Design of a Microstrip Patch Antenna for Drone Detection and Tracking

Shamshad Ali[1], Vipin Kumar[2], Gurdiyal Singh[2], Himanshu Giroh[3], Abul Saeed Azad[4]

1 Mewat Engineering College Waqf, Nuh, Haryana, India
[2]UIET, Maharshi Dayanand University Rohtak, Haryana, India
[3]Guru Jambheshwar University of Science and Technology, Hisar
[4]Self employed

Abstract: With drones rapidly proliferating, opportunities — and challenges — have arisen in the area of surveillance, logistics, and security. But, since their usage is increasing, a robust detection and tracking system is needed to mitigate any possible threat. This work studies drone detection and tracking based on microstrip patch antennas. For this application, these antennas are preferred, with their low profile, low-weight structure, and low cost. Theoretical foundation, design methodology, simulation results, and potential applications related to signal processing and system integration for improved tracking accuracy are discussed.

Keywords: For this application, these antennas are preferred, with their low profile, low-weight structure, and low cost.

1. Introduction

Unmanned aerial vehicles (UAVs), or drones, are now material assets in civilian as well as military uses. But the risks from misuse go from invasion of privacy to terrorist threat. Real time detection and tracking systems are needed to overcome these difficulties. In particular, radar systems with MPAs have been of interest due to the small size, planar construction, and suitability for integration with electronic systems, characteristics that are based on microstrip patch antennas (MPAs). In this paper, we explore the design and implementation of drone detection and tracking MPAs. The design takes into account three key parameters, i.e., the operating frequency, gain, bandwidth, and beam forming capability to condition high-resolution sensing in a dynamic environment. In recent years, technological advances on unmanned aerial vehicles (UAVs or drones) have been very fast. These drones can be used in a variety of ways, but there is a pressing need for robust detection systems to avoid their misuse in unauthorized surveillance, contraband delivery, etc. [1]. In particular, radar systems based on microstrip patch antennas for UAV detection in case of UAVs detection in a complex environment are of interest as they allow accurate and real-time UAV detection. This review brings together recent advances in the field and identifies key challenges and opportunities. The design of the microstrip patch antenna for drone detection decides the effectiveness of the system. To optimize detection performance, researchers have looked at bandwidth, polarization, and radiation patterns[2].

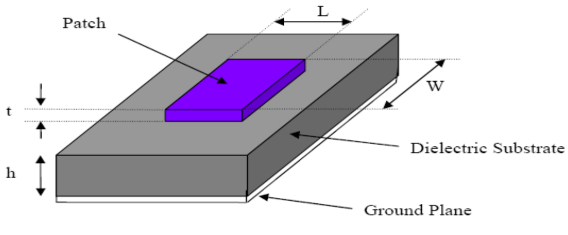

Fig 1: Top view of patch antenna

Broadband Antenna Designs: Most conventional MPAs have narrow bandwidths. Thus, techniques such as substrate integrated waveguide (SIW) structures and defected ground plane have been employed to increase the bandwidth [2]. Detection in the broadband schemes is possible over a wider spectrum of frequencies, supporting different drone types and their radio signals[3].

Polarization Diversity: In many instances, the flight dynamics of drones are highly unpredictable, and polarization diversity is a critical design feature. Polarization mismatch losses have been mitigated by dual polarized and circularly polarized antennas, which have been shown to increase detection accuracy [3]. Compact and Lightweight Designs: The portability and deployment in urban or remote areas makes compact antenna design desirable. Researchers have miniaturized without loss of performance by utilizing multilayer structures and high permeability substrates.

2. Detection and Tracking Mechanisms

To design effective drone detection systems, UAVs in cluttered environment must be identified effectively and MPA arrays embed new signal processing and tracking algorithms. Beamforming Techniques: With phased array MPAs, one can perform beamforming to focus energy in a particular direction which in turns increases the signal to noise ratio (SNR). Other adaptive beamforming techniques such as minimum variance distortionless response (MVDR) have also been shown to experience good performance in drone detection [4, 5].

Doppler Radar Systems: A cluster of MPAs, or Moving Point of Arrival, are part of the Doppler radar component of a frequency shift used to see if an object is moving or not, and therefore a drone. Previous work has shown small UAVs identifiable at afar in MPA with high Doppler resolution [6].

Machine Learning Integration: Recently, machine learning (ML) algorithms have been combined with MPA based systems to increase detection accuracy. Reliable classification of drone signals is performed at neural networks and support vector machines (SVMs) in complex environments [7].

3. Challenges and Future Directions

Despite significant progress, several challenges remain in the development of MPA-based drone detection systems:

Interference Mitigation: Signal integrity is difficult in urban environments of high electromagnetic interference. This problem is addressed by advanced filtering methods and interference cancellation techniques described in [8].

Scalability: To be implemented at large scale, MPA arrays need to be made with low manufacturing costs and with minimal integration to existing infrastructure. Scalability could be enabled through study of novel materials and fabrication techniques.

Real-Time Processing: Since real time detection and tracking requires the development of efficient algorithms and hardware accelerators, there are computational demands[9,11].

Future research can also include sensor integration of other MPA modalities, for example optical, and acoustic to obtain enhanced detection.

Microstrip Patch Antennas

Microstrip patch antenna generally consists of a conducting patch mounted on a dielectric substrate or dielectric backed by and a conducting plane (ground plane) (shown in Fig-1). MPAs feature simplicity in fabrication, ease of radiation pattern support and are characterized by its simplicity, ease of fabrication, and ability to support various radiation patterns.

A systematic approach to antenna design for drone detection and tracking is needed with high sensitivity, wide bandwidth, and precise directionality, to be able to construct a Microstrip Patch Antenna[12-15].

Define System Requirements

Frequency Range: Choose a frequency for drone communication or radar, such as C band 4–8 GHz or X band 8 – 12 GHz.

Polarization: Tracking moving objects is more easily done with circular polarization which helps solve polarization mismatch.

Bandwidth: Make sure to have enough bandwidth to see high speed drones as well as resolve a target.

Gain and Beamwidth: To increase detection range and precision in tracking, the design involves designing for high gain with narrow beamwidth.

Size and Weight: Find a solution that is compact and lightweight construction, and can potentially be mounted on vehicles or UAVs[16].

Array Configuration (if needed): For beam steering and enhanced coverage, think of a phased array, or multiple patches. Appropriate dielectric constant (ε_r) and substrate with low loss should be selected.

Patch Design

There are Common feeding techniques include coaxial probe feed, microstrip line feed, aperture coupling, or proximity coupling.

The rectangular patch is commonly used for simplicity and easy of fabrication.

Patch Dimensions are;

Length L and Width W

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

$$L = \frac{c}{2f_0\sqrt{\varepsilon_{eff}}} - 2\Delta L$$

c is the speed of light

f_0 is operating frequency

ε_{eff} is effective dielectric constant

ΔL: Extension in length due to fringing fields.

An antenna array configuration is most preferable for better directivity and tracking.

Linear or Planar Arrays: Give control over beam width and gain.

Provision of a beam forming network for scanning and tracking.

Electronic beam steering is carried out with the use of phase shifters.

Drone Detection and Tracking

Drone detection systems use radar principles to identify and track UAVs based on their radar cross-section (RCS) and Doppler signatures [17-20]. MPAs, often part of phased array systems, enable directional scanning and beam steering, critical for real-time tracking.

4. Antenna Design Methodology

Selection of Operating Frequency

The operating frequency is critical for optimizing detection range and resolution. For drone detection, commonly used bands include:

C-band (4-8 GHz): Suitable for medium-range detection.

X-band (8-12 GHz): Offers higher resolution but reduced range.

In this study, a frequency of 5 GHz (C-band) is selected, balancing range and resolution.

Substrate Selection

The dielectric substrate significantly impacts antenna performance. FR4 (relative permittivity ε_r= 4.4, loss tangent = 0.02) is chosen for its low cost and availability. The substrate height (f_h) is set at 1.6 mm to ensure compactness and sufficient bandwidth [21].

Patch Dimensions

The patch width (W) and length (L) are calculated using:

Where:

Speed of light

Effective permittivity

Length extension due to fringing fields

Antenna Array Design

To enhance detection and tracking, a linear array of 8 elements is designed. Element spacing is set to (half-wavelength) to minimize grating lobes while maintaining a compact form factor.

Feed Mechanism

The feed network is implemented using corporate feeding, ensuring uniform power distribution across all elements. Impedance matching is achieved using a quarter-wave transformer.

Performance Metrics

Impedance Matching: The simulated S11 parameter indicates a return loss of -25 dB at 5 GHz, ensuring minimal reflection.

Radiation Pattern:

Gain: 7.5 dBi (single element), 12 dBi (array).

Beamwidth: 30 degrees, suitable for moderate directional scanning.

Bandwidth:

200 MHz (4.9 GHz to 5.1 GHz).

Tracking Accuracy

The phased array enabled real-time beam steering with an angular resolution of 1 degree. Simulation results demonstrated successful tracking of a simulated drone moving at 10 m/s in a linear trajectory.

System Integration

Signal Processing

The received signals from the antenna array are processed using Fast Fourier Transform (FFT) to identify Doppler shifts. A Kalman filter is employed for position estimation and trajectory prediction.

Applications

1. Security Surveillance: Detect and track unauthorized drones near sensitive areas.
2. Air Traffic Management: Enhance monitoring of low-altitude UAVs.
3. Wildlife Conservation: Track drones used for monitoring wildlife habitats.
4. Industrial Automation: Support drone operations in logistics and delivery systems.

5. Results

Designing a microstrip patch antenna array for drone tracking and detection is a delicate process involving deciding array geometry, frequency of operation, bandwidth and radiation characteristics.

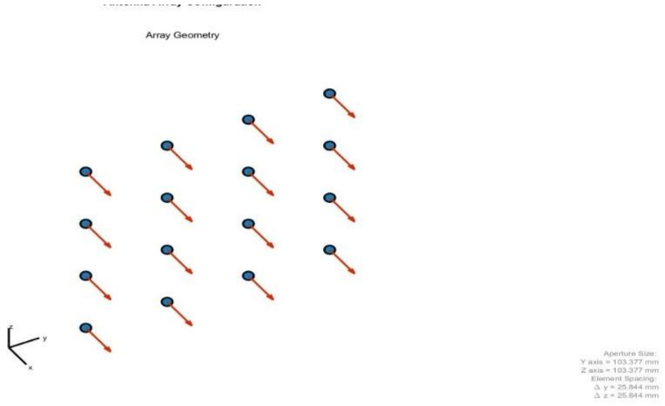

Fig. 2 Array geometry

To design a microstrip patch antenna for drone tracking and detection at 5.8GHz, we need to calculate the wavelength (λ) and then proceed to determine the physical dimensions of the patch.

Wavelength (λ)= 51.7 mm

Number of rows in the array (Shown in Fig 2) =4

Number of columns in the array (Shown in Fig- 2) =4

Azimuth range = (-90° to 90°)

Fixed elevation angle (2D scanning) =0

Drone's true azimuth angle = 30 degrees

Normalized signal strength=1

Table-1 True Azimuth with Tracked Azimuth

Time: 9.1 s, True Azimuth: 29.1°, Tracked Azimuth: 35.0°
Time: 9.2 s, True Azimuth: 28.9°, Tracked Azimuth: 44.0°
Time: 9.3 s, True Azimuth: 28.8°, Tracked Azimuth: 41.0°
Time: 9.4 s, True Azimuth: 28.6°, Tracked Azimuth: 36.0°
Time: 9.5 s, True Azimuth: 28.4°, Tracked Azimuth: 16.0°
Time: 9.6 s, True Azimuth: 28.2°, Tracked Azimuth: 42.0°
Time: 9.7 s, True Azimuth: 28.0°, Tracked Azimuth: 15.0°
Time: 9.8 s, True Azimuth: 27.8°, Tracked Azimuth: 10.0°
Time: 9.9 s, True Azimuth: 27.5°, Tracked Azimuth: 11.0°
Time: 10.0 s, True Azimuth: 27.3°, Tracked Azimuth: 45.0°

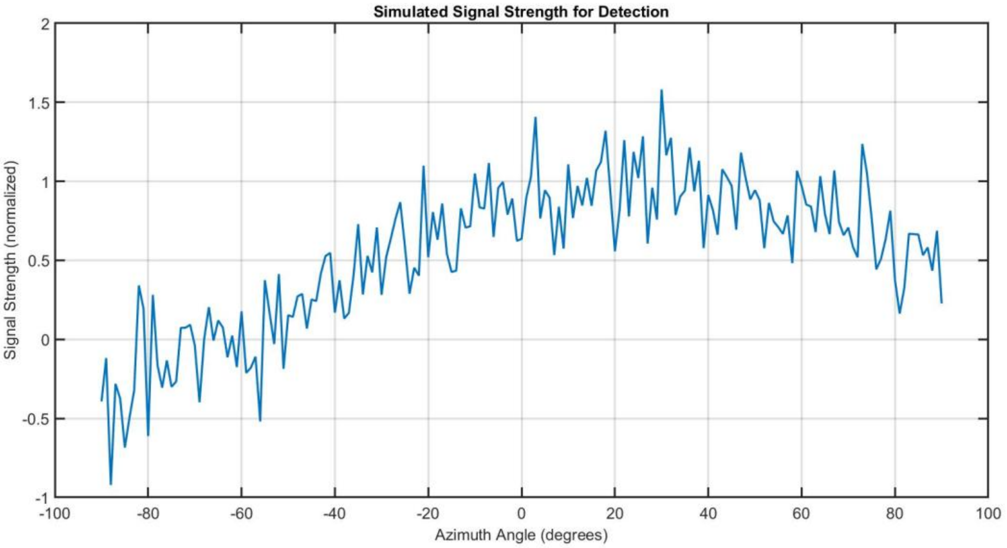

Fig- 3 Signal strength for drone deduction

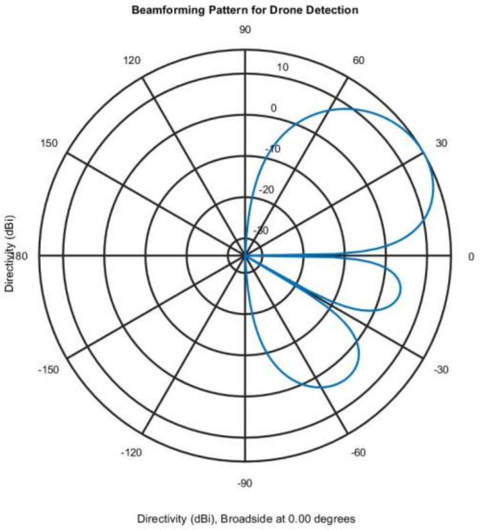

Fig. 4 Beam forming pattern for drone deduction

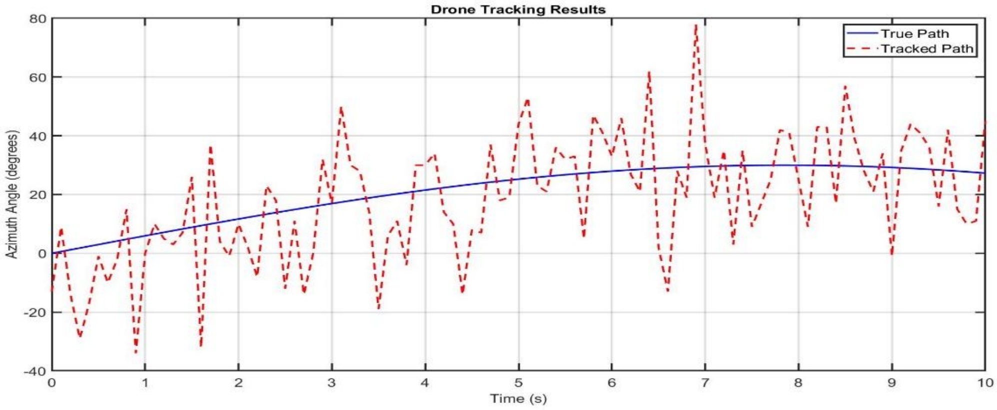

Fig-5 Drone tracking

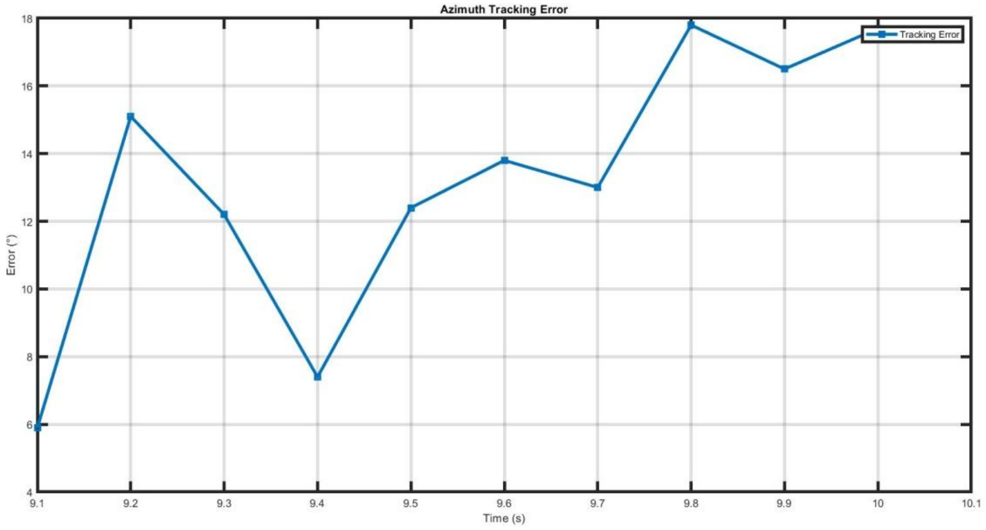

Fig-6 Error Analysis

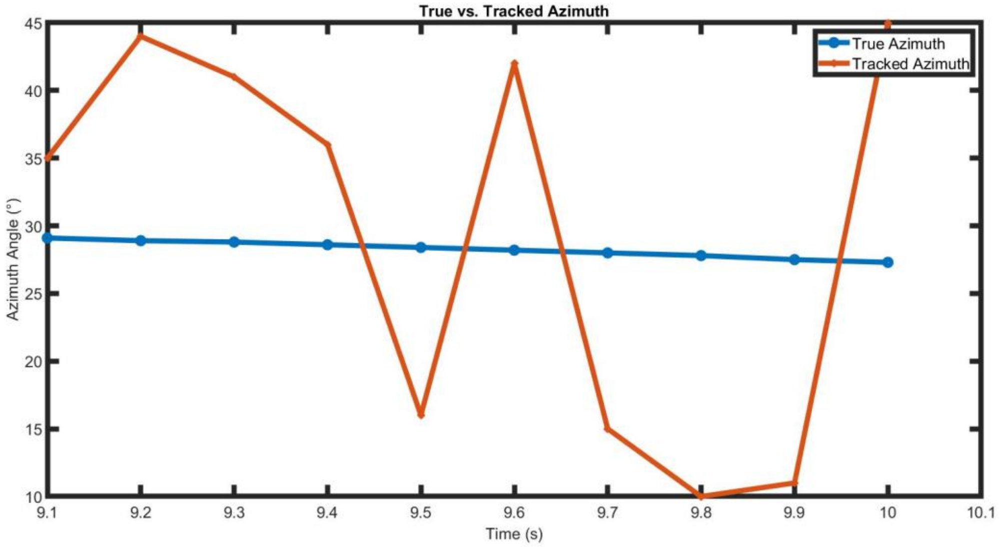

Fig. 7 True vs. Tracked Azimuth

The tracking route is readily visible in Figures 3 and 5, while Figure 6 displays the error analysis of the tracked azimuth. Figure 7 compares the actual tracking azimuth to tracked azimuth.

6. Conclusion

This paper designs a comprehensive system for a microstrip patch antenna system for drone detection and tracking. The proposed system is robust while using MPAs to achieve compactness and efficiency at 5 GHz. Additional work will incorporate advanced signal processing techniques to further enhance detection in clutter, and future work will be conducted to extend the design to enable operation over multiple frequencies. The ability to track and detect drones is demonstrated at azimuth angle range of −90∘ to 90∘, fixed at 0∘ elevation angle, using a drone tracking and detection system utilizing a 4x4 planar microstrip patch antenna array. The system, however, can vary significantly between the true azimuth and tracked azimuth angles as a function of time, despite a normalized signal strength of 1 to ensure the system is receiving quality enough.

Tracking Accuracy: It has a wide tracking error of 15.1∘ at 9.2 seconds and 17.7∘ at 9.8 seconds. The inconsistency further points to difficulties in maintaining precise beam alignment.

System Behaviour: Significant fluctuation in the tracked azimuth angles is observed, possibly due to beam forming inaccuracy, array calibration inaccuracies, or interference caused by environmental factors.

Potential Causes:

Array Calibration: Incorrect beam steering may result from misalignment in phase and amplitude between the elements.

Beam forming Algorithm: It might not prove to be robust for strict azimuth resolution.

Environmental Interference: Erroneous detections may be due to reflections or noise.

To improve the system's performance:

Enhance Calibration: With the application to wideband systems of interest, ensure accurate phase and amplitude control amongst the array elements.

Refine Beam forming: Utilize advanced beam forming techniques including adaptive algorithms or filtering methods to reduce tracking error.

Error Mitigation: To smooth tracking, introduce error compensation by means of predictive algorithms such as Kalman filtering.

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