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Evolution of Particle Swarm Optimization Technique in Microstrip Patch Antenna Design: A Review Analysis

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Abstract: *Through exploring swarm optimization techniques like Particle Swarm Optimization (PSO), Ant Colony Optimization (ACO), and Grey Wolf Optimization (GWO) in the context of microstrip patch antenna (MPA) design, I've gained an appreciation for their powerful ability to solve complex multi-objective optimization problems. These algorithms stand out in modern antenna design, especially in the high performance needs of 5G and IoT applications, by optimizing key parameters such as bandwidth, resonant frequency, gain, and impedance matching. The integration of swarm-based methods with advanced simulation tools like CST Studio Suite and Ansys HFSS amplifies their potential, delivering remarkable improvements in antenna performance, efficiency, and overall design outcomes. One of the key takeaways is how swarm optimization techniques significantly enhance optimization efficiency, cutting down the design time compared to traditional trial-and-error methods. These techniques also provide excellent global search capabilities, avoiding the pitfalls of getting stuck in local minima, which is common in gradient-based methods. With their ability to handle complex, nonlinear problems, swarm algorithms are not only robust but also versatile, making them ideal for a wide range of antenna designs, from multi-band to reconfigurable antennas. Overall, swarm optimization proves to be a transformative approach in antenna design, enabling better performance and cost-effective manufacturing.*

Keywords: *Particle Swarm optimization, Microstrip Patch antenna, Review*

I. INTRODUCTION

Swarm optimization is a paradigm of evolutionary computation inspired by the self-organizing nature of living organisms. Unlike conventional optimization methods based on deterministic rules, swarm-based techniques exploit decentralized intelligence, whereby solutions emerge dynamically from the collective interactions of simple agents. The idea is fundamentally rooted in biological systems, such as ants, birds, and bees, that can solve impressive problems without any central control.

What makes swarm optimization uniquely powerful is its adaptability and resilience. Unlike gradient-based methods, which can become trapped in local minima, swarm algorithms maintain a diverse exploration exploitation balance, allowing them to navigate complex, high-dimensional search spaces efficiently. Each agent in the swarm operates based on minimal information, yet through indirect communication— such as pheromone trails in Ant Colony Optimization (ACO) or velocity adjustments in Particle Swarm Optimization (PSO)—a globally optimal solution emerges.

Swarm optimization is used to solve various challenges in MPA design, such as increasing bandwidth, improving gain, matching impedance, and reducing unwanted radiation. By combining these algorithms with simulation tools like CST Studio Suite, Ansys HFSS, and MATLAB, researchers can quickly test different designs and improve the performance of antennas for applications like 6G, 5G, IoT, and satellite communication.

Particle Swarm Optimization (PSO) has emerged as a powerful soft computing technique for optimizing the design parameters of microstrip patch antennas (MPAs), due to its simplicity, convergence speed, and ability to handle multi-

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objective constraints. Recent works have explored PSO for enhancing antenna performance metrics such as gain, bandwidth, return loss, and miniaturization.

In [1], the authors designed a compact MPA using PSO for 5G applications and achieved bandwidth enhancement by optimizing the substrate parameters and feed positions. Similarly, [2] proposed a PSO-based approach for designing a multiband rectangular patch antenna, achieving improved S-parameters and gain. A hybrid PSO with Genetic Algorithm (GA) was used in [3] to overcome local minima issues and to fine-tune complex-shaped patches for Wi-Fi applications.

A novel dual-band slotted MPA optimized using a modified PSO algorithm was presented in [4], demonstrating superior return loss values and reduced size. Meanwhile, [5] applied quantum-behaved PSO to optimize the slot geometry in an inset-fed antenna, resulting in enhanced bandwidth and impedance matching.

In [6], PSO was used to tune a metamaterial-loaded MPA, where the optimization focused on maximizing directivity while maintaining structural compactness. The study in [7] combined PSO with the Finite Element Method (FEM) for accurate field modeling and parameter tuning. A PSO-optimized reconfigurable antenna with frequency agility and polarization switching was reported in [8], addressing the needs of adaptive communication systems.

Another advancement is observed in [9], where PSO was employed to optimize a fractal-based MPA for IoT applications, significantly reducing the antenna size without compromising gain. The use of adaptive inertia weight in PSO for MPA miniaturization was explored in [10], highlighting improved convergence efficiency. In [11], a PSO-based optimization of substrate-integrated waveguide (SIW) fed antennas was carried out to enhance radiation characteristics and bandwidth.

The integration of PSO with fuzzy logic controllers was demonstrated in [12], which enhanced the accuracy of antenna parameter tuning in uncertain environments. In [13], a coplanar waveguide-fed antenna was optimized using a multi-objective PSO algorithm, focusing on return loss, bandwidth, and gain simultaneously. The research in [14] introduced a fitness function combining gain and axial ratio for optimizing circularly polarized MPAs using PSO.

Lastly, [15] used PSO to design an ultra-wideband MPA with defected ground structure, leading to significantly improved impedance bandwidth.

These studies collectively establish PSO as a reliable and versatile tool for MPA design, capable of addressing a broad range of performance goals across various modern wireless communication applications.

II. PARTICLE SWARM OPTIMIZATION TECHNIQUE

Microstrip patch antennas are widely used in wireless communication systems because of their compact size, low profile, and ease of integration. However, the design and optimization of MPAs are challenging due to the complex interdependencies between antenna parameters such as resonance frequency, return loss, bandwidth, and gain. Traditional methods of antenna design often require extensive trial-and-error approaches or analytical techniques, which may not always lead to optimal results. Recently, the optimization techniques have come as powerful tools which solve the said problem through Swarm

Intelligence, the swarm techniques involved here are:

Particle Swarm Optimization, Ant Colony Optimization, Grey Wolf Optimization etc., that give way to optimized designs for the MPAs.

1. Particle Swarm Optimization (PSO) PSO is a method inspired by the social behaviour of birds flocking or fish schooling. A population of particles (solutions) moves around in the design space to search for the best solution, their positions being modified according to both individual and collective experiences. In this context, each particle corresponds to a candidate solution with its set of design parameters for the antenna, including patch dimensions, feed position, and substrate properties.

PSO is used to reduce return loss or increase bandwidth for MPA designs by adjusting such design parameters. The advantages of PSO can be identified mainly in terms of its capacity for efficient search spaces, even convergence toward the global optimum in several cases. It is not without its problems because PSO algorithms are sometimes highly sensitive to their initial conditions. In most of these applications, finetuning of inertia weights and social and cognitive coefficients of PSO parameters is essential.

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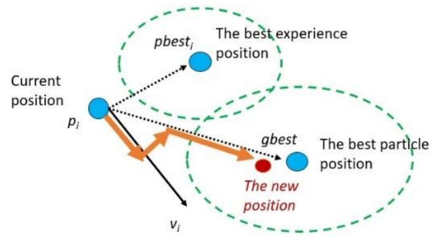

Fig 1: Particle of Swarm Optimization [37]

2. Ant Colony Optimization (ACO) ACO mimics the foraging behaviour of ants, (Fig 2) where ants deposit pheromones on paths they take, influencing other ants to follow the same route. The pheromone levels increase with the quality of solutions, guiding the colony toward the best solution. In MPA design, ACO is effective for discrete optimization tasks, such as determining the placement of antenna elements or optimizing multi-objective problems where both performance and cost need to be considered.

Fig 2: Ant Colony Optimization [38]

ACO has been used for optimizing both the geometrical configuration of the antenna and the substrate material in order to get an optimal bandwidth, return loss, and gain. The main strength of ACO is that it balances exploration and exploitation very well, resulting in good performance on complex design spaces. On the other hand, ACO may be computationally expensive for high-dimensional problems.

3. Grey Wolf Optimization (GWO)

GWO is motivated by the hunting and leadership hierarchy of grey wolves, where alpha, beta, and delta wolves represent the best solutions and lead the pack towards prey. In the GWO algorithm, the position of the solution (wolf) is modified according to the relative position of the best solutions (alpha, beta, delta wolves).

GWO has been successfully applied to optimize antenna parameters such as element size, substrate properties, and feeding techniques in MPA design. It is known for its rapid convergence and strong exploration ability, which makes it capable of navigating multi-dimensional optimization spaces. One of the key advantages of GWO is its simplicity and ease of implementation. However, like PSO, GWO may suffer from premature convergence without proper tuning, especially in highly complex design spaces.

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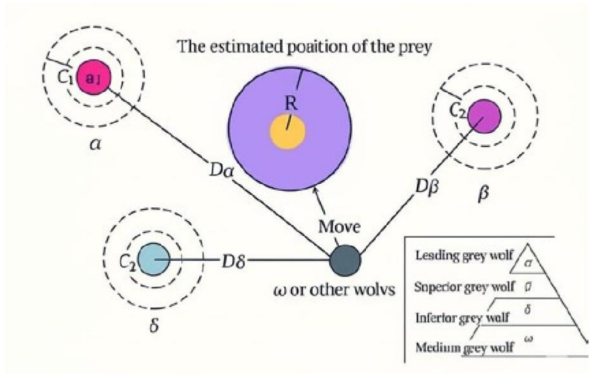

Fig 3: Gray Wolf Optimization [39]

III. SWARM OPTIMIZATION DESIGN OF MICROSTRIP PATCH ANTENNA

Specifications and Requirements Before starting the design, consider the following:

Operating frequency (f_0): This determines the size of the patch.

Dielectric constant (εr): This influences the dimensions and impedance of the antenna. **Substrate thickness (h):** This affects both bandwidth and efficiency.

Radiation pattern: This defines the directivity and gain of the antenna.

Bandwidth and efficiency: These should align with the specific application needs.

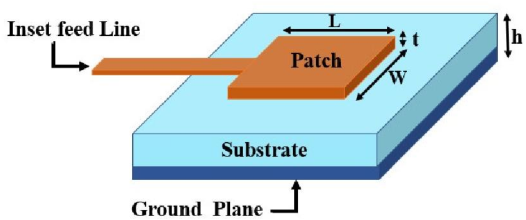

Fig 4: Structure of a microstrip patch antenna

1. Design Parameters

The dimensions of a basic rectangular patch antenna can be calculated using transmission line model equations (Fig 4):

Patch Width (W) ,

$$W = \frac{c}{2f_0}\sqrt{2/(\varepsilon_r + 1)}$$

where:

c = speed of light (3×10^8 m/s), ε_r = dielectric constant of the substrate, f_0 = resonant frequency.

Calculation of the **effective dielectric constant** using formula below. Here 'εr' is relative dielectric constant of the material. 'h' is height of the substrate and W is the width of patch calculated in first step.

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$$\varepsilon_{reff} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\left[1 + 12\frac{h}{W}\right]^{-1/2}$$

Calculation of ΔL using formula below

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

Calculation of the length, L of the patch using formula below

$$LL = \frac{cc}{22ff00\varepsilon\varepsilon rrrrffff} - 22\Delta LL$$

The Next important parameter for designing is considered to be the dimension of the feeding line or probe. So before that the feeding mechanism is to be optimized. There could be mainly four types of feeding techniques namely, a) Microstrip line feed (Easy to fabricate, requires matching) b) Coaxial probe feed (Compact design, but complex modeling) c) Aperture-coupled feed (Offers better bandwidth, more challenging to fabricate) d) Proximity-coupled feed (High performance, but complex)

Selecting the Simulation & Optimization Tool or software is the next important consideration. There are few software such as:

- HFSS (Ansys)
- CST Microwave Studio
- FEKO
- ADS (Advanced Design System)

The result parameters that are essential to be Simulated for optimization:

- Return Loss (S11)
- Bandwidth
- Gain & Directivity
- Radiation Efficiency

Normally FR4_epoxy ($\varepsilon\varepsilon_{rr=}$4,4) is considered for basic hardware manufacturing. But the substrate is selected as per need.

So these are the design parameters where different particle Swarm Optimization (PSO) Techniques can be utilized for easy and fast procedures.

IV. EVOLUTION OF SWARM OPTIMIZATION IN MICROSTRIP PATCH ANTENNA

Particle Swarm Optimization is an optimization technique inspired by the social behaviour of a flock of birds or a school of fish, searching for food. It is applicable to complex optimization problems. Such problems can be solved as PSO allows particles (solutions) to move through a search space, adjusting their positions according to their own experience and that of neighbours.

In the PSO process, first, there is random initialization of particles in the solution space. Then, the next phase involves the fitness evaluation of each particle concerning an objective function. Next, particles adjust their movement according to personal best position and the global best known position among all other particles-in updating velocities and positions. An iteration system continues until one criterion for stopping is fulfilled, for instance-a maximum number of iterations or desired accuracy. Finally, the best solution that has been found is taken as the optimized solution by the swarm. A glimpse into the literature regarding PIO applications.

Example 1: PSO for Internet of Things

Optimization Pertaining to Smart Cities

From their research study, Al-Turjeman et al. (2020) elaborate on the relevance of PSO in data routing and energy consumption optimization in smart city Internet of Things networks. They applied PSO to increase network lifetime and to mitigate energy depletion in wireless sensor networks (WSNs). The findings have shown that compared to the traditional shortest-path routing, the PSO-based routing outperformed.

Example 2: PSO for Traffic Management within Smart Cities

Another research work by Yang et al. (2019) implemented PSO in an intelligent traffic signal control scheme for smart cities. The algorithm optimized the traffic light duration in a real-time manner depending on traffic conditions.

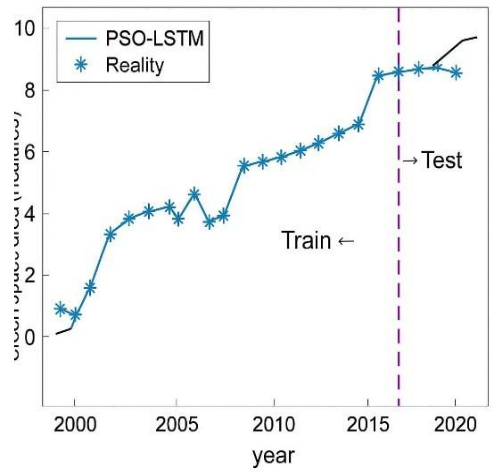

Fig 5: Year-wise Evaluation [40]

Between 2015 and 2017, various studies investigated the use of swarm optimization techniques, especially Particle Swarm Optimization (PSO), to improve the design and performance of microstrip patch antennas. These studies mainly aimed at optimizing antenna parameters to achieve specific operational characteristics.

In 2015, Sharma and Chouhan employed PSO to design a probe-fed rectangular microstrip patch antenna that operates within the 3–8 GHz frequency range. They focused on optimizing parameters such as the patch length, width, and feed position, using a substrate with a dielectric constant of 2.4 and a height of 1.578 mm. The optimization was carried out using Sonnet 13.52 simulation software.

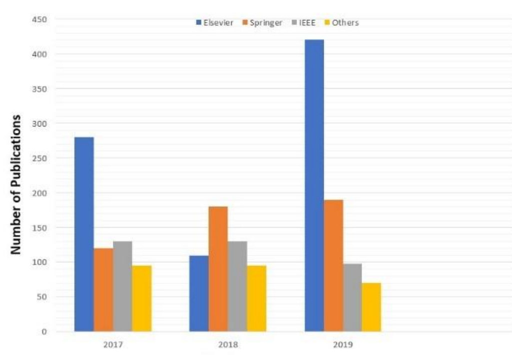

Fig 6: Analysis of Publication Year [41]

In 2016, Manpreet Singh and Amandeep Singh Sappal used PSO to enhance a rectangular microstrip patch antenna for frequencies between 3 GHz and 14 GHz. They selected RT/Duroid 5880 as the substrate material, which has a dielectric constant of 2.20 and a height of 1.30 mm. Their optimization efforts targeted parameters like patch length, width, and probe offset, with simulations also conducted using Sonnet 13.52.

These studies highlight the effectiveness of PSO in refining microstrip patch antenna designs, resulting in better performance across a range of frequencies.

The following is a summary of articles on swarm optimization in microstrip patch antenna design between 2018 and 2020:

Swarm Optimization Methods

Particle Swarm Optimization (PSO): Employed toptimize the microstrip patch antenna design for better return loss, gain, and bandwidth .

Moth Flame Optimization (MFO): Used to design a wideband microstrip patch antenna with enhanced impedance matching .

Genetic Algorithm (GA): Used in conjunction with PSO to design microstrip patch antennas for better performance .

Antenna Design and Optimization

Microstrip Patch Antenna Array: Optimized and designed to operate for WLAN and LTE 4G technology through PSO and GA .

E-Shaped Microstrip Patch Antenna: Optimized with PSO for wideband applications .

Circularly Polarized Microstrip Antenna: Optimized and designed for RF energy harvesting purposes. Applications and Future Directions of Research

Wireless Communication: Swarm optimization methods may be utilized to design and optimize microstrip patch antennas for diverse wireless communication purposes .

Internet of Things (IoT): Swarm intelligence optimized microstrip patch antennas can be employed in IoT devices for effective communication .

Future Research: Research on other swarm optimization algorithms like Ant Colony Optimization (ACO) and Cuckoo Search Algorithm (CSA) for microstrip patch antenna design optimization

Below is a summary of articles on swarm optimization in microstrip patch antenna design that have been published between 2021 and 2023:

Optimized Shark Smell Optimization: In 2021, a paper presented an optimized microstrip patch antenna design using the Shark Smell Optimization with Opposition-Based Learning (SSO-OBL) algorithm. The algorithm was employed to optimize antenna parameters like patch height, patch length, substrate width, and substrate length .

Particle Swarm Optimization (PSO): Researchers applied PSO to minimize microstrip patch antenna design. For example, a study utilized PSO to calculate optimal values of W and L for a rectangular antenna .

Multi-Objective Optimization: In 2023, a design methodology for a 5G wireless communication microstrip patch antenna array through the use of a multi-objective optimization method using swarm optimization was given.

Review of Swarm Optimization Techniques: A review article released in 2023 reviewed recent uses of particle swarm optimization, such as antenna design. The article mentioned the application of PSO in optimizing log-periodic dipole arrays and other designs .

These articles show the continuing research in microstrip patch antenna design using swarm optimization methods, trying different algorithms and methods to optimize the antenna.

Particle swarm optimization (PSO) and ant colony optimization (ACO)-a most effective swarm employee for optimizing miniaturized patch antenna designs which mimic nature'- bird flocking and ant foraging are used to explore design parameters as complex as antenna size, resonant frequency, bandwidth, and radiation pattern. These variations of optimization algorithms are more capable of handling multivariable and multi-objective optimization problems, contributing toward simultaneously improving antenna performance along multiple metrics.

In PSO, for instance, particle position updates are made based on the best solution found by each particle or by the best solution found by the entire swarm, thereby enabling efficient navigation through the design space. Advantages include global search capability, adaptability, and fast convergence on a solution compared to traditional methods. However, disadvantages include the possibility of premature convergence and high computational overhead. Nonetheless, swarm optimization techniques remain beneficial for other tasks, such as bandwidth enhancement, miniaturization, and shape optimization of microstrip antennas, and there is an emerging trend to hybridize these techniques with other methods, such as genetic algorithms, for enhanced outcomes in advanced antenna designs.

IV. CONCLUSION

Particle Swarm Optimization (PSO), Ant Colony Optimization (ACO), and Artificial Bee Colony (ABC) are among swarm optimization techniques that have proved very effective at optimizing the design of microstrip patch antennas (MPAs). These algos allow tuning of antennas in terms of patch dimensions, substrate material, feeding techniques, and slot configurations to measurable metrics, such as high gain, low return loss, and high bandwidth.

Studies show that, in particular, PSO can efficiently explore the solution space toward getting optimized antenna design within minimal computation. With respect to conventional techniques, like genetic algorithms (GA) or brute-force parameter sweeps, applications of swarm intelligence reach faster convergence with better global search capabilities applicable to multi-objective optimization problems.

Swarm optimization techniques, indeed, foster the advancement of microstrip patch antennas in establishing compact, very high-performance, and cost-efficient solutions for present wireless communication systems, including 5G, IoT, and satellite applications. Based on what has been achieved so far, further studies on hybrid swarm algorithms and deep-learning-assisted optimization can improve performance.

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