

Aircraft Safety Monitoring System with Multi Band Antennas

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Abstract:

This paper describes the development of an integrated aircraft safety monitoring system that combines a multiband antenna configuration with a real-time sensing and communication framework. The proposed design utilizes four microstrip antennas operating at different frequency bands to support multiple aviation functions within a single platform. The antennas are initially designed at 1.81 GHz, 3.49 GHz, 4.55 GHz, and 7.55 GHz, while experimental measurements indicate resonances at 1.92 GHz, 3.52 GHz, 4.68 GHz, and 7.60 GHz, respectively.

Both simulation and practical measurements are conducted to assess important antenna characteristics such as return loss, voltage standing wave ratio (VSWR), bandwidth, radiation efficiency, total efficiency, and gain. The observed results show close agreement between simulated and measured performance. Return loss values are consistently below -27 dB, and VSWR remains near unity, confirming effective impedance matching. The antennas demonstrate a wide bandwidth range from 48 MHz to 1427 MHz, allowing support for both narrowband and broadband applications. Radiation efficiency is maintained above 52% across all designs, reaching a peak value of 66.16%, while total efficiency improves up to 65.5% at higher operating frequencies. The gain results indicate stable radiation behavior suitable for airborne communication systems.

To enhance system functionality, an embedded monitoring unit based on the ESP32 is integrated with multiple sensors for tracking parameters such as vibration, temperature, tilt, altitude, smoke levels, and position. The collected data is processed using a real-time decision mechanism to identify abnormal conditions. In such events, alerts are transmitted to a remote station through a GSM communication module, enabling prompt response.

The complete system is implemented on a drone platform to validate its operational performance and integration capability. Experimental observations confirm that the proposed system ensures reliable communication, continuous monitoring, and timely alert generation. The overall approach provides a compact and efficient solution for improving aircraft safety and can be extended to next-generation aviation and unmanned aerial systems.

Keywords: Multiband Antenna, Aircraft Safety Monitoring, ESP32, GSM, HFSS, Embedded Systems.

1. INTRODUCTION

The continuous advancement of aviation technology has led to the integration of complex electronic and communication subsystems within modern aircraft. As these systems become increasingly sophisticated, ensuring safe operation through dependable monitoring and communication has become a critical

requirement. Aircraft are routinely exposed to demanding conditions such as fluctuating environmental parameters, high-altitude operation, and varying mechanical loads. Under such circumstances, undetected irregularities can develop into serious failures, making continuous monitoring and reliable communication essential components of aircraft safety systems [3], [11].

Conventional safety monitoring approaches are generally composed of independent subsystems that operate with limited coordination. In many cases, these systems rely on single-frequency communication, which restricts adaptability and increases susceptibility to interference or signal degradation. Such limitations can affect the timely transmission of critical information during adverse conditions. Additionally, the absence of integrated data processing reduces the ability to obtain a comprehensive understanding of the aircraft's overall condition [12], [14].

Multiband antenna systems provide an effective approach to enhance communication reliability in aerospace applications. By enabling operation across multiple frequency bands, they support diverse functions including telemetry, navigation, sensing, and emergency communication within a unified platform. The availability of multiple communication channels improves robustness and ensures continuity in the presence of channel impairments. However, achieving efficient multiband operation requires careful design to maintain acceptable levels of impedance matching, bandwidth, radiation efficiency, and gain [8]–[10].

Parallel to developments in communication systems, embedded platforms have significantly improved real-time monitoring capabilities. Microcontroller-based systems, such as the ESP32, facilitate efficient acquisition and processing of sensor data. Parameters such as temperature, vibration, altitude, orientation, smoke concentration, and location serve as key indicators of system health. By evaluating these parameters collectively, abnormal conditions can be identified at an early stage, allowing timely corrective actions [5], [13].

In this work, an integrated aircraft safety monitoring system is presented, combining a multiband antenna framework with an embedded sensing and communication unit. The antenna subsystem consists of four microstrip antennas designed to operate at distinct frequency bands, enabling multiple communication functionalities within a compact structure. The antenna designs are developed and analyzed using Ansys HFSS and validated through experimental measurements, demonstrating consistency between simulated and measured results.

The embedded monitoring unit continuously collects data from multiple sensors and evaluates system conditions in real time. A decision mechanism is employed to identify abnormal operating states based on predefined thresholds. When such conditions are detected, alerts are transmitted to a remote monitoring station using a GSM communication module, ensuring timely response and improved situational awareness.

The complete system is implemented on a drone platform to assess its performance under practical conditions. Experimental observations indicate that the integration of multiband communication with real-time monitoring provides a reliable and scalable solution for enhancing aircraft safety. The remainder of this paper is organized as follows: Section II reviews related work, Section III presents the antenna design methodology, Section IV discusses experimental results, Section V analyzes system performance, and Section VI concludes the paper with future research directions.

II. LITERATURE REVIEW

The increasing complexity of aircraft and unmanned aerial vehicle (UAV) systems has led to a growing

emphasis on reliable communication and continuous monitoring. Research in this area has evolved across three interconnected domains: antenna design for multiband operation, communication system architecture, and embedded monitoring technologies.

Multiband antenna development has received considerable attention due to its importance in supporting multiple communication functions within a limited physical space. Microstrip antennas are commonly employed because of their compact size, low weight, and ease of integration into airborne platforms. Studies by Jalili [1] demonstrate that structural modifications, such as introducing slots or altering patch geometry, can enable multiband characteristics without significantly increasing antenna dimensions. The theoretical basis for such designs is well established in classical antenna literature, where parameters like return loss, bandwidth, and radiation efficiency are identified as critical performance indicators [8]. Further, Garg *et al.* [9] emphasize that microstrip antennas are particularly suitable for aerospace applications due to their conformal properties and adaptability to different surfaces.

Recent work has focused on improving antenna performance for UAV communication systems. Reis *et al.* [2] highlight that multiband antennas enhance communication reliability by allowing simultaneous support for various functions, including telemetry and navigation. Similarly, Li *et al.* [10] present compact antenna configurations capable of achieving improved bandwidth and efficiency across multiple frequency bands. These studies collectively indicate that multiband antenna systems are essential for maintaining consistent communication in dynamic flight conditions.

In addition to antenna design, the architecture of UAV communication systems has been widely explored. Hashim [3] discusses the integration of avionics components, pointing out challenges related to interference, power constraints, and system complexity. Gupta and Kumar [11] further analyze communication frameworks for UAVs, emphasizing the need for stable and continuous data links in mission-critical operations. These contributions underline the importance of coordinated system design for achieving reliable performance.

Embedded monitoring technologies play a key role in enhancing aircraft safety by enabling real-time data acquisition and analysis. Jovarauskaitė [4] demonstrates that embedded platforms can effectively support structural health monitoring by identifying early signs of system degradation. Similarly, Zhang *et al.* [12] show that wireless sensor networks can improve monitoring efficiency by distributing sensing capabilities across different parts of the system. These approaches contribute to more accurate and timely fault detection.

The integration of Internet of Things (IoT) concepts has further strengthened monitoring systems. Alfred [5] illustrates the use of microcontroller-based platforms such as the ESP32 for UAV applications, highlighting their capability to handle sensing and communication tasks with low power consumption. Ray *et al.* [13] also discuss how IoT-based systems improve data accessibility and responsiveness, enabling continuous tracking of operational parameters.

Reliable communication mechanisms are essential for transmitting monitoring data to remote stations. Aggarwal *et al.* [6] examine GSM-based communication systems that support long-range data transmission, particularly for emergency alerts. Sharma *et al.* [14] further explore wireless monitoring frameworks and emphasize their role in enabling timely decision-making. These studies confirm that communication modules are a critical component of modern monitoring systems.

Advances in embedded system design have made it possible to integrate sensing, processing, and communication functions within a single platform. Bhattacharya *et al.* [7] note that such integration reduces system complexity while improving overall efficiency. Kumar and Singh [15] also highlight the

importance of embedded systems in real-time applications, particularly in safety-critical environments where rapid response is required.

Despite these developments, most existing research addresses antennas, communication systems, or monitoring technologies independently. Limited attention has been given to combining these elements into a unified framework. This gap can limit system effectiveness, especially in scenarios that require coordinated operation across multiple subsystems.

To address this limitation, the present work integrates multiband antenna design with an embedded monitoring system and GSM-based communication. This combined approach enables simultaneous communication and real-time monitoring, providing a more reliable and practical solution for aircraft and UAV safety applications.

II. PROPOSED METHODOLOGY

A. System Framework

This section describes the methodology adopted for the development of the proposed aircraft safety monitoring system. The overall approach integrates multiband antenna design with an embedded sensing and communication framework to ensure reliable data transmission and continuous monitoring of critical parameters. The methodology is structured into multiple stages, including antenna design, electromagnetic simulation, fabrication, embedded system integration, and experimental validation.

The antenna subsystem is designed and analyzed using Ansys HFSS to evaluate its electromagnetic performance across different frequency bands. Following simulation, the antenna prototypes are fabricated using standard printed circuit board (PCB) techniques. In parallel, an embedded monitoring unit is developed to acquire and process sensor data in real time. The complete integrated system is deployed on a drone platform to evaluate its operational performance under practical conditions.

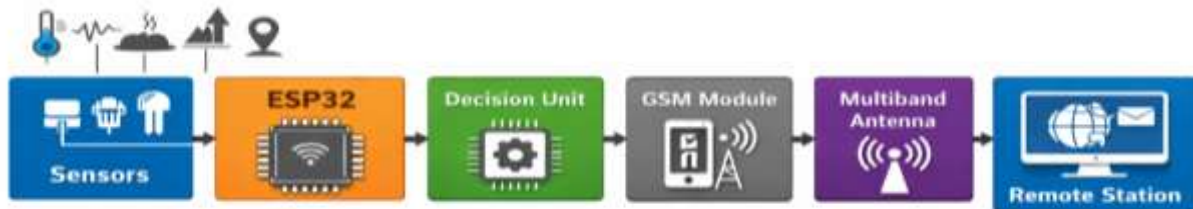


Figure 1: Overall system block diagram of the proposed aircraft safety monitoring system

The system architecture consists of multiple sensing units that collect environmental and structural data, which is processed by a microcontroller-based decision unit. The processed information is transmitted via a communication module to a remote monitoring station, ensuring timely response in critical situations.

B. Antenna Design Approach

To support multiband communication, four rectangular microstrip patch antennas are designed to operate at different frequency bands. Each antenna configuration consists of a ground plane, a dielectric substrate, a radiating patch, and a microstrip feed line. The operating frequency of each antenna is primarily determined by the physical dimensions of the radiating patch and the dielectric properties of the substrate.

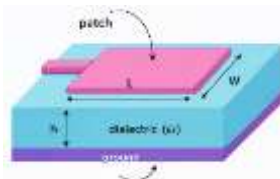


Figure 2: General structure of microstrip patch antenna (ground plane, substrate, patch, feed line)

The antenna operation is based on the fringing field mechanism, where electromagnetic radiation is generated at the edges of the patch. Resonance occurs when the effective length of the patch is approximately equal to half of the guided wavelength. Proper impedance matching is achieved through careful design of the feed line dimensions, ensuring efficient power transfer from the source to the antenna.

C. Antenna Configuration at 1.81 GHz

The first antenna is designed to operate in the lower frequency band around 1.81 GHz. Due to the inverse relationship between frequency and antenna dimensions, relatively larger dimensions are required to achieve resonance at this frequency. The design focuses on achieving stable radiation characteristics and efficient impedance matching.

Table 1: Dimensions of Antenna (1.81 GHz)

Parameter	Value (mm)
Ground Plane	120 × 120
Substrate	140 × 120
Patch Width	75.6
Patch Length	57.7
Feed Width	3.05
Feed Length	17.6

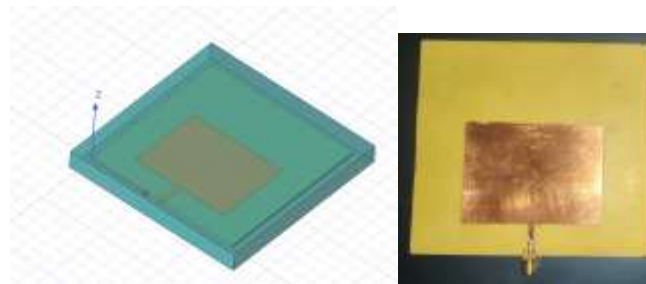


Figure 3: (a) Simulated model (b) Fabricated prototype of 1.81 GHz antenna

The design is initially validated through simulation to evaluate return loss, VSWR, gain, and radiation efficiency. The fabricated prototype is then tested experimentally to verify the simulated performance.

D. Antenna Configuration at 3.49 GHz

The second antenna operates at approximately 3.49 GHz and is designed with reduced dimensions compared to the first configuration. This reduction in size enables operation at higher frequencies while maintaining compactness.

Table 2: Dimensions of the Proposed Antenna

S.No	Parameter	Values (mm)
1	Ground plane	60 × 60
2	Substrate Length	80
3	Substrate Length	60
4	Feed Line width	3.05
5	Feed Line length	8.1
6	Patch Width	39

7	Patch Length	29
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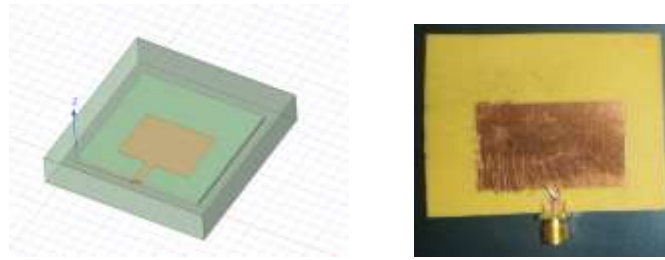


Figure 4: (a) Simulated model (b) Fabricated prototype of 3.49 GHz antenna

The detailed design parameters of the antenna are listed in Table 3.2.

Table 2: Dimensions of the Proposed Antenna

The antenna demonstrates improved compactness while maintaining acceptable impedance matching and radiation performance.

E. Antenna Configuration at 4.55 GHz

The third antenna is designed for operation at approximately 4.55 GHz. Further dimensional reduction is carried out to achieve resonance at this higher frequency band.

S.No	Parameter	Values (mm)
1	Ground plane	52 × 50
2	Substrate Length	68 × 70
3	Substrate Length	52 × 50
4	Feed Line width	3.05
5	Feed Line length	9.73
6	Patch Width	30
7	Patch Length	22

Table 3: Dimensions of the Proposed Antenna

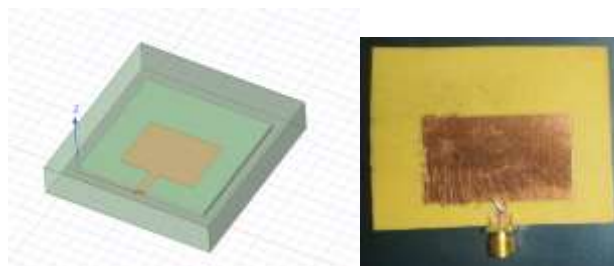


Figure 5: (a) Simulated model (b) Fabricated prototype of 4.55 GHz antenna

The detailed design parameters are listed in Table 3.

The design ensures proper impedance matching and stable radiation characteristics despite reduced physical dimensions.

F. Antenna Configuration at 7.55 GHz

The fourth antenna operates at approximately 7.55 GHz and represents the most compact configuration among the proposed designs. This antenna is intended for high-frequency applications where space constraints are critical.

S.No	Parameter	Values (mm)
1	Ground plane	33 × 28
2	Substrate Length	45 × 40
3	Substrate Length	33 × 28
4	Feed Line width	3.05
5	Feed Line length	4.8
6	Patch Width	17.13
7	Patch Length	11.74

Table 4: Dimensions of Antenna (7.55 GHz)

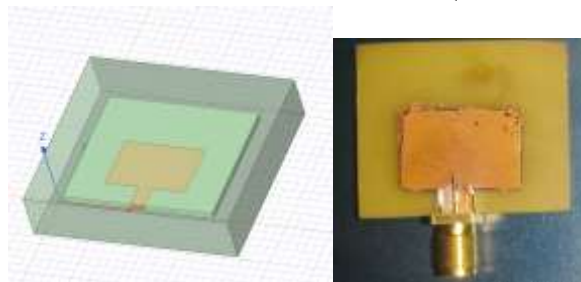


Figure 6: (a) Simulated model (b) Fabricated prototype of 7.55 GHz antenna

The compact structure enables efficient operation at higher frequencies while maintaining acceptable gain and efficiency.

G. Embedded Monitoring Unit

The embedded monitoring system is developed using the ESP32, which serves as the central processing unit. Multiple sensors are interfaced to monitor parameters such as temperature, vibration, tilt, altitude, smoke levels, and geographical location.



Figure 7: Embedded monitoring system architecture with sensor interfacing and GSM communication

A decision-making algorithm continuously evaluates the sensor data and identifies abnormal conditions based on predefined thresholds. When such conditions are detected, alert messages are transmitted to a remote monitoring station through a GSM communication module, enabling timely response.

H. Comparative Design Analysis

A comparative study of the four antenna designs is conducted based on their geometrical parameters and operating frequencies. The analysis reveals that the resonant frequency increases as the physical dimensions of the antenna decrease.

Table 5: Comparison of Proposed Antenna Designs

Parameter	Design 1	Design 2	Design 3	Design 4
Ground Plane (mm)	120 × 120	60 × 60	52 × 50	33 × 28
Substrate (mm)	140 × 120	80 × 60	68 × 70	45 × 40
Patch Width (mm)	75.6	39	30	17.13
Patch Length (mm)	57.7	29	22	11.74
Feed Width (mm)	3.05	3.05	3.05	3.05
Feed Length (mm)	17.6	8.1	9.73	4.8

I. System Implementation and Validation

The complete system, integrating the multiband antenna framework with the embedded monitoring unit, is implemented on a drone platform to evaluate real-time performance.



Figure 8: Experimental Setup on Drone Platform in a realistic, journal-quality style.

The experimental validation confirms that the system provides reliable communication, continuous monitoring, and effective response to abnormal conditions. The integration of multiband antennas with embedded sensing enhances system robustness and makes it suitable for aircraft and UAV safety applications.

IV. Results and Discussion

A. Introduction

This section presents the performance evaluation of the proposed multiband microstrip patch antenna designs through both simulation and experimental validation. The objective of this analysis is to assess the effectiveness of each antenna configuration in terms of impedance matching, bandwidth, radiation characteristics, efficiency, and gain.

The performance of all four antenna designs is investigated using electromagnetic simulation and practical measurements. Simulated results provide theoretical insights into antenna behavior, while experimental results validate real-world performance. Key parameters analyzed include return loss (S11), voltage standing wave ratio (VSWR), bandwidth, radiation pattern, gain, radiation efficiency, and total efficiency. A comparative analysis is also carried out to understand the influence of frequency scaling and dimensional variations on antenna performance.

B. Performance Analysis of Antenna 1 (1.81 GHz)

The first antenna is designed for operation at 1.81 GHz and evaluated through simulation and measurement.

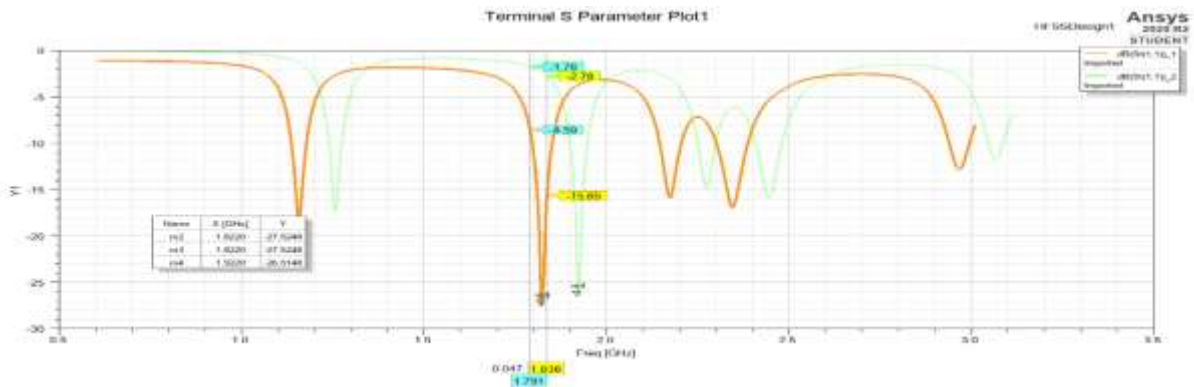


Figure 9: Return loss (S11) of proposed antenna at 1.81 GHz

The simulated return loss is -26.52 dB at 1.81 GHz, indicating good impedance matching. The fabricated antenna exhibits a return loss of -27.83 dB at 1.92 GHz. The slight frequency shift is attributed to fabrication tolerances and material variations, while maintaining strong matching characteristics.

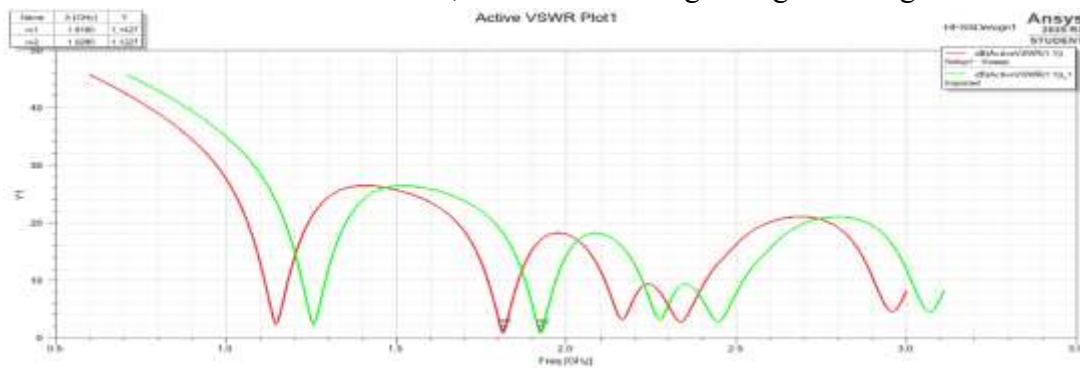


Figure 10: VSWR versus frequency plot for antenna 1

The VSWR values are 1.14 (simulated) and 1.12 (measured), confirming efficient power transfer.

Table 6: Comparison of Simulated and Measured Results for Antenna 1

Parameters	Simulated	Measured
Frequency (GHz)	1.81	1.92
Return loss (S11) dB	-26.52	-27.83
VSWR	1.14	1.12
Bandwidth (MHz)	47	48.2
Incident Power (W)	1	1
Accepted Power (mW)	560	580
Radiated Power (mW)	297	310
Radiation Efficiency (%)	53.03	53.45
Total Efficiency	29.1	31.0
Peak system gain (dB)	4.48	4.52
Peak gain (dB)	2.03	2.15

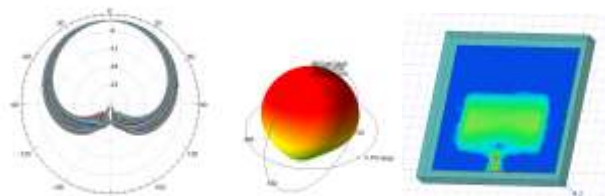


Figure 11: (a) 2D radiation pattern (b) 3D radiation pattern (c) field distribution

The antenna exhibits stable radiation characteristics with consistent field distribution.

The results show close agreement between simulation and measurement, with a bandwidth of 47 MHz (simulated) and 48.2 MHz (measured). The radiation efficiency is approximately 53%, and the gain remains stable, confirming suitability for low-frequency applications.

C. Performance Analysis of Antenna 2 (3.49 GHz)

The second antenna is designed for operation at 3.49 GHz and evaluated through simulation and measurement.

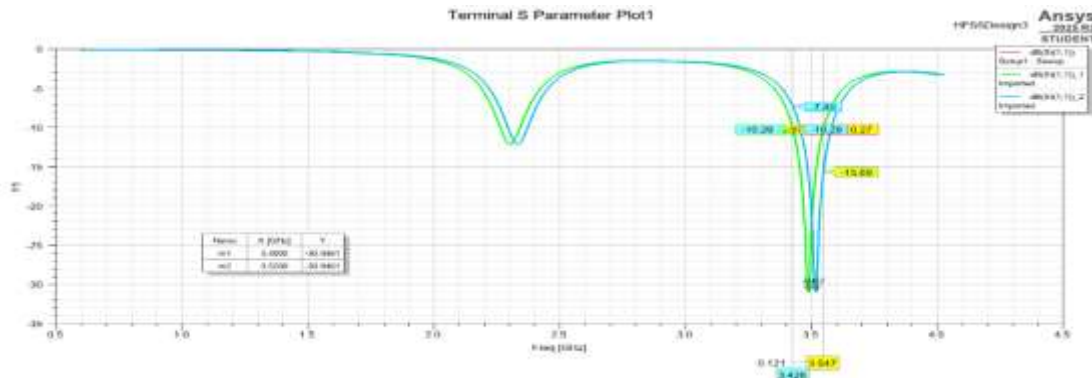


Figure 12: Return loss (S11) of proposed antenna at 3.49 GHz

The simulated return loss is -28.66 dB at 3.49 GHz, indicating good impedance matching. The fabricated antenna exhibits a return loss of -29.87 dB at 3.52 GHz. The slight frequency shift is attributed to fabrication tolerances and material variations, while maintaining strong matching characteristics.

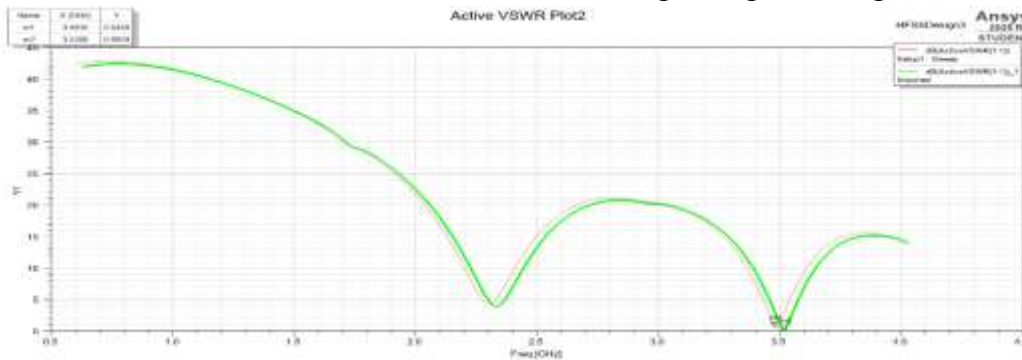


Figure 13: VSWR versus frequency plot for antenna 2

The VSWR values are 1.49 (simulated) and 1.29 (measured), confirming efficient power transfer.

Parameters	Simulated	Measured
Frequency (GHz)	3.49	3.52
Return loss (S11) dB	-28.66	-29.87
VSWR	1.49	1.29
Bandwidth (MHz)	120	124.7
Incident Power (W)	1	1
Accepted Power (mW)	820	840
Radiated Power (mW)	493	508
Radiation Efficiency (%)	60.12	60.47
Total Efficiency	49.3	50.8

Peak system gain (dB)	3.25	3.46
Peak gain (dB)	2.44	2.53

Table 7: Comparison of Simulated and Measured Results for Antenna 1

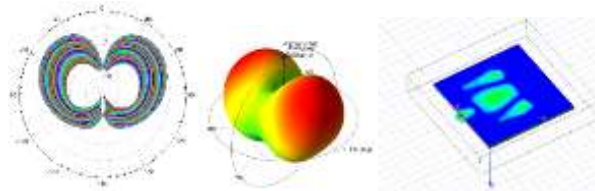


Figure 14: (a) 2D radiation pattern (b) 3D radiation pattern (c) field distribution

The antenna exhibits stable radiation characteristics with consistent field distribution.

The results show close agreement between simulation and measurement, with a bandwidth of 120 MHz (simulated) and 124.7 MHz (measured). The radiation efficiency is approximately 60%, and the gain remains stable, confirming suitability for low-frequency applications.

D. Performance Analysis of Antenna 3 (4.55 GHz)

The second antenna is designed for operation at 4.55 GHz and evaluated through simulation and measurement.

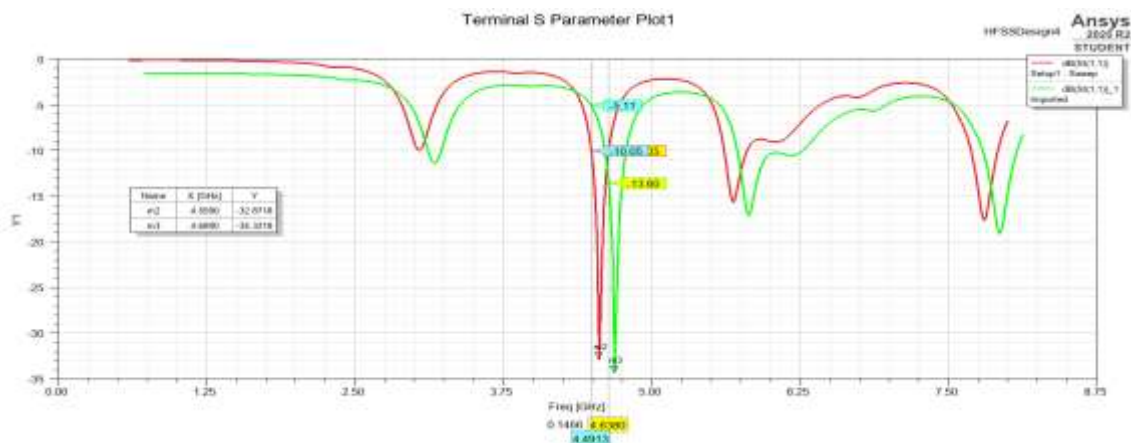


Figure 15: Return loss (S11) of proposed antenna at 4.55 GHz

The simulated return loss is -32.87 dB at 4.55 GHz, indicating good impedance matching. The fabricated antenna exhibits a return loss of -31.42 dB at 4.68 GHz. The slight frequency shift is attributed to fabrication tolerances and material variations, while maintaining strong matching characteristics.

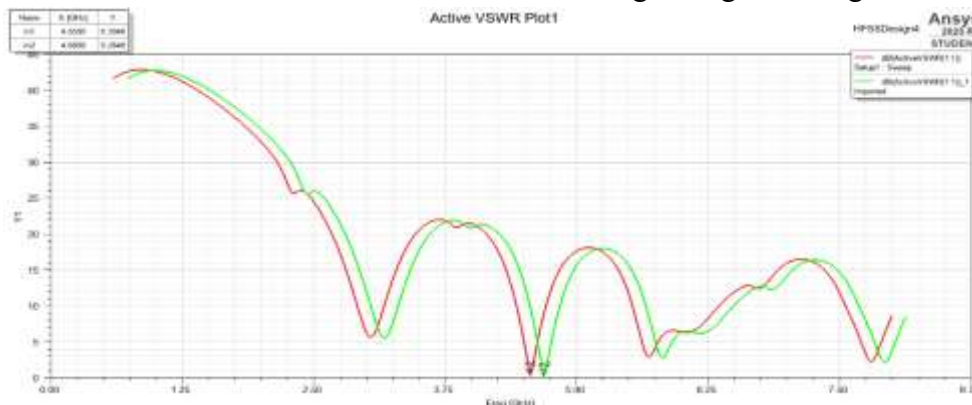


Figure 16: VSWR versus frequency plot for antenna 3

The VSWR values are 1.39 (simulated) and 1.28 (measured), confirming efficient power transfer.

Parameters	Simulated	Measured
Frequency (GHz)	4.55	4.68
Return loss (S11) dB	-32.87	-31.42
VSWR	1.39	1.28
Bandwidth (MHz)	150	149.45
Incident Power (W)	1	1
Accepted Power (mW)	740	720
Radiated Power (mW)	396	378
Radiation Efficiency (%)	53.51	52.50
Total Efficiency	39.6	37.8
Peak system gain (dB)	1.20	1.33
Peak gain (dB)	1.10	1.23

Table 8: Comparison of Simulated and Measured Results for Antenna 3

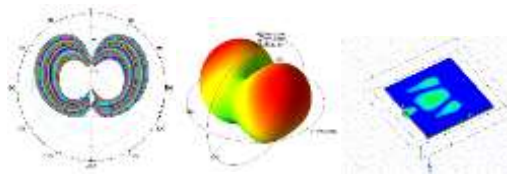


Figure 17: (a) 2D radiation pattern (b) 3D radiation pattern (c) field distribution

The antenna exhibits stable radiation characteristics with consistent field distribution.

The results show close agreement between simulation and measurement, with a bandwidth of 150 MHz (simulated) and 149.45 MHz (measured). The radiation efficiency is approximately 52%, and the gain remains stable, confirming suitability for low-frequency applications.

E. Performance Analysis of Antenna 4 (7.55 GHz)

The second antenna is designed for operation at 7.55 GHz and evaluated through simulation and measurement.

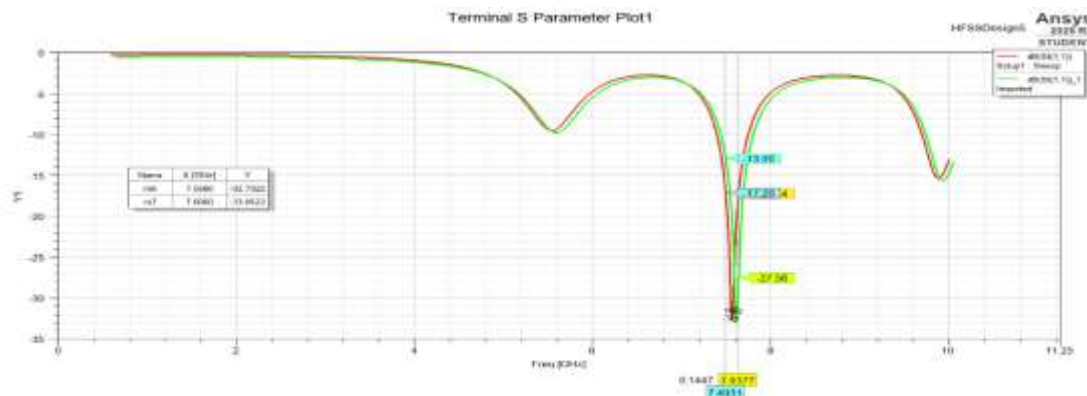


Figure 18: Return loss (S11) of proposed antenna at 7.55 GHz

The simulated return loss is -32.79 dB at 7.55 GHz, indicating good impedance matching. The fabricated antenna exhibits a return loss of -33.05 dB at 7.60 GHz. The slight frequency shift is attributed to fabrication tolerances and material variations, while maintaining strong matching characteristics.

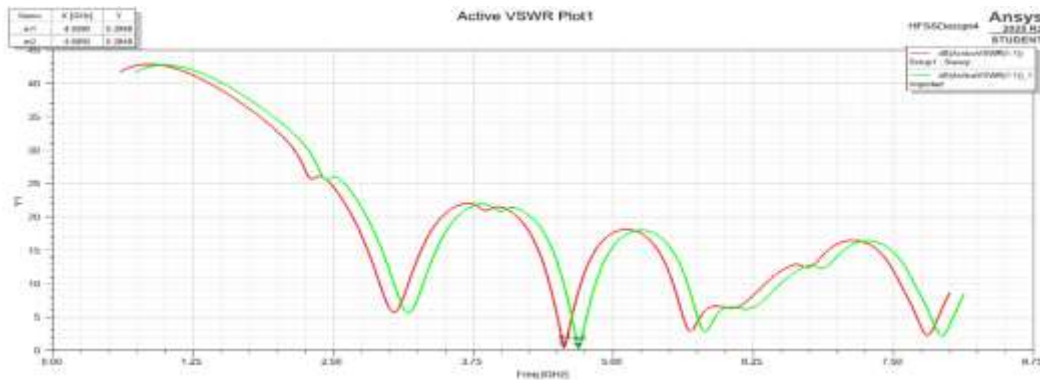


Figure 19: VSWR versus frequency plot for antenna 4

The VSWR values are 1.55 (simulated) and 1.42 (measured), confirming efficient power transfer.

Table 9: Comparison of Simulated and Measured Results for Antenna 4

Parameters	Simulated	Measured
Frequency (GHz)	7.55	7.60
Return loss (S11) dB	-32.79	-33.05
VSWR	1.55	1.42
Bandwidth (MHz)	1440	1427
Incident Power (W)	1	1
Accepted Power (mW)	990	990
Radiated Power (mW)	651	655
Radiation Efficiency (%)	65.75	66.16
Total Efficiency	65.1	65.5
Peak system gain (dB)	1.68	1.75
Peak gain (dB)	1.60	1.65

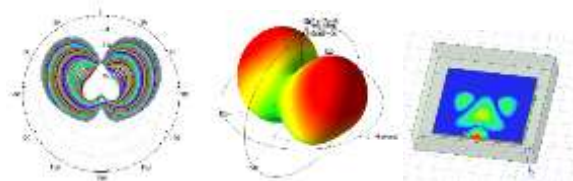


Figure 20: (a) 2D radiation pattern (b) 3D radiation pattern (c) field distribution

The antenna exhibits stable radiation characteristics with consistent field distribution.

The results show close agreement between simulation and measurement, with a bandwidth of 1440 MHz (simulated) and 1427 MHz (measured). The radiation efficiency is approximately 65%, and the gain remains stable, confirming suitability for low-frequency applications.

CONCLUSION

This work presents the development of an integrated aircraft safety monitoring system that combines multiband antenna design with real-time sensing and communication. The proposed approach addresses the limitations of conventional systems by providing continuous monitoring along with reliable communication across multiple frequency bands within a single framework.

The multiband microstrip antennas were designed and analyzed using Ansys HFSS, and their performance

was verified through fabrication and measurement. The close agreement between simulated and measured resonant frequencies confirms the validity of the design methodology. Key performance parameters such as return loss, VSWR, bandwidth, efficiency, and gain indicate that the antennas provide stable and efficient operation suitable for aviation applications. The observed impedance matching and radiation characteristics ensure effective signal transmission with minimal losses.

The integration of the embedded system based on the ESP32 enables continuous monitoring of important flight parameters through multiple sensors. The system is capable of identifying abnormal conditions and generating alerts through a GSM communication module, thereby supporting timely intervention. The combined operation of sensing, processing, and communication enhances overall system reliability.

The implementation of the complete system on a drone platform demonstrates its practical applicability and effectiveness under real-time conditions. The results confirm that the proposed system can provide both communication redundancy and intelligent monitoring, making it a suitable solution for improving aircraft safety.

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