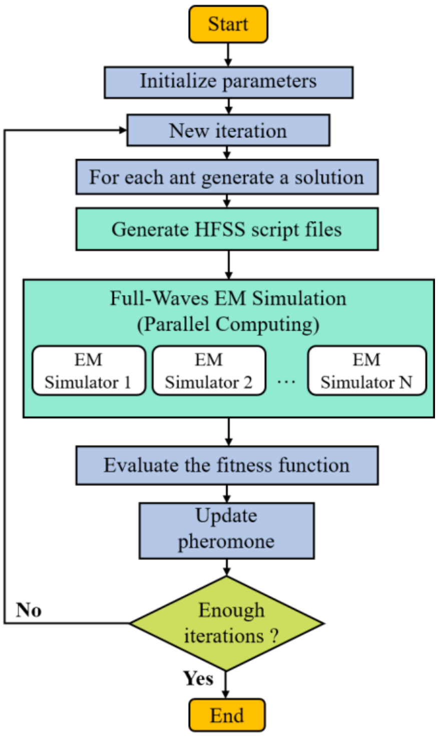


Fig. 3. ACO Algorithm flowchart for patch antenna optimization.

For each ant k, the path between a city i and a city j depends on the probability of selecting a path, as well as the pheromone update mechanisms.

- **The probability of the path selection:**

$$p_{ij}^k(t) = \begin{cases} \frac{[\tau_{ij}(t)]^\alpha\,[\eta_{ij}(t)]^\beta}{\sum_{l\in J_i^k}[\tau_{il}(t)]^\alpha\,[\eta_{il}(t)]^\beta} & if\ j \in J_i^k \\ 0 & if\ j \notin J_i^k \end{cases} \tag{1}$$

Equation (1) defines the probability $p_{ij}^k(t)$ that an ant k at node i will choose node j at time t as part of its path. This probability is based on two factors: the pheromone level $\tau_{ij}(t)$ on the edge connecting nodes i and j, raised to the power α, and the heuristic desirability $\eta_{ij}(t)$, raised to the power β.

- **Local Pheromone Update:**

$$\Delta\tau_{ij}^k(t) = \begin{cases} \frac{Q}{F^k(t)} & if\ (i,j) \in T^k(t) \\ 0 & if\ (i,j) \notin T^k(t) \end{cases} \tag{2}$$

Equation (2) outlines the local pheromone update rule. When an ant k traverses the edge *(i, j)* at time t. The pheromone deposit $\Delta\tau_{ij}^k(t)$ is proportional to Q, (i.e., a constant), divided by $F^k(t)$, which is the objective function value associated with the path $T^k(t)$ followed by ant k. If the edge *(i, j)* is not part of the ant's path $T^k(t)$, no pheromone will be deposited.

- **Global Pheromone Update:**

$$\tau_{ij}(t+1) = (1-\rho)\tau_{ij}(t) + \sum_{k=1}^{m}\Delta\tau_{ij}^k(t) \tag{3}$$

Equation (3) defines the global pheromone update rule, which is applied after all ants have completed their paths. The pheromone level $\tau_{ij}(t)$ on edge *(i, j)* is updated by a combination of evaporation and deposition. The existing pheromone value is reduced by a factor of $(1-\rho)$, where ρ represents the evaporation rate, ensuring that older pheromone trails decrease over time. The second term sums the contributions $\Delta\tau_{ij}^k(t)$ from all m ants, representing the new pheromone deposited based on the paths taken by the ants during the current iteration.

Fig. 4 illustrates the ground plane of the patch antenna, structured into a grid format. The overall dimension of the ground plane is 37.59×33.04 mm^2. The plane is divided into 8×10 smaller square cells, each measuring 4×4 mm^2, forming the grid structure. These cells will be used by the ACO algorithm to introduce slots in the ground plane in order to enhance the antenna's performance.

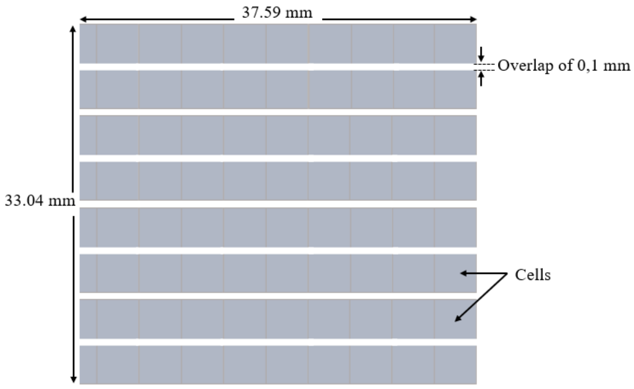


Fig. 4. Gridded ground plane.

By using this grid structure, the ACO algorithm will selectively create slots in the ground plane, optimizing the antenna's performance parameters such as reflection coefficient, bandwidth, and impedance matching. The ACO algorithm can be applied to this ground plane structure by treating each cell as a node in the search space. The ants, in this case, represent potential paths that explore various configurations of slots within the ground plane. Each slot configuration affects the electromagnetic behavior of the antenna, with the objective of optimizing its performance, specifically reducing the resonant frequency while improving the reflection coefficient.

The optimization objective is defined by the fitness function:

$$F^k(t) = min\ [S_{11}^k(f_c)] \tag{4}$$

where S_{11}^k is the reflection coefficient that needs to be minimized to enhance antenna efficiency and f_c is the target resonant frequency of 2.45 GHz.

The ACO algorithm iteratively explores different slot configurations within the antenna's ground plane by updating pheromone levels based on the fitness function. Paths that lead to better S_{11} values and a closer shift towards the desired frequency of 2.45 GHz are reinforced with more pheromone, guiding future ants toward those solutions.

3 Simulation results and discussion

Fig. 5 illustrates the convergence curve of the cost function for the ACO algorithm. Around 50 iterations, the cost stabilizes at approximately 0.025, indicating that the algorithm has converged to an optimal or a sub-optimal solution. After 50 iterations, there is no significant improvement in the cost function, confirming that the algorithm has achieved its target.

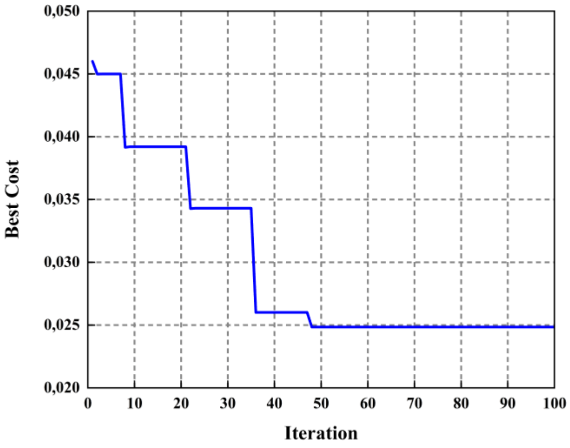
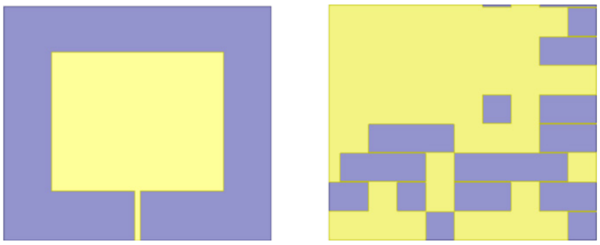


Fig. 5. Convergence of best fitness value over 100 iterations.

Through the iterative process of the ACO algorithm, the antenna's resonant frequency is gradually shifted closer to the target frequency of 2.45 GHz, while the reflection coefficient becomes more optimized, indicating enhanced antenna performance. Fig. 6 presents the optimized antenna design using the ACO algorithm. Through iterative updates, the algorithm introduces slots in the ground plane, which significantly enhances the antenna's performance.



(a) Front view (b) Back view

Fig. 6. Optimal slot configuration using ACO.

The simulated reflection coefficient S_{11} for both the reference and the optimized antenna over a frequency range of 1.5 GHz to 4.5 GHz is presented in Fig. 7. The blue curve represents the optimized antenna, which exhibits a significant reduction in S_{11} to -32.09 dB, particularly at the desired frequency of 2.45 GHz. The introduction of slots in the ground plane significantly improves antenna performance by reducing the reflection coefficient, which indicates better impedance matching at 2.45 GHz. By carefully adjusting the slot configuration, the algorithm not only minimized the S_{11} at the target frequency but also broadened the operating bandwidth, leading to enhanced overall antenna performances.

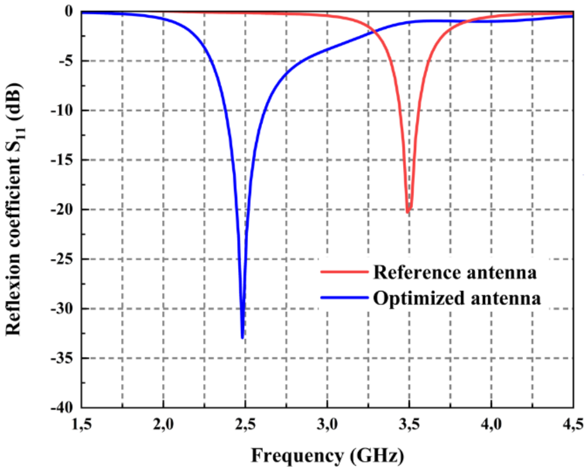


Fig. 7. Simulated reflection coefficient.

Fig. 8 illustrates the simulated input impedance of the antenna across its operating bandwidth. The impedance is characterized by a real part of 50 Ω and an imaginary part of 0 Ω throughout the entire bandwidth, indicating good impedance matching. This optimal matching enhances the antenna's performance, ensuring efficient power transfer and minimizing reflections.

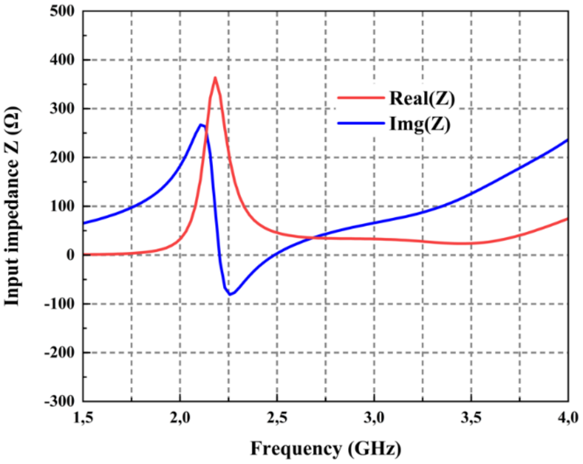


Fig. 8. Simulated input impedance of the optimized antenna.

Table 3 provides a comparison of the proposed antenna design with existing studies, illustrating improvements in return loss, bandwidth, and size reduction, highlighting the best performance and compactness of the proposed antenna.

Table 3. Comparison of the Proposed Antenna with Existing Works.

Works	f_r(GHz)	S_{11}(dB)	BW(MHz) (−10dB)	Dimension (mm^3)	%of Reduction
[1]	2.45	−27	72	49.21×38.21×1.6	-
[3]	2.39 2.4	−12.5 −13.5	30 22	46.5×41.2×1.6 38.7×35.5×1.6	24.4 45.8
[4]	2.4	−32.09	100	47.04×38.48×1.5	-
Our work	2.45	−32.93	230	37.6×33.04×1.6	50.9

4 Conclusion

In this paper, we have successfully reached the miniaturization of a rectangular patch antenna for 2.45 GHz wireless applications using the ACO algorithm. Starting from a 3.5 GHz design, the ACO algorithm optimized the ground plane structure by introducing slots to shift the resonant frequency to 2.45 GHz while maintaining the original dimensions. This approach achieved a significant size reduction of 50.9 %, resulting in a compact antenna suitable for applications such as Wi-Fi and Bluetooth. The simulation results have shown that the proposed antenna design maintains an optimal reflection coefficient and exhibits improved performance at the target frequency.

In future work, the antenna design can be refined further by exploring additional optimization techniques to improve performance parameters such as bandwidth and gain.

References

1. A. S. Oluwole, A. A. Adebayo, and O. Akinsanmi, “Inset-Fed 2.45 GHz Microstrip Patch Antenna for Wi-Fi Applications,” Adeleke University Journal of Engineering and Technology (AUJET), vol. 6, no 2, pp. 181- 186, 2023.
2. I. Bahlaouane, A. Belhabib, S. Ibnyaich and A. Zeroual, “Design and Optimization of Microstrip Patch Antenna using Ant Colony Optimization,” 2024 International Conference on Global Aeronautical Engineering and Satellite Technology (GAST), Marrakesh, Morocco, 2024, pp. 1-5, doi:10.1109/GAST60528.2024.10520747.
3. S. Gokulakkrizhna, M. Subha, and V. Mekaladevi, “Rectangular microstrip patch antenna miniaturization using improvised genetic algorithm,” In 2020 4th International Conference on Trends in Electronics and Informatics (ICOEI)(48184), pp. 894-898. IEEE, 2020.
4. A. Arora, A. Rana, A. Yadav and R.L. Yadava, “Design of microstrip patch antenna at 2.4 GHz for Wi-Fi and Bluetooth applications,” In Journal of Physics : Conference Series, vol. 1921, no. 1, p. 012023, 2021.
5. M. Boudjerda, A. Reddaf, A. Kacha, K. Hamdi-Cherif, T.E.A. Alharbi, M.S. Alzaidi, M. Alsharef, S.S.M. Ghoneim, “Design and Optimization of Miniaturized Microstrip Patch Antennas Using a Genetic Algorithm,” Electronics vol. 11, no. 14: 2123, 2022.
6. A. Dejen, J. Jayasinghe, M. Ridwan, J. Anguera, “Synthesis of Quadband mm-Wave Microstrip Antenna Using Genetic Algorithm for Wireless Application,” Technologies vol. 11, no. 14 2023.
7. L. Wakrim, S. Ibnyaich, and M. M. Hassani, “The study of the ground plane effect on a Multiband PIFA Antenna by using Genetic Algorithm and Particle Swarm Optimization,” Journal of Microwaves, Optoelectronics and Electromagnetic Applications, pp. 293-308, vol. 15, no 4, 2016.
8. L. Wakrim, S. Ibnyaich, and M. M. Hassani, “Multiband Operation and Performance Enhancement of the PIFA Antenna by Using Particle Swarm Optimization and Overlapping Method ,” Applied Computational Intelligence and Soft Computing, vol. 2017, 2017.
9. R. Fernandez, T. Putra, H. Andre and Firdaus, “A Circular Patch Microstrip Antenna with Partial Ground Plane for WiMAX and WLAN Applications,” IOP Conference Series: Materials Science and Engineering vol. 1041, no. 1, p.012018, 2022.
10. M. Dorigo, V. Maniezzo et A. Colorni, “Ant System: An Autocatalytic Optimizing Process,” Technical Report 91-016, Department of Electronics and Information. Polytechnic of Milan, Italy, 1991.
11. M. Dorigo, V. Maniezzo et A. Colorni, “Ant system: optimization by a colony of cooperating agents,” IEEE Transactions on Systems, Man, and Cybernetics, Part B (Cybernetics), vol. 26, no 1, pp. 29-41, 1996.