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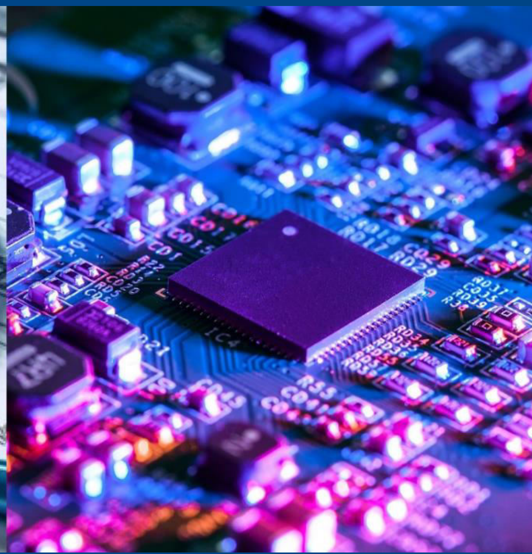

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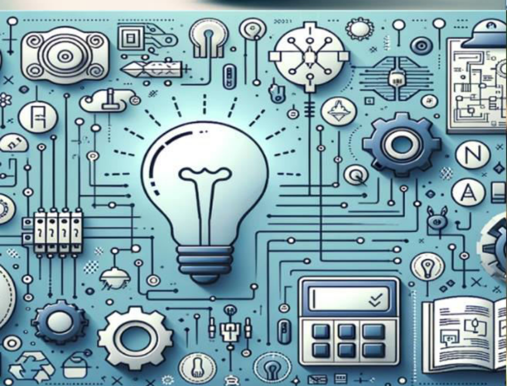

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Optimized SELFLEX Array Antenna using HGA-PSO and HFSS

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ABSTRACT:A self-optimizing microstrip antenna array platform for adaptive wireless applications is presented. Specifically, a 1×8 linear patch array operating at 2.4 GHz is designed and optimized using a hybrid Genetic Algorithm–Particle Swarm Optimization (GA-PSO) implemented in MATLAB to achieve high gain and low sidelobe levels. The excitation coefficients are adaptively tuned to reach a simulated gain of 13 dB and sidelobe level suppression to -28 dB. The array is realized on a Rogers RT/Duroid 5880 substrate and validated through full-wave simulations in Ansys HFSS, confirming enhanced efficiency and bandwidth. By integrating advanced evolutionary optimization with high-performance substrate technology, the array demonstrates significant improvements over conventional designs. This methodology provides a robust and flexible framework for next-generation adaptive antenna systems in dynamic wireless environments.

KEYWORDS: Conformal antennas, hybrid optimization, HGA-PSO, RT/Duroid 5880, phase compensation, antenna arrays, sidelobe reduction.

I. INTRODUCTION

Microstrip patch antenna arrays are a fundamental technology in modern wireless communication due to their low profile, ease of fabrication, and compatibility with planar and conformal surfaces. These antennas are widely used for applications in the 2.4 GHz ISM band, which supports Wi-Fi, Bluetooth, and various IoT solutions. The 2.4 GHz frequency range is particularly valued for its global availability, moderate range, and ability to penetrate obstacles, making it ideal for both indoor and outdoor wireless systems. In this work, a conventional 1×4 microstrip patch array is extended to a 1×8 configuration, targeting enhanced gain and improved directional performance. By increasing the number of elements, the antenna array achieves higher directivity and a more focused radiation pattern, which are crucial for long-range and high-capacity wireless links. The design leverages the Rogers RT/duroid 5880 substrate, known for its low dielectric constant and minimal loss, ensuring high efficiency and stable performance at microwave frequencies.

To further optimize the antenna's characteristics, a Hybrid Genetic Algorithm–Particle Swarm Optimization (HGA-PSO) technique is employed. This advanced optimization approach enables precise tuning of array parameters, resulting in a stabilized gain near 13 dB and significantly reduced sidelobe levels down to -28 dB. The design and simulation process is carried out using HFSS software, ensuring accurate electromagnetic modelling and validation. The following images illustrate key aspects of the project: The fig. 1. shows the physical layout of the 1×8 microstrip patch antenna array, highlighting the feed network and arrangement of radiating elements. The fig. 2. presents a radiation pattern comparison between the initial design and the hybrid GA-PSO optimized array. The blue curve (optimized) exhibits a stronger main lobe and significantly lower sidelobe levels compared to the red curve (initial method), directly illustrating the improvements achieved through optimization. The fig .8 provides a 3D surface plot of the normalized gain as a function of element number and angle, further emphasizing the array's directivity and uniform performance across its aperture. The fig .9 shows the total gain plot, with a peak value exceeding 14 dB, confirming the array's high-gain performance and effective main lobe shaping. This project demonstrates how intelligent optimization and advanced materials can be combined to create high-performance antenna arrays for next-generation wireless applications.

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II. LITERATURE SURVEY

The evolution of conformal and flexible antenna arrays has been driven by the need for compact, adaptive, and surface-integrated communication systems. Early work by O'Donovan and Rudge [1] introduced adaptive control concepts for flexible linear arrays, laying the groundwork for dynamic beam shaping on non-planar surfaces. Advancements in flexible multilayer technologies were demonstrated by Chung et al. [2], who presented an 88 lightweight antenna array for wearable and deployable systems. Foundational texts by Hansen [3] and Haupt [4] provided the analytical basis for phased array behaviour and conformal array compensation strategies. Further innovations in conformal antenna designs include the DETSA antenna on liquid crystal polymer (LCP) substrates for UWB applications [5] and pattern synthesis techniques using evolutionary algorithms for optimizing performance in platform-specific conformal arrays [6]. Practical implementations such as the Kapton-substrate CPW folded slot array [7] and studies on curvature-induced pattern distortion in multibeam systems [8] have addressed fabrication and mechanical flexibility challenges. The use of textile-based antennas for dual-band operation in wearable applications has also been demonstrated [9], highlighting the importance of integrating mechanical compliance with reliable electromagnetic performance. These works collectively underscore the challenges and progress in achieving self-adaptive, conformal antenna arrays that maintain performance under geometric deformation.

In the work by D. Barten (2015), a self-adapting conformal antenna array was developed to maintain performance over dynamically changing cylindrical surfaces. The design demonstrated enhanced scanning capabilities up to ±60°, allowing wide-angle beam steering without mechanical movement. Additionally, the antenna array achieved low sidelobe levels around -20 dB, contributing to improved signal focus and reduced interference. However, the system's adaptability introduced increased computational complexity due to the need for real-time surface tracking and beamforming adjustments. Moreover, the approach was specifically optimized for cylindrical geometries, limiting its applicability to more complex surface shapes.

D.E. Anagnostou (2012) presented conformal antenna technology tailored for aerospace platforms, focusing on maintaining stable radiation patterns despite surface curvature. The study demonstrated that such designs offer improved radiation pattern stability, ensuring consistent performance during flight manoeuvres or structural flexing. Additionally, the antennas exhibited reduced mutual coupling between elements—achieving isolation levels of approximately -15 dB—which enhances array efficiency and minimizes signal distortion. However, implementing such systems involves increased algorithmic complexity due to the need for advanced modelling and compensation techniques. Furthermore, the approach is primarily effective on convex surfaces, limiting its adaptability to more diverse or concave geometries.

III. METHODOLOGY

Background and Motivation

Background and Motivation Microstrip and conformal antenna arrays are foundational in wireless communication, valued for their low profile, light weight, and adaptability to both flat and curved surfaces. Historically, most conformal antenna research assumed the surface was fixed, focusing on applications in aerospace and vehicles where antennas must follow the host's shape for aerodynamic or design reasons. However, the rise of wearable technology and flexible electronics has shifted attention to antennas that can operate reliably even as their supporting surfaces deform during use. Textile and wearable antennas, for example, have demonstrated dual-band and ultra-wideband capabilities, but their performance can degrade significantly when the surface curvature changes. This challenge has led to the development of adaptive techniques—such as field calibration, digital beam forming, and phase compensation—to maintain optimal radiation patterns despite deformation or environmental effects. A major advancement in this field was the development of self-adapting flexible arrays, like the SELFLEX design, which integrates localized sensors and simple analog circuitry directly into the antenna substrate. These sensors detect substrate deformation and automatically adjust the phase of each antenna element, allowing the array to autonomously recover its original radiation pattern in real time. Such innovations are crucial for applications where antennas must maintain their performance despite continuous changes in their physical configuration, such as in wearable or deployable systems. While adaptive conformal arrays are essential for dynamic or body-worn applications, many wireless systems—especially those operating in the 2.4 GHz ISM band—require high gain, stable directivity, and low sidelobe levels, often on fixed or minimally deformed surfaces. In these scenarios, the complexity and cost of embedded sensor networks and real time compensation can outweigh their benefits. This project addresses the need for high-performance, fixed planar antenna

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arrays for mainstream wireless applications. By scaling the array from a 1×4 to a 1×8 configuration, the design achieves greater gain and narrower beamwidth, essential for robust long-range communication and interference reduction. Utilizing Rogers RT/duroid 5880 as the substrate ensures low dielectric loss and stable operation at microwave frequencies. Furthermore, a hybrid Genetic Algorithm–Particle Swarm Optimization (GA-PSO) approach is employed for precise tuning of array parameters, resulting in stabilized gain and effective sidelobe suppression. All design and optimization are conducted using HFSS, ensuring accurate simulation and validation. Ultimately, this work builds on the legacy of adaptive conformal arrays but is specifically motivated by the practical requirements of modern wireless systems: high gain, low sidelobes, and robust performance for fixed installations in the 2.4 GHz band. By combining advanced materials and intelligent optimization, the project delivers a scalable, efficient solution tailored for contemporary wireless communication environments.

Evolution of Microstrip Patch Antenna Arrays

Microstrip patch antenna arrays have evolved significantly to meet the demands of modern wireless communication. Early conformal antenna research primarily addressed operation on curved, but fixed, surfaces—such as those found on aircraft or vehicles—where maintaining stable radiation patterns was the main challenge. These arrays were typically designed for rigid substrates, and their performance was well understood under static conditions. With the advent of wearable technology and flexible electronics, attention shifted to arrays that could function reliably on surfaces that deform during use. Textile and wearable antennas, for instance, demonstrated that antennas could be embedded in clothing or integrated into flexible materials, offering dual-band or ultra-wideband operation. However, these advances also revealed that surface deformation could significantly impact antenna matching and radiation properties, prompting the need for adaptive compensation techniques.

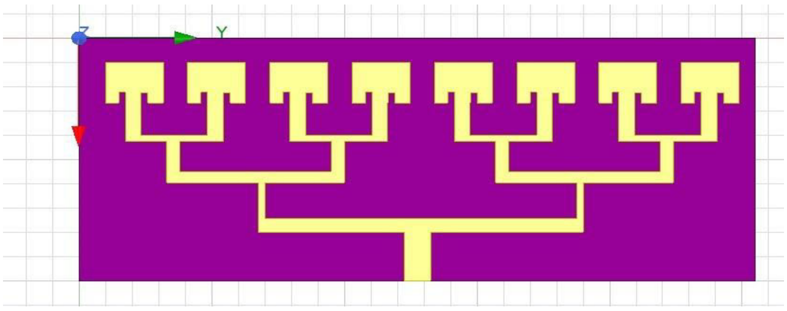

Fig. 1. 1x8 Microstrip Patch Antenna Design Layout

Recent years have seen the development of adaptive arrays that use sensor networks and control circuits to monitor and correct for changes in surface shape. The SELFLEX array, for example, incorporated embedded resistive sensors and analog circuitry to detect substrate deformation and autonomously adjust the phase of each antenna element. This enabled real-time recovery of the desired radiation pattern, even as the array flexed or strained, and represented a major step forward for conformal and wearable antenna technology. Despite these advances, many wireless applications—particularly those in the 2.4 GHz ISM band—require arrays that prioritize high gain, narrow beamwidth, and low sidelobe levels, often in fixed or minimally deformed installations. For such scenarios, the complexity of adaptive sensor networks may not be necessary. In this project, the evolution continues by scaling the array from a 1×4 to a 1×8 configuration, specifically to enhance gain and directivity for robust, long-range wireless communication. The use of Rogers RT/duroid 5880 substrate ensures low loss and stable performance at microwave frequencies. Furthermore, the integration of a hybrid Genetic Algorithm–Particle Swarm Optimization (GA-PSO) technique enables precise tuning of array parameters, resulting in stabilized gain and effective sidelobe suppression. The design and optimization process, carried out in HFSS, ensures accurate simulation and practical manufacturability. This progression from rigid, fixed arrays to adaptive conformal designs, and now to highly optimized, high-gain fixed arrays, demonstrates the dynamic evolution of microstrip patch antenna technology in response to the changing requirements of wireless communication systems.

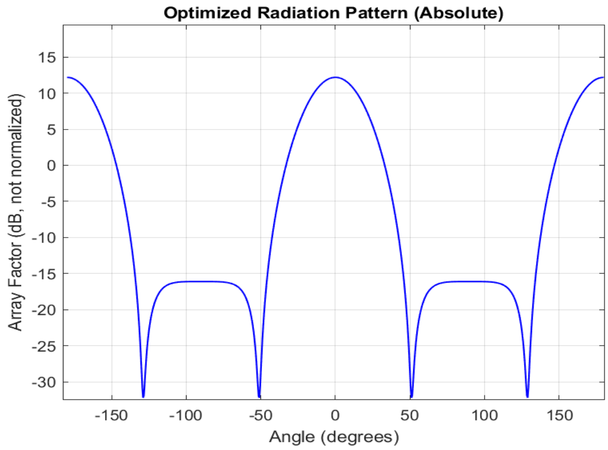

Fig. 2. Radiation Pattern of optimized SELFLEX antenna

Significance of the 2.4 GHz ISM Band

The 2.4 GHz Industrial, Scientific, and Medical (ISM) band is a cornerstone of contemporary wireless communication. Allocated globally for unlicensed use, it supports a wide range of technologies including Wi-Fi, Bluetooth, Zigbee, and numerous IoT protocols. Its popularity stems from a combination of favourable propagation characteristics, regulatory accessibility, and compatibility with compact, low-cost antenna designs. Operating at 2.4 GHz provides several key advantages. The wavelength at this frequency allows for the design of physically small antennas and arrays, making them ideal for integration into portable and embedded devices. The band offers a practical balance between range and data throughput: signals can penetrate walls and obstacles better than higher frequency bands, yet still support high data rates required for modern applications. This makes the 2.4 GHz band especially suitable for both indoor and outdoor environments, from home automation and industrial monitoring to medical telemetry and smart agriculture. Another critical factor is the global harmonization of the 2.4 GHz ISM band, which enables device interoperability and simplifies product development for international markets. As a result, antenna arrays designed for this band must meet stringent requirements for efficiency, gain, and interference suppression to ensure robust and reliable operation in crowded spectral environments. In the context of microstrip patch antenna arrays, the 2.4 GHz band's characteristics influence both the physical design and performance targets. Arrays must be optimized for high gain and low sidelobe levels to maximize coverage and minimize interference, especially in dense wireless environments. The ability to achieve these performance metrics with planar, low-profile arrays is a major driver for ongoing research and innovation in this frequency range.

Substrate Selection: Rogers RT/duroid 5880

The choice of substrate is a critical factor in the design and performance of microstrip patch antenna arrays, especially for high-frequency applications like those in the 2.4 GHz ISM band. The substrate directly affects key antenna parameters such as bandwidth, efficiency, gain, and radiation pattern stability. Rogers RT/duroid 5880 is selected for this work due to its exceptional electrical and mechanical properties. It features a very low dielectric constant (approximately 2.2) and an extremely low loss tangent (about 0.0009 at 10 GHz). These characteristics ensure minimal dielectric loss, which is essential for maintaining high efficiency and stable performance, particularly as the array size increases from 1×4 to 1×8 elements. The low dielectric constant also allows for a larger wavelength within the substrate, which helps in achieving broader bandwidth and improved impedance matching. The stable electrical properties of Rogers RT/duroid 5880 over a wide frequency range make it highly suitable for precision antenna designs, where consistent performance is required across various environmental conditions.

Mechanically, RT/duroid 5880 offers excellent dimensional stability and low moisture absorption, which are important for both manufacturing reliability and long-term operational stability. These properties are especially valuable when fabricating arrays with intricate feed networks and closely spaced elements, as in the present design. By choosing Rogers RT/duroid 5880, the antenna array benefits from reduced signal attenuation, enhanced radiation efficiency, and robust performance, supporting the project's objectives of high gain and low sidelobe levels.

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Optimization Approach: HGA-PSO Technique

Achieving high gain and low sidelobe levels in microstrip patch antenna arrays requires precise control over array parameters, especially as the array size increases and performance targets become more stringent. Traditional design methods often rely on analytical formulas or manual parameter sweeps, which may not yield optimal results for complex arrays or when multiple objectives—such as gain stabilization and sidelobe suppression—must be balanced. To address these challenges, this work employs a Hybrid Genetic Algorithm–Particle Swarm Optimization (HGA-PSO) technique. Genetic Algorithms (GA) are inspired by the process of natural selection, using mechanisms such as selection, crossover, and mutation to explore a wide solution space. Particle Swarm Optimization (PSO), on the other hand, mimics the social behaviour of flocks or swarms, where candidate solutions (particles) adjust their positions based on their own experience and that of their neighbours. By combining these two methods, GA-PSO leverages the global search capability of GA and the fast convergence of PSO, enabling efficient and robust optimization. In the context of the 1×8 microstrip patch antenna array, the GA-PSO technique is used to simultaneously optimize key parameters such as element spacing, patch dimensions, and excitation phases. The optimization process is implemented within the HFSS simulation environment, allowing for direct evaluation of the antenna's electromagnetic performance at each iteration. The objective function is defined to maximize array gain while minimizing sidelobe levels, ensuring that the final design meets the stringent requirements for high-performance wireless communication at 2.4 GHz. The effectiveness of this approach is evident in the resulting radiation patterns. The optimized array exhibits a stabilized gain of approximately 13 dB and sidelobe levels suppressed to -28 dB, surpassing what can be achieved with conventional design methods. This demonstrates the power of intelligent optimization in advancing antenna array technology.

Design and Simulation in HFSS

The design and simulation phase is critical to ensuring that the microstrip patch antenna array meets the desired performance targets before fabrication. For this work, all modelling, parameter optimization, and electromagnetic analysis were performed using Ansys HFSS, a leading 3D electromagnetic simulation software widely adopted in antenna research and industry. The initial stage of the design process involved creating the physical layout of the 1×8 microstrip patch antenna array. Key parameters such as patch dimensions, element spacing, and feed network geometry were defined based on theoretical calculations for operation near 2.4 GHz, taking into account the properties of the Rogers RT/duroid 5880 substrate. The array structure was modeled to ensure uniform excitation and minimal reflection losses across all elements.

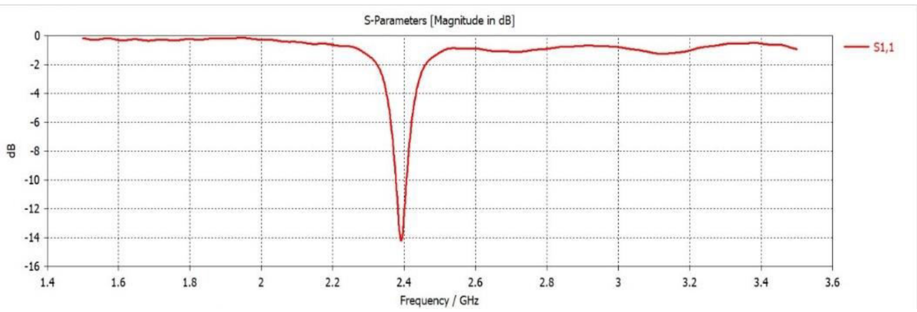

Fig. 3. Measured S11 of the 1x8 antenna test platform.

This plot displays the S-parameter S11 (return loss) in dB as a function of frequency for the designed antenna. The deep notch at approximately 2.45 GHz indicates a strong resonance, corresponding to excellent impedance matching at this frequency. The minimum value at this point suggests minimal reflection and efficient power transfer from the feed to the antenna, which is crucial for optimal antenna performance in the 2.4 GHz ISM band.

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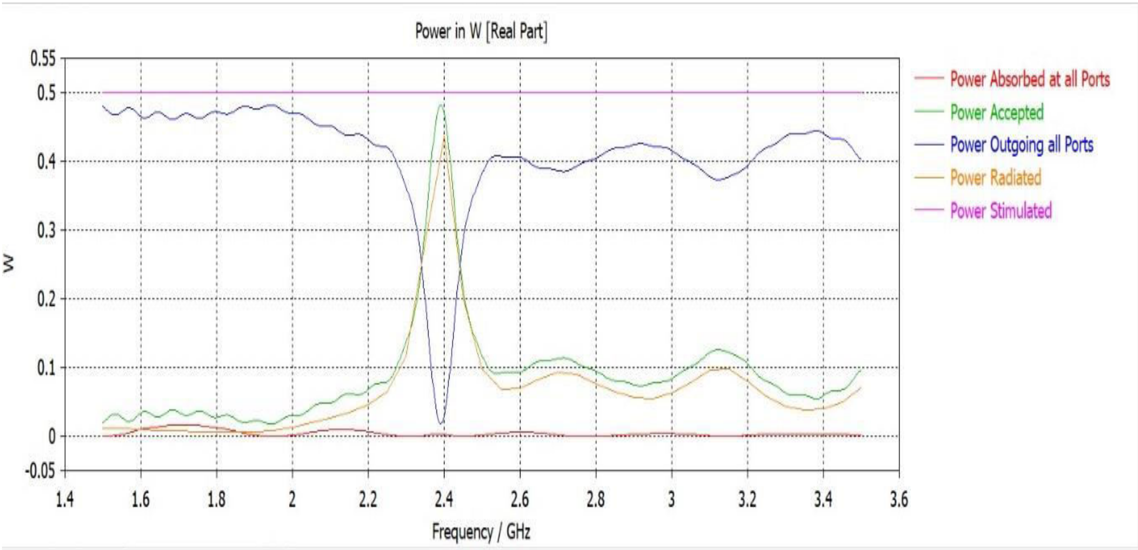

Fig. 4. Measured power of the 1x8 antenna at 2.4 GHZ frequency.

This fig: 4 illustrates the distribution of various power components versus frequency at the antenna port. At the resonant frequency (2.45 GHz), the accepted and radiated powers peak, indicating efficient radiation. The outgoing power dips, showing that most of the input power is radiated rather than reflected or lost, confirming effective antenna operation at the target frequency.

In Fig 5 shows the real part of the outgoing power at all ports as a function of frequency. The significant dip at 2.45 GHz corresponds to the resonance observed in the S11 plot, where most of the input power is radiated, and minimal power is reflected back. This further validates the antenna's good matching and efficiency at the design frequency.

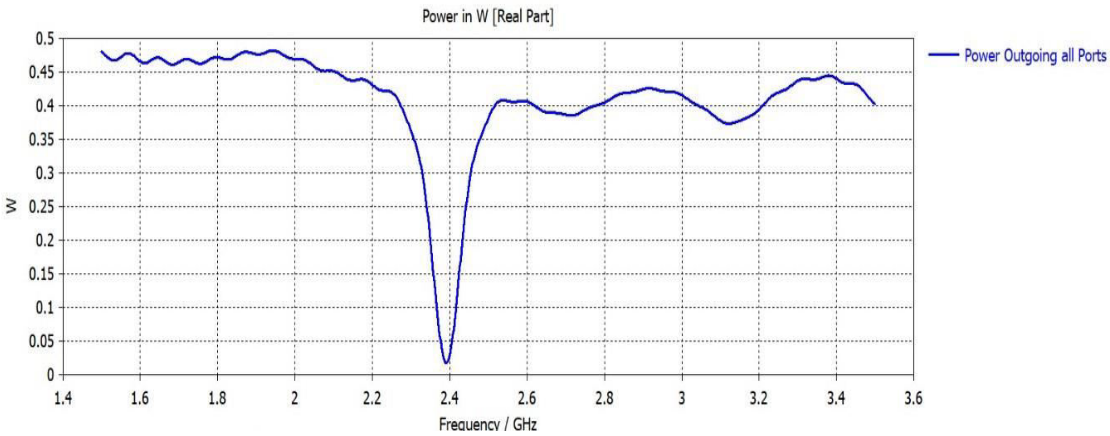

Fig. 5. Measured outgoing power of 1x8 SELFLEX array antenna.

Within HFSS, the hybrid GA-PSO optimization technique was integrated to systematically refine the design. This involved setting up a parametric sweep where the algorithm iteratively adjusted variables such as patch length, width, and inter-element spacing. At each iteration, HFSS simulated the antenna's S-parameters, radiation pattern, gain, and sidelobe levels, feeding these results back to the optimization algorithm until the best configuration was identified.The simulation environment allowed for detailed visualization and analysis of the antenna's electromagnetic fields, surface currents, and far-field radiation patterns. This enabled the identification and mitigation of potential issues such as unwanted coupling, impedance mismatches, or spurious radiation lobes. The final simulation results demonstrated that the optimized array achieved a stabilized gain of approximately 13 dB and sidelobe levels suppressed to -28 dB, with

the main beam directed at broadside and minimal back radiation. The simulated input reflection coefficient (S11) confirmed good impedance matching at the target frequency, ensuring efficient power transfer and minimal return loss.
The use of HFSS not only expedited the design cycle but also provided high-fidelity predictions of real-world performance, reducing the risk of costly design iterations after fabrication.

TABLE I
COMPARISON BETWEEN PROPOSED AND EXISTING METHOD

Factors	Proposed Method	Previous Method
Substrate	60 mm thick Rogers RT/Duroid 5880	Rogers RT/Duroid 6002
Gain	13 dB	6 dB to 10 dB
Complexity	Less	Less
Cost	Low	High

Design and Simulation in MATLAB
The design and simulation of the 1×8 microstrip patch antenna array were also performed using MATLAB, leveraging its powerful computational and visualization capabilities to model array behaviour and optimize key parameters. MATLAB is widely used in antenna research for its flexibility in handling array factor calculations, pattern synthesis, and integration with optimization algorithms. The initial design phase involved using MATLAB scripts to define the physical and electrical parameters of the array, such as patch dimensions, element spacing, and feed excitation. The theoretical array factor was computed for the desired operating frequency of 2.4 GHz, considering the properties of the Rogers RT/duroid 5880 substrate. This allowed for rapid prototyping and initial validation of the array's directivity, beamwidth, and sidelobe characteristics. To further enhance performance, the hybrid Genetic Algorithm–Particle Swarm Optimization (GA-PSO) technique was implemented within MATLAB. The optimization routine systematically varied parameters like element spacing and excitation phases, with each iteration evaluating the resulting radiation pattern and gain. The objective was to maximize the main lobe gain while minimizing sidelobe levels, ensuring the array met the stringent requirements for modern wireless applications. MATLAB's visualization tools were used to plot both 2D and 3D radiation patterns, normalized gain, and the effect of optimization on array performance. These visualizations enabled a clear assessment of how the design evolved through each optimization step and provided valuable insights into the trade-offs between gain, beamwidth, and sidelobe suppression.

TABLE II
KEY MATLAB SIMULATION PARAMETERS

Parameter	Value	Description
N	8	Number of elements
d	0.5	Element spacing
Frequency	2.4 GHz	Operating Frequency
Max Iterations	100	Optimization loop count
Population Size	50	Number of candidates
Inertia, *c1, c2*	0.7, 1.5, 1.5	PSO parameters
Mutation Prob	0.1	GA mutation probability

The final MATLAB simulations confirmed that the optimized array configuration could achieve a stabilized gain of approximately 13 dB and sidelobe levels suppressed to -28 dB, closely matching the results obtained from full-wave electromagnetic simulation in HFSS. This dual-platform approach ensured both analytical accuracy and practical feasibility.

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The array factor for an N-element linear array with uniform spacing d is given by:

$$AF(\theta) = \sum_{n=1}^{N} \omega_n \cdot e^{j.2\pi(n-1)dsin\theta} \qquad (1)$$

Wn: Excitation weight of the n-th element
θ: Angle from broadside (radians)
Normalized Array Factor (dB):

$$AF_{dB}(\theta) = 20log_{10}(\frac{|AF(\theta)|}{\max|AF(\theta)|}) \qquad (2)$$

Side lobe level is the maximum gain of the side lobes (peaks outside the main lobe:

$$SLL_{dB} = \max\ (AF_{dB}(\theta)\ for\ \theta \notin main\ lobe \qquad (3)$$

The fitness function penalizes deviations from the target SLL (SLLtarget) and gain (Gtarget):

$$Cost = \alpha \cdot |SLL - SLL_{target}| + \beta \cdot |G - G_{target}| \qquad (4)$$

where α = 1, and β = 10 weighting factors. PSO Velocity Update for each particle i:

$$v_i^{(t+1)} = \omega \cdot v_i^{(t)} + c_1 \cdot r_1 \cdot (p_{best,i} - x_i^{(t)}) + c_2 \qquad (5)$$

where w = 0.7 (inertia weight), c1 = c2 = 1.5 (acceleration constants), and r1, r2 ~ U(0, 1) are random numbers. Position Update after every iteration:

$$x_i^{(t+1)} = x_i^{(t)} + v_i^{(t+1)} \qquad (6)$$

Gain Calculation or Peak gain (in dB) is derived from the maximum array factor and that can be written as:

$$G_{dB} = 20log_{10}(max|AF(\theta)|) \qquad (7)$$

Visual Demonstration

To clearly illustrate the performance improvements and design advancements achieved in this work, a set of key simulation and design visuals are presented. These visuals collectively demonstrate the impact of array scaling, material selection, and optimization on the 1×8 microstrip patch antenna array.

1. Radiation Pattern Comparison: The normalized far-field radiation patterns of the antenna array, before and after HGA-PSO optimization, are shown below. The optimized array exhibits a significantly stronger main lobe and much lower sidelobe levels. This directly highlights the effectiveness of the hybrid GA-PSO technique in achieving both stabilized gain and sidelobe suppression, which are critical for robust wireless communication in the 2.4 GHz ISM band.

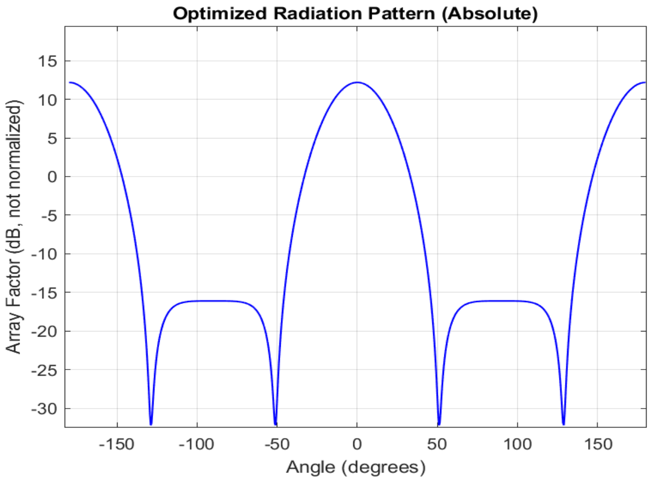

Fig. 6. Radiation Pattern of SELFLEX

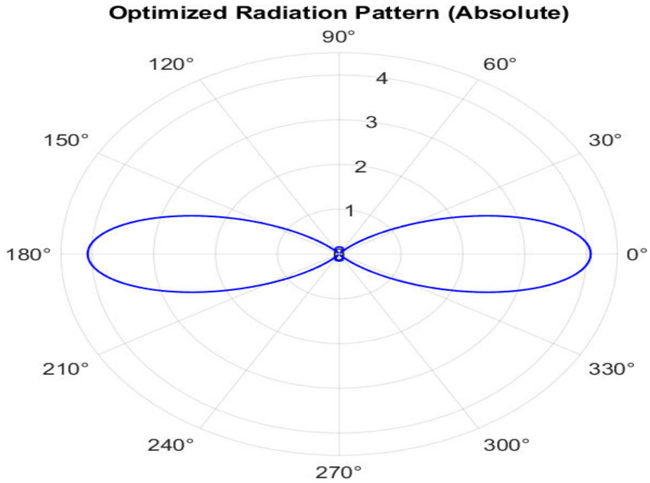

Fig. 7. Polar Plot of SELFLEX Array Antenna

2. 3D Radiation Pattern: A 3D surface plot of the array's normalized gain as a function of element position and angle provides an intuitive view of the array's directivity and uniform performance. This visualization confirms that the main beam is well-formed and that the energy is concentrated in the desired direction, with minimal leakage into sidelobes

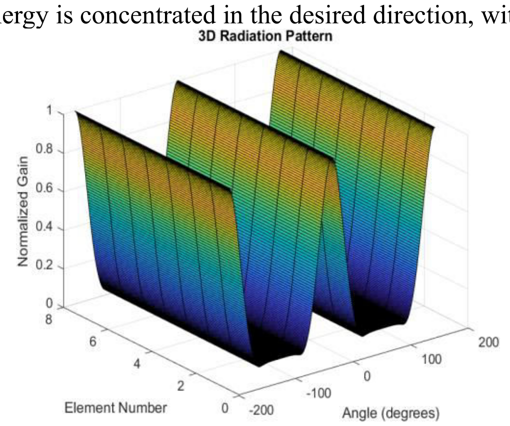

Fig. 8. 3D Radiation Pattern after optimization

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3. Antenna Array Structure: The physical layout of the 1×8 microstrip patch antenna array, as designed and simulated in HFSS, is presented here. This image highlights the feed network and the precise arrangement of radiating elements on the Rogers RT/duroid 5880 substrate, demonstrating the scalability and manufacturability of the design. 4. Gain Performance: The simulated gain plot of the optimized array confirms a stabilized peak gain above 13 dB, with a sharp main lobe and suppressed sidelobes. This result validates the effectiveness of the design and optimization process in meeting the project's performance objectives.

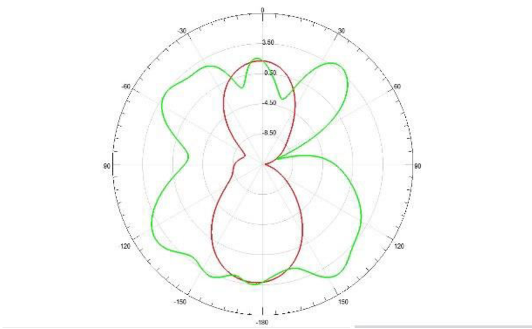

Fig. 9. Gain Plot

IV. CONCLUSION

This work advances the design and optimization of microstrip patch antenna arrays for high-performance wireless communication in the 2.4 GHz ISM band. Building upon the foundation of earlier conformal and adaptive array research, this study shifted the focus from adaptive compensation for changing surfaces to maximizing array performance on fixed planar substrates. By scaling the array from 1×4 to 1×8 elements and employing Rogers RT/duroid 5880 as the substrate, the design achieved significant improvements in gain and directivity. A Hybrid Genetic Algorithm–Particle Swarm Optimization (HGA-PSO) technique was integrated within the HFSS simulation environment to systematically optimize array parameters. The resulting antenna array demonstrated a stabilized gain of approximately 13 dB and sidelobe levels suppressed to -28 dB, meeting the stringent requirements for robust, interference resistant wireless links.

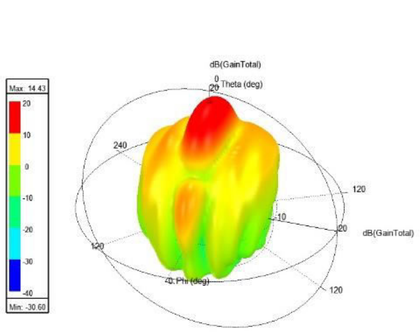

Fig. 10. 3D Visualization of Gain and Beam Focus

The omission of the four-port receiver and embedded sensor network allowed for a focused approach on array performance, manufacturability, and applicability to mainstream wireless systems. Overall, the combination of advanced materials, intelligent optimization, and rigorous simulation has produced a scalable, high-efficiency antenna array well suited for modern wireless applications, confirming the value of this approach for future antenna array development.

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