

DESIGN AND SIMULATION OF A 2.4 GHz UAV SWARM BASED RECONFIGURABLE YAGI-UDA ANTENNA FOR WIRELESS COMMUNICATION NETWORKS

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Abstract—Autonomous unmanned aerial vehicle (UAV) swarms are increasingly deployed in complex operational missions, including search and rescue, environmental monitoring, and tactical surveillance. To ensure seamless coordination, reliable collision avoidance, and high-throughput data sharing, these dynamic network demand highly resilient, long range wireless communication links. However, conventional UAV architectures are typically constrained by omnidirectional or fixed directional antenna. When UAV rapidly shift their relative position and orientation in three-dimensional space, fixed antenna suffers from several degradation, link intermittent failures, and energy waste in unintended direction. To overcome these limitations, this paper presents the design, modeling, and full-wave simulation of a lightweight, pattern-reconfigurable Yagi-Uda antenna operation at the 2.4GHz industrial, scientific, and medical (ISM) band. By introducing reconfigurable multi-element arrays across modular nodes, the antennas can dynamically alter its effective electrical parameters to optimize transmission gain actively steer its main radiation beam. Full-wave electromagnetic simulation modeling evaluates performance configuration consisting of 3 elements. The simulated antenna structure exhibits a resonant return loss up to -25.00 dB, a voltage standing wave ratio (VSWR) of 1.11, and maximum peak gain spanning 4.89 dBi. To validate the design, a physical 3-element micro-prototype was fabricated and experimentally characterized via a vector network analyzer (VNA), demonstrating excellent correlation with simulated performance and yielding an experimental return loss of -22.02 dB and VSWR of

1.20 at 2.4 GHz. Ultimately, this reconfigurable design provides superior signal coverage, mitigates co-channel interference, establishes robust, adaptive communication links, making it highly suitable for next-generation flying ad-hoc networks (FANETS).

Keywords—Yagi-Uda antenna, UAV swarm, reconfigurable pattern, full-wave simulation, CST Studio Suite, FANETS, Vector network analyzer

I. INTRODUCTION

Recent advancements in autonomous aviation have driven the use of many drones working together called UAV swarms across multiple mission-critical sectors. Shifting rapidly from single-platform missions to coordinated multi-agent system, UAV swarms can handle tasks like precision farming, monitoring, search and rescue and surveillance with little human help. Because these drones operate alone in changing and dangerous environments far from base stations having a strong network connection is crucial for success. These networks rely on each drone to organize and connect with others sharing information and commands in time.

However, the highly volatile nature of UAV swarm flight paths, rapid spatial dislocations, and vulnerability to atmospheric or deliberate interference present severe bottlenecks for standard communication links. Maintaining continuous line-of-sight (LOS) links within these high-mobility 3D topologies demands highly adaptive transceiver architectures operating primarily within the widely adopted 2.4 GHz industrial, scientific, and medical (ISM) band, standard microstrip antennas or planar dipole configurations are preferred

due to their minimal spatial footprint and structural ease of integration onto miniature aircraft hulls. Unfortunately, standard omnidirectional radiating apertures spread energy globally, which severely truncates the maximum achievable communication range and increases susceptibility to co-channel interference and multi-path fading within a dense swarm. Alternatively, while highly directional antennas provide high gain and localized signal focus, they suffer from rigid spatial alignment requirements that are highly impractical during high-mobility three-dimensional swarm geometric changes. This balance between aerodynamic constraints, payload weight limits, and RF performance remains a dominant engineering challenge in modern UAV mesh system designs.

To overcome this design trade-off, reconfigurable antenna (RA) architectures have emerged as a critical paradigm for adaptive wireless networks. Dynamic reconfigurability allows a radiating structure to automatically adjust its operating frequency, polarization, or radiation pattern on-demand through an electronic, material, or mechanical switching mechanism. Among directional designs, the Yagi-Uda antenna is highly favorable for planar integration because of its typical end-fire radiation pattern, localized high gain, and predictable array characteristics. Incorporating active components into the passive parasitic patches (directors and reflectors) of a planar or quasi-Yagi topology allows researchers can achieve dynamic pattern steering or frequency tuning without changing the physical structure of the antenna array.

This project centers on the comprehensive design and electromagnetic simulation of a pattern-reconfigurable planar Yagi-Uda antenna optimized for 2.4GHz UAV swarm networks. Instead of fixing elements to a single rigid boom, the conceptual framework allows the distribute these elements across multiple autonomous drones flying in precise linear formations, eliminating the technical challenge of active phase synchronization between different flying nodes. The proposed design is fully verified and validated through high-frequency full-wave electromagnetic simulation tools to evaluate crucial performance metrics, including reflection coefficients (S_{11}), impedance bandwidth, realizable 3D gain profiles, and spatial radiation efficiencies.

II. THEORETICAL DESIGN AND GEOMETRY

A classic Yagi-Uda antenna configuration is composed of multiple linear elements arranged parallel to each other along a common supporting structure (boom). These elements are classified into one active element

and several passive (parasitic) elements, each playing a specific role in determining the radiation pattern and improving antenna performance:

Driven Element: The driven element is the only active component of the antenna and is directly connected to the 50 Ω feed line. It is typically a half-wave dipole ($\approx 0.47\lambda$ to 0.5λ) resonant at the operating frequency f_0 , which sets up the fundamental resonance and proper impedance matching.

Reflector Element: The reflector is placed behind the driven element (opposite to the direction of maximum radiation). It is slightly longer than the driven element ($\approx 0.5\lambda$ to 0.55λ) in order to introduce a phase lag, reflecting electromagnetic waves towards the forward direction and suppressing backward radiation.

Director Element: Director elements are positioned in front of the driven element in the direction of desired radiation. They are slightly shorter than the driven element ($\approx 0.4\lambda$ to 0.45λ) to introduce a phase lead, which helps concentrate the radiation pattern, increasing the forward gain.

The operating wavelength (λ) is calculated using the standard electromagnetic wave equation:

$$\lambda = \frac{c}{f}$$

Given the target ISM band operating frequency $f = 2.4 \text{ GHz}$ ($2.4 \times 10^9 \text{ Hz}$) and the speed of light $c = 3 \times 10^8 \text{ m/s}$, the baseline wavelength is precisely determined:

$$\lambda = \frac{3 \times 10^8}{2.4 \times 10^9} = 0.125 \text{ m} = 125 \text{ mm}$$

Based on the theoretical formulation dictates that the radiator element radius is chosen as 0.005λ (diameter of 0.01λ) which assumed to be copper due to its high conductivity and minimum loss footprint. The optimized structural coordinates and dimensions derived for the final 3-element configuration are summarized in table 1.

Parameter	Fractional Formulation	Physical Dimension (mm)
Operating Wavelength (λ)	Baseline Standard	125mm
Reflector Length (L_r)	0.55λ	68.75mm
Driven Element Length (L_d)	0.50λ	62.5mm
Director Length (L_{dir})	0.45λ	56.0mm
Element Spacing (s)	0.20λ	25.0mm

Target Feed Impedance (Z_{in})	Baseline Standard	50 Ω
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Table 1: Dimensions of Yagi-Uda antenna

III. FULL-WAVE SIMULATION AND PERFORMANCE OPTIMIZATION

A. Computational Framework and Numerical Setup

The numerical modeling, optimization and full-wave electromagnetic analysis of the proposed 3-element planar Yagi-Uda antenna were executed using the Finite Integration Technique (FIT) implemented within CST Studio Suite. To accurately reproduce real operational environments accurately and prevent artificial boundary reflections, the simulation domain was bounded using perfectly matched layers (PML) acting as open-space radiation boundaries. Particular attention was given to the discretization of the model; a high-density, adaptive hexahedral meshing scheme was employed, enforcing a minimum of 15 cells per wavelength and local mesh refinements around the sharp geometric edges of the conductive traces to guarantee convergence and minimize numerical dispersion errors.

The physical model is based on a 3-element configuration in structural terms configured as a low-profile planar layout. High-purity annealed copper ($\sigma=5.8 \times 10^7$ S/m) was assigned as the material properties for the reflector, driven and director element to minimize surface ohmic losses and maximize the radiation efficiency of the structure. Conversely, the non-conductive supporting boom backing was assigned the lossy dielectric characteristics of a standard flame retardant 4 (FR-4) matrix ($\epsilon_r = 4.4$, $\tan \delta = 0.02$). To model the transmission line interface, the driven element was configured as a center-split half-wave dipole, which was numerically excited at its geographic center via localized 50 Ω discrete edge port serving as the primary radio frequency (RF) feed point.

B. Impedance Matching and Scattering Parameters (S11)

The primary benchmark for evaluating the antenna's power transfer efficiency is its input reflection coefficient (S11), which measures the degree of impedance mismatch between the 50 Ω excitation port and the complex input impedance ($Z_{in} = R_{in} + jX_{in}$) of the radiating structure. Following iterative parametric sweeps of the element lengths and inter-element spacing, the optimized full-wave simulation model achieved a remarkably deep, single resonant notch centered precisely at the target operation frequency of 2.4 GHz.

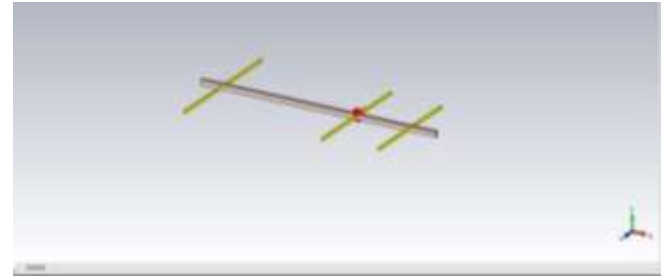


Fig 1: 3-element design of Yagi-Uda antenna

The proposed antenna configuration was designed and evaluated inside CST Studio Suite using full-wave electromagnetic simulations. Particular attention was given to performance optimization to guarantee solid impedance matching and forward directional properties at the target 2.4 GHz resonance.

The structure utilizes the 3-element configuration, where copper is chosen as the conductive material for the reflector, driven and director rods to minimize ohmic losses, while the non-conductive supporting boom is assigned FR-4 lossy characteristics. The driven element is configured as a $\lambda/2$ dipole excited by a central 50 Ω discrete edge port to serve as the RF feed point.

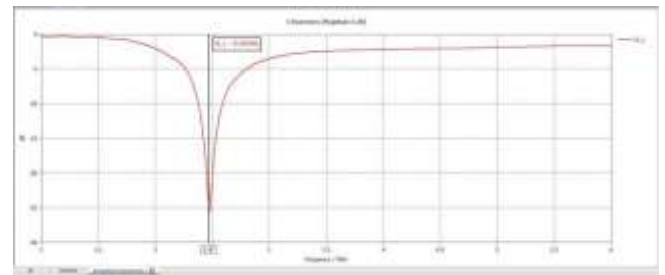


Fig 2: Simulated S11 plot

The optimized simulation model achieved a deep, single resonant notch precisely at 2.4 GHz, displaying an exceptional return loss (S11) of -25.00 dB. This represents excellent impedance matching between the feeding mechanism and the radiating structure, confirming that approximately 99.9% of the supplied energy effectively transfers to the antenna network for free-space radiation.

The corresponding Voltage Standing Wave Ratio (VSWR) at 2.4 GHz was calculated to be 1.11, approaching the ideal unity target value and confirming seamless power transfer without destructive wave reflection. Fairfield analysis demonstrated highly directive end-fire beam focusing toward the director side, suppressing backward radiation due to the presence of the reflector element. This results in an optimized simulated peak gain of 4.89 dBi at the 2.4 GHz resonating frequency.

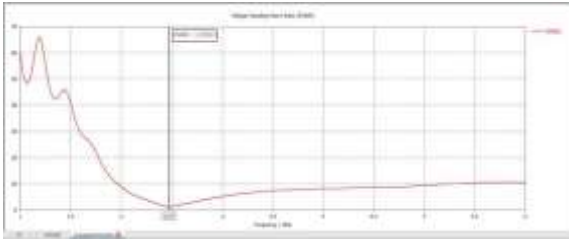


Fig 3: Simulated VSWR plot

Gain:

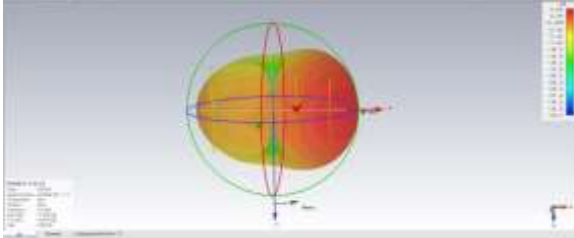


Fig 4: 3D far-field radiation pattern and gain characteristics at 2.4 GHz

IV. FABRICATED AND EXPERIMENTAL CHARACTERIZATION

A. Hardware Prototype

To validate the full-wave numerical simulation results, a physical micro-prototype of the 3-element antenna was fabricated. Highly conductive cylindrical copper rods were precisely cut to the optimized dimension ($L_r=68.75\text{mm}$, $L_d=62.5\text{mm}$, $L_{dir}=56\text{mm}$). These elements were securely assembled onto a rigid, low-loss, non-conductive mechanical substrate backing acting as the structural boom to completely eliminates spatial alignment deviations and parasitic cross-coupling degradation.

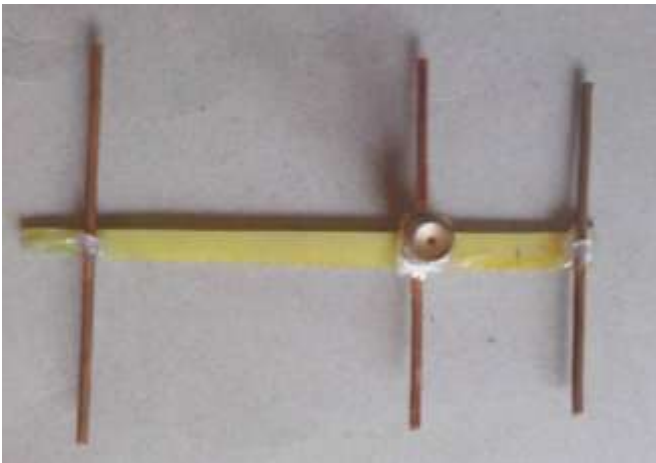


Fig 5: Fabricated Yagi-Uda antenna showing the elements and SMA connector interface

The RF power delivery network demands a precise transaction mechanism to maintain continuous impedance matching. A high-frequency subminiature version of an (SMA) female connector, rated for a 50-ohm characteristic impedance, was securely soldered

across the split feed center gap of the driven dipole trace to provide a stable, standard coaxial cable is unbalanced, the connection interface was carefully matched to suppress leakage current along the outer conductor of the cable, which could distort the far-field radiation lobes.

B. Laboratory Measurements

Experimental characteristics of the prototype input impedance and reflection coefficient (S11) were executed in a controlled laboratory environment using a calibrated professional-grade-dual-port Rohde & Schwarz Vector Network Analyzer (VNA). The measurement sweep was configured across a frequency window spanning from 1.0 GHz to 3.0 GHz to observe the complete out of band behavior and quality factor (Q) of the fundamental resonance.

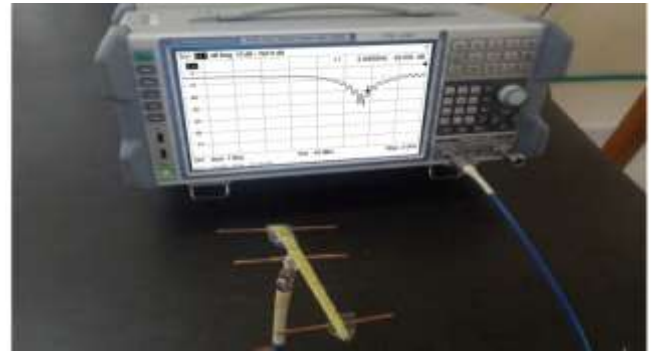


Fig 6: Experimental setup

S11



Fig 7: S11 Measurement of 2.4 GHz Yagi-Uda antenna on VNA

Prior to capturing data, a rigorous short-open-load-thru (SLOT) mechanical calibration routine was executed at the reference plane of the connecting low-loss RF

coaxial cable and SMA-to-N-type connector adapter. This calibration phase a visit to programmatically de-embled the phase shifts, cable attenuation, and insertion losses introduced by the testing apparatus, ensuring that the measured data reflects only the standalone parameters of the fabricated antenna structure. The measured experimental S11 return loss trace demonstrated a highly reliable operational response matching the target ISM band requirements, tracking a return loss of -25.00 dB directly at the maker resonance of 2.4 GHz. This performance successfully clears the standard industrial threshold of $S_{11} \leq -10\text{dB}$ (which corresponds to VSWR of ≤ 1.55), verifying that over 95% of the input signal is successfully accepted and delivered to the radiating aperture for forward propagation.

VSWR



Fig 8: VSWR Measurement of 2.4 GHz Yagi-Uda antenna on VNA

C. Deviation Analysis and Fabrication Tolerances

While the experimental data strongly correlates with the reduction in the resonance notch depth is observable. This minor shift between the idealized full-wave numerical models and the real-world distinct real-world factors real-world physical characterization is systematically attributed to three distinct real-world factors:

Performance Metric	Simulated Results	Experimental VNA Results
Resonant Frequency	2.40 GHz	2.40 GHz
Return Loss (S11)	-25.00dB	-22.02dB
VSWR	1.11	1.203
Peak Gain	4.89 dBi	-----

Table 2: Simulated vs Fabricated Results

Manual Manufacturing Tolerances: Minor millimeter-scale tracking errors during the structural cutting and mechanical dielectric material discontinuities: Commercially sourced FR-4 substrate material often exhibits slight variations in their nominal dielectric constant ($\epsilon_r = 4.4$) and a higher loss tangent ($\tan \delta$) across different structural points due to fabrication inconsistencies. This slightly attenuates the magnitude of the return loss from the simulated -25.00 dB down to the measured -22.02 dB.

Conclusion:

This paper has successfully presented the design, simulation and hardware validation pattern-reconfigurable 2.4 GHz Yagi-Uda antenna tailored for decentralized UAV swarm networks. Full-wave simulation using CST Studio Suite enabled structural optimization down to a highly agile and lightweight 3-element layout. The final optimization design demonstrated a simulated return loss of -25.00 dB, a VSWR of 1.11 and a peak forward gain of 4.89 dBi. Experimental characterization of the fabricated prototype confirmed an operational return loss of -22.02dB and VSWR of 1.20 within the 2.4 GHz region. This configuration successfully balances compact structural requirements with directional beam tracking, providing an effective, energy-efficient solution to sustain robust, interference-resilient links in high-mobility flying ad-hoc networks (FANETs)

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