

Design and Analysis of Multiband Microstrip Patch Antenna for UAV wireless Power Transfer and Communication

Damaracharla Sasi Kumar
M.Tech student, Department of
ECE
JNTUGV-CEV

Dr. Kota Chandra Bhushana Rao
Professor of ECE & Principal
JNTUGV-CEV

Dogga Manisha
M.Tech student, Department of
ECE
JNTUGV-CEV

Abstract—Unmanned Aerial Vehicle (UAV) increasingly demand compact, lightweight, and multifunctional antennas capable of supporting both wireless power transfer (WPT) and communication networks across multiple frequency bands. This paper presents the design, simulation, fabrication, and performance evaluation of a multi-band microstrip patch antenna targeting operation at 2.4 GHz, 3.5 GHz and 5.8 GHz frequency channels. The proposed antenna architecture integrates slot-loaded patch techniques on a single substrate to achieve distinct multi-band resonance while maintaining radiation characteristics suitable for localized RF energy harvesting and data links. Full-wave electromagnetic simulation conducted in CST Microwave Studio confirms strong impedance matching below the standard -10 dB return loss threshold, yielding simulated resonant frequencies at 2.32 GHz (-21 dB), 3.52 GHz (-15 dB) and 5.75 GHz (-16.7 dB). To validate the design, a physical prototype was fabricated on a low-profile dielectric substrate using an inset-fed microstrip transmission line and an SMA connector. Experimental evaluation of the hardware via a Vector Network Analyzer (VNA) demonstrates successful practical deployment, exhibiting actual resonances at 2.31 GHz (-13.6 dB), 3.65 GHz (-20.8 dB), and 6.09 GHz (-16.8 dB). The resulting single-element design offers a compact, lightweight, and highly integrated RF front-end solution for modern UAV platforms requiring simultaneous power reception and wireless communication.

Keywords: Microstrip patch antenna, Multiband antenna, Wireless power Transfer (WPT), Unmanned Aerial Vehicle (UAV), Slot-loaded patch.

I. INTRODUCTION

In recent years, Unmanned Aerial Vehicles (UAVs) have transitioned from specialized military assets into versatile tools across a broad spectrum of civil applications, including monitoring, package delivery, agriculture, and complex search and rescue operations during extreme environmental events like mountain

avalanches [1], [2]. Despite their expanding utility, the operational capabilities of modern drones face a major bottleneck: severe flight endurance limitations imposed by the low energy density of on-board lithium batteries [2]. To address this challenge and establish continuous, long-term flight functionality, Microwave Wireless Power Transfer (WPT) systems have emerged as a revolutionary alternative to physically grounding or manually recharging aerial platforms [1], [3]. This technological approach dates back to pioneering mid-20th-century experimentation, which successfully validated the basic concept of a microwave-powered helicopter system [1].

Integrating effective communication networks and concurrent WPT systems within modern UAV infrastructures places rigorous demands on the aircraft's RF subsystems. Microstrip patch antennas (MPAs) are heavily favoured for drone integration because they feature low production costs, a minimal physical profile, lightweight construction, and simple integration directly onto the vehicle's planar fuselage [4], [5]. However, implementing these antennas on dynamic aerial systems introduces severe design trade-offs. Maximizing the transmission or reception capability for long-range communication links or high-efficiency WPT demanding high beam efficiency requires the use of broad multi-element antenna arrays or specialized quasi-optical architectures [4], [6]. Yet, physically scaling up a standard patch antenna structure expands its total surface area, drastically increasing aerodynamic drag and introducing structural instability during flight [7].

To circumvent these mechanical and electromagnetic limitations, contemporary antenna engineering focuses on advanced geometric optimization and spatial miniaturization. Designers utilize innovative techniques such as drilling patterned through-hole arrays or etching strategically localized slits into the radiating patch to reduce surface drag without degrading the underlying electromagnetic integrity of the antenna system [7], [14]. Additionally, integrating coplanar waveguide (CPW) feeds, implementing

defected ground structures, or adding asymmetric tuning stubs enables engineers to compress the physical footprint of the array while preserving high efficiency and narrow-band isolation at desired target bands like 5.8 GHz [8], [13].

Beyond single-frequency operations, UAV mission profiles increasingly demand multi-functional RF systems capable of simultaneous data-link communication and wireless power tracking across multiple discrete frequency bands [9]. These multi-service requirements are satisfied by modern dual-band directional or omnidirectional circularly polarized antennas that integrate composite right/left-handed transmission lines to cover concurrent communication networks [9], [10]. Furthermore, thin, wideband Multiple-Input Multiple-Output (MIMO) antenna arrays are implemented to maintain seamless, high-throughput connectivity under continuous flight maneuvering without suffering from deep multipath fading [11]. In addition to mitigating multipath issues, specialized compact aerodynamic profiles—such as tilted folded slot configurations—are utilized to achieve substantial beam-squinting capabilities for precision tracking during rapid ground-to-air data link telemetry [12].

For dedicated high-power microwave transmission to moving aerial targets, modern systems require high-power phase-adjustable array architectures to ensure stable, dynamic beam tracking and optimized power collection efficiency [15]. Building on these advanced methodologies, researchers have successfully designed specialized 4×4 aerodynamic antenna arrays configured for 5.8 GHz operation; by eliminating low current-density areas of the substrate using physical holes and airflow slits, these advanced configurations drastically reduce the platform's drag coefficient while providing an exceptional measured gain of 16.6 dBi [14]. Collectively, these interdisciplinary advancements in patch antenna miniaturization, multiband agility, and aerodynamic engineering form the foundational pillars required to implement next-generation, self-sustaining UAV networks.

II. THEORETICAL CALCULATIONS

Initial Dimension Calculations:

The first stage of antenna design involved calculating the initial dimensions of the microstrip patch using standard rectangular patch design equations. These equations provide the approximate width and length of a reference patch resonating at a selected design frequency. Because the proposed antenna is multiband,

the analytical dimensions were used only as a starting point, after which the geometry was modified and optimized to generate additional resonances at 3.5 GHz and 5.8 GHz.

For a chosen resonant frequency f_r , substrate dielectric constant ϵ_r , substrate thickness h , and velocity of light

c , the patch width is estimated as

$$w = \frac{c}{2f_r} \sqrt{\frac{2}{\epsilon_r + 1}}$$

The effective dielectric constant is expressed as:

$$\epsilon_{eff} = \frac{\epsilon_r + 1}{2} + \frac{\epsilon_r - 1}{2} \left[1 + 12 \frac{h}{w} \right]^{-\frac{1}{2}}$$

The fringing field extension is given by:

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

The effective length and actual patch length are then calculated using:

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

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

These equations provide the initial physical dimensions of the patch before multiband modification and array formation.

In many practical microstrip designs, the lowest frequency is used as the reference frequency for obtaining the initial dimensions because it usually determines the largest electrical size of the radiator. Accordingly, the 2.4 GHz band was considered the baseline frequency for estimating the starting dimensions of the patch in this work. Additional resonance at 3.5 GHz and 5.8 GHz was later achieved through geometry evolution and timing of the feed and patch parameters.

Geometry Evolution:

The development of the proposed multiband antenna began with a conventional rectangular microstrip patch, systematically modified to overcome its inherent single-resonance limitation. To introduce the additional current paths and resonant discontinuities required for triple-band operation, techniques such as slots, slits, stubs, and partial ground modifications were strategically integrated. The geometry evolution started with a baseline structure tuned to the lowest operating band, followed by iterative structural modifications to the patch and feed regions. Each alteration was rigorously analyzed both individually and in combination, allowing for precise optimization of the resonant bands, impedance matching, and radiation characteristics to achieve the desired multiband response from a single radiating element.

TABLE I: Parameters List

Elements	Parameters(mm)
Patch length	29.4
Patch width	38
Ground length	39
Ground width	48
Feed width	3
Inset depth	9

III. SIMULATION ENVIRONMENT

The proposed antenna array was designed and analyzed using a full-wave electromagnetic simulation tool such as CST Microwave Studio. These simulation environments are widely used for microstrip antenna research because they can accurately model the effect of substrate material, metal properties, feed structure and free space radiation on antenna frequencies, return loss, VSWR, gain, current distribution, directivity, and radiation patterns before fabrication.

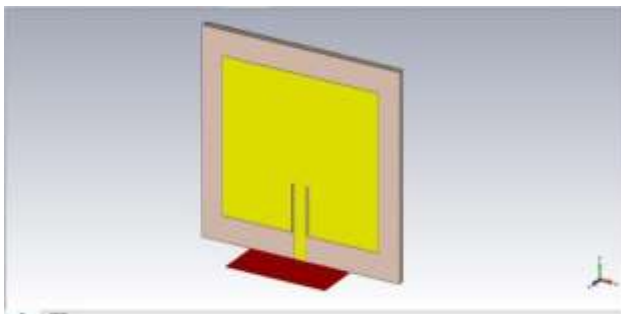


Figure 1: Design of Microstrip patch antenna

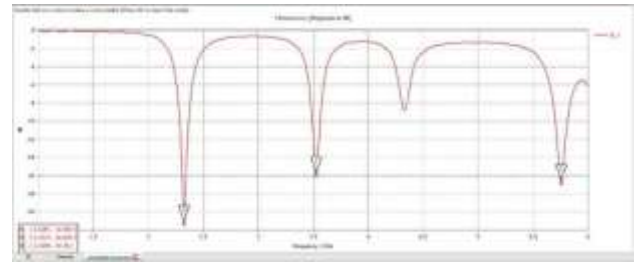


Figure 2: Simulated Return Loss (S11)

In the simulation model, the substrate was defined as FR4 lossy material, and the metal conductor was assigned as annealed copper. The patch, feed line and ground plane were created with their actual dimensions, and the feed arrangement was modelled to correspond with the SMA-fed realisation used in fabrication. A suitable wave port or lumped port was assigned depending on the software configuration so that the reflection coefficient and input impedance characteristics could be obtained over the required frequency range.

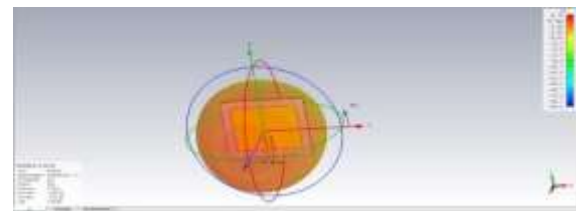


Figure 3: simulated gain of microstrip patch antenna

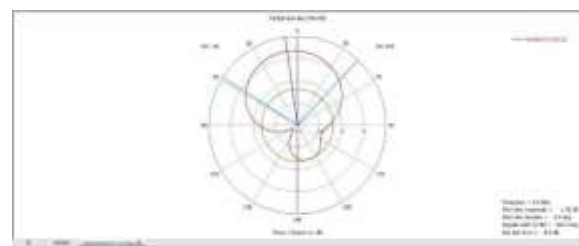


Figure 4: Polar plot of simulated gain

Radiation boundary conditions were applied around the antenna structure to approximate free space operation. The frequency sweep covered the required multiband spectrum containing 2.4 GHz, 3.5 GHz and 5.8 GHz so that all desired resonances could be observed within a single simulation environment. Meshing was carried out carefully, especially around the feed transitions.

Optimization Process:

Because analytical formulas only provide initial geometric approximations, a parametric optimization

process was executed to account for the complex electromagnetic interactions between the patch dimensions, slot geometries, feed network, and array spacing. Using an iterative simulation approach, key parameters—including feed width, ground plane modifications, and inter-element spacing—were progressively refined. The tuning process focused on tracking the shifting of resonant frequencies and the deepness of the return loss curves to align the antenna's response precisely with the targeted 2.4 GHz, 3.5 GHz, and 5.8 GHz bands.

The design optimization was governed by strict performance targets: a reflection coefficient S_{11} better than -10 dB, a Voltage Standing Wave Ratio (VSWR) of less than 2, and maximized broadside gain across all three bands. For the array configuration, particular emphasis was placed on maximizing directivity while suppressing mutual coupling between adjacent elements. Ultimately, a delicate balance was struck between achieving these high-performance electromagnetic targets and maintaining a compact, low-profile footprint suitable for practical fabrication and UAV integration.

IV. FABRICATION PROCESS

After completion of the simulation and optimization stage, the finalized antenna geometry was prepared for fabrication using standard PCB fabrication practice. The optimized layout of the multiband patch array was transferred to the FR4 substrate, with the radiating elements and feed network formed in copper on the top surface and the ground plane realized on the opposite surface. The use of annealed copper makes the design compatible with conventional copper-clad PCB processing.



(a)



(b)

Figure 5: Fabricated microstrip patch antenna (a) top view. (b) bottom view

The fabrication procedure includes substrate cutting, transfer of the antenna layout, chemical etching or PCB milling of unwanted copper regions, cleaning of the fabricated board, and finishing of the feed point for connector attachment. An SMA connector was soldered carefully to the feed line in order to enable measurement using standard RF instrumentation. Proper soldering and alignment of the SMA connector were important because connector mismatch and poor contact quality can significantly affect the measured return loss of microstrip antennas.

After fabrication, the prototype was visually inspected to verify the continuity of the patch array, feed network and ground plane. The dimensions of the critical features were checked against the optimized design so that fabrication tolerances could be minimized. This step is important because small errors in slot width, feed alignment, or connector mounting can shift the resonant frequencies and alter the multiband response.

Experimental Setup/ Measurement Setup:

The fabricated antenna prototype was characterized using a standard RF measurement setup. The primary measurement was the reflection coefficient S_{11} , which was obtained using a Vector Network Analyzer (VNA) connected to the antenna through the SMA connector. Before measurement, the VNA was calibrated over the frequency range of interest so that cable and connector effects could be reduced. The antenna was then tested over a sweep covering 2.4 GHz, 3.5 GHz, and 5.8 GHz to identify the measured resonant bands and compare them with simulation results.

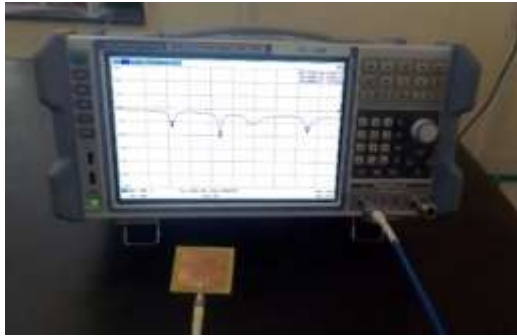


Figure 6: Experimental set up

From the measured S11 response, the return loss, resonant frequencies, and corresponding VSWR values were extracted. The measured results were then compared with the simulated results obtained from the electromagnetic model. Any observed difference between measurement and simulation could be attributed to fabrication tolerances, dielectric constant variation in FR4, conductor loss, connector mismatch, soldering effects, and environmental factors during testing.

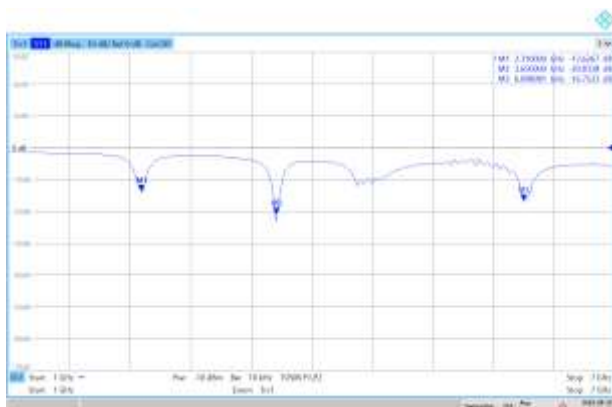


Figure 7: Measured return loss using VNA

If radiation pattern and gain measurements were available, the antenna was tested in a radiation measurement arrangement using a transmitting antenna and receiving antenna placed in the far-field region or within an appropriate indoor antenna measurement environment. For wireless power transfer validation, the setup may additionally include a transmitter antenna, a receiving antenna, or rectifying power at different distances. Such testing is useful to examine the suitability of the proposed multiband array for both communication and RF port transfer-related operation.

V. CONCLUSION

This paper successfully demonstrated the design, optimization, and hardware realization of a compact, low-profile, tri-band microstrip patch antenna engineered for modern Unmanned Aerial Vehicle (UAV) platforms. By utilizing a slot-loaded patch architecture on an FR4 dielectric substrate, the design overcomes the single-resonance limitations of conventional patches to enable concurrent operation across 2.4 GHz, 3.5 GHz, and 5.8 GHz within a single, lightweight radiating element. Full-wave electromagnetic simulations conducted in CST Microwave Studio established a solid baseline with strong impedance matching ($S_{11} < -10$ dB). Subsequent fabrication and hardware testing using a Vector Network Analyzer (VNA) validated the physical feasibility of the design, yielding prominent measured resonances at 2.31 GHz, 3.65 GHz, and 6.09 GHz. Minor deviations between the numerical models and the experimental prototype are reasonably attributed to practical fabrication tolerances, SMA connector soldering effects, and slight variations in the substrate's dielectric constant.

Ultimately, this single-element, multi-band configuration minimizes the aerodynamic drag and structural footprint on the aircraft fuselage that would otherwise be caused by mounting multiple single-band antennas. By effectively accommodating both localized RF wireless power transfer (WPT) and high-throughput communication data links simultaneously, the proposed antenna front-end serves as a highly integrated, self-sustaining solution for next-generation drone infrastructures and long-endurance aerial operations. Future work will focus on characterizing the absolute far-field radiation patterns in an anechoic chamber, integrating the prototype into a complete rectenna network to evaluate RF-to-DC conversion efficiencies, and exploring advanced aerodynamic optimization techniques to further enhance platform stability without degrading electromagnetic performance.

References

- [1] W. Brown, J. Mims and N. Heenan, "An experimental microwave-powered helicopter," *1958 IRE International Convention Record*, New York, NY, USA, 1965, pp. 225-235, doi: 10.1109/IRECON.1965.1147518.

- [2] M. U. Hoque, D. Kumar, Y. Audet, and Y. Savaria, "A Complete Look at the Design, Performance, and Uses of Microstrip Antennas," *TechRxiv*, preprint, pp. 1-19, 2025.
- [3] M. M. H. Mahfuz and C. W. Park, "Review of Patch Antennas used in Drone Applications," *IEEE Access*, vol. 11, pp. 58367-58388, 2023.
- [4] V. U. Oliveira et al., "Aerodynamic Antenna Array for 5.8 GHz UAV Wireless Power Applications," *IEEE Journal of Radio Frequency Identification*, vol. 9, pp. 1-8, 2025.
- [5] M. U. Hoque, D. Kumar, Y. Audet, and Y. Savaria, "Design and Analysis of a 35 GHz Rectenna System for Wireless Power Transfer to an Unmanned Air Vehicle," *Energies*, vol. 15, no. 1, p. 320, Jan. 2022.
- [6] S. I. Kayed, D. N. Elsheakh, H. A. Mohamed, and H. A. Shawkey, "Multiband Microstrip Rectenna Using ZnO-Based Planar Schottky Diode for RF Energy Harvesting Applications," *Micromachines*, vol. 14, no. 5, p. 1006, 2023.
- [7] A. B. Patwary and I. Mahbub, "4×4 UWB Phased Array Antenna With >51° Far-Field Scanning Range for Wireless Power Transfer Application," *IEEE Open Journal of Antennas and Propagation*, vol. 5, pp. 354-367, Feb. 2024.
- [8] A. D. Boursianis et al., "Multiband Patch Antenna Design Using Nature-Inspired Optimization Method," *IEEE Transactions on Antennas and Propagation*, vol. 69, no. 4, pp. 1965-1972, Apr. 2021.
- [9] A. Menath et al., "Multi Band Miniaturized 2x2 MIMO Antenna for Sub-6-GHz Applications," *IEEE Access*, vol. 14, pp. 1024-1033, 2026.
- [10] Y. Albaihani, "5.8 GHz Microstrip Patch Antennas for Wireless Power Transfer: A Comprehensive Review of Design, Optimization, Applications, and Future Trends," *Electronics*, vol. 15, no. 2, p. 311, Jan. 2026.
- [11] H. Khalil, U. Rafique, M. M. Ahmed, S. Rahman, and W. Nazar, "A Comparative Study of Conformal Antenna Arrays for Aerodynamic Applications," in *Proceedings of IEEE PIERS*, Xiamen, China, 2019, pp. 3211-3217.
- [12] X. Nan et al., "Flexible Symmetric-Defection Antenna with Bending and Thermal Insensitivity for Miniaturized UAV," *Micromachines*, vol. 15, no. 1, p. 159, Jan. 2024.
- [13] A. U. Fakhridinovich, M. A. Sufian, W. A. Awan, N. Hussain, and N. Kim, "A compact antenna with multiple stubs for ISM, 5G sub-6 GHz, and WLAN," *IEEE Access*, vol. 11, pp. 130418-130425, 2023.
- [14] "Aerodynamic Antenna Array for 5.8 GHz UAV Wireless Power Applications," *IEEE J. Radio Freq. Identif.*, early access, Aug. 2025.
- [15] H.-Y. Zhang, F.-S. Zhang, F. Zhang, F.-K. Sun, and G.-J. Xie, "High power array antenna based on phase-adjustable array element for wireless power transmission," *IEEE Antennas Wireless Propag. Lett.*, vol. 16, pp. 2249-2253, 2017.