APAN-Based Direction of Arrival Estimation and Signal in UAV Communication Platforms

Manidipa Roy[1], Sai Kiran Oruganti[2]

[1]Post Doctoral Researcher, Lincoln University College, Petaling Jaya, Selangor Darul Ehsan-47301, Malaysia; [2]Faculty of Engineering and Built Science Lincoln University College, Petaling Jaya, Selangor, Malaysia ;

Email ID [1]pdf.manidipa@lincoln.edu.my, [2]saisharma@lincoln.edu.my

Abstract

Direction of Arrival estimation in UAV (Unmanned Aerial Vehicle) systems is required for navigation, beam estimation and pattern formation, localization and interference suppression. The factors that affect the system accuracy are UAV mobility, multipath propagation, low signal to noise ratio etc. The proposed solution to these problems is the use of Adaptive Phase Antenna Network based Direction of Estimation for UAV communications. The methodology proposed utilizes the combination of signal processing of antenna array, adaptive beam formation, covariance matrix estimation, angle prediction using deep learning. The parameters optimized using the proposed methodology are angular resolution, localization accuracy, reduction in complexity under dynamic environment. The simulation results showcase that the parameters like Root Mean Square Error, detection probability and robustness are improved as compared to ESPRIT and MUSIC algorithm architecture.

Keywords: Antenna Arrays, APAN, Beam forming, DOA estimation, Machine Learning, Signal Processing, UAV Communications

I. INTRODUCTION

The recent studies show that UAV assisted wireless networks have applications in disaster management, precision agriculture, intelligent transportation, border surveillance, search and rescue missions, accurate estimation of signal arrival angles is essential for target tracking, spectrum monitoring, adaptive beam steering, and UAV swarm coordination. The Direction of Arrival estimation algorithms such as MUSIC and ESPRIT offer high angular resolution but the performance degrades in dynamic aerial environments. The method proposed utilizes adaptive signal processing and machine learning based enhancement for improvement of estimation accuracy. The proposed work showcases development of an APAN architecture for UAV communications, integration of adaptive beamforming with subspace-based DOA estimation, Machine-learning-assisted angular prediction and performance evaluation under varying UAV mobility and SNR conditions.

II. RELATED WORK

The Direction of Arrival estimation on basis of subspace evaluation like MUSIC and ESPRIT have been employed on large scale due to high resolution [1-5]. Recent developments in this domain include Deep Learning based Direction of Arrival estimation [6-7], cooperative localization in UAV swarms, RIS assisted aerial communication and sparse array processing techniques.

The research gap identified in most of the techniques is the failure to maintain estimation accuracy under dynamic movements of UAV and severe multipath fading conditions.

III. SYSTEM MODEL

A. APAN Architecture

The proposed architecture as shown in Figure 1 consists of Uniform Linear Antenna Array (ULA), RF Front-End, Signal Conditioning Module, Adaptive Covariance Estimator, DOA Processing Unit, Navigation Controller and Beam Steering Module.

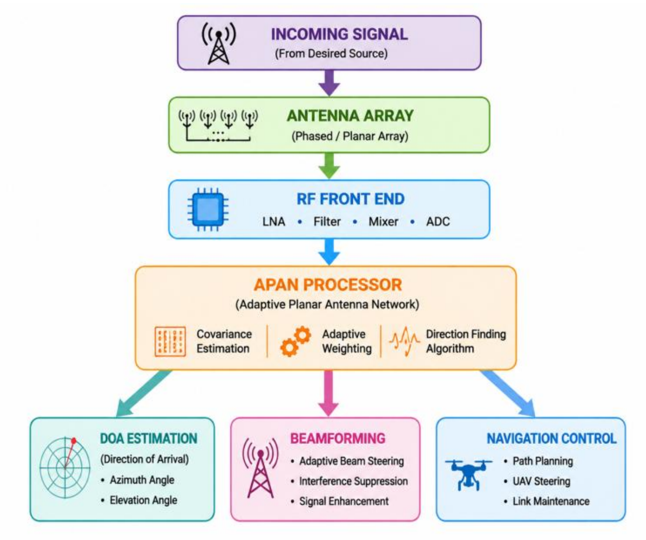

Figure 1. Block diagram of proposed APAN based DOA estimation framework

B. Signal Model

Assume N antenna elements receiving M narrowband signals.

$$x(t) = As(t) + n(t)$$

where

$$x(t) \in C^{NX1}$$

Is the received signal vector,

$$A = [a(\theta_1), a(\theta_2), \dots a(\theta_M)]$$

Is the steering matrix,

$$s(t)$$

represents source signals, and

$$n(t)$$

denotes additive White Gaussian noise.

IV. APAN-BASED DOA ESTIMATION

A. Covariance Matrix

$$R_{xx} = E[x(t)x^{\mathrm{H}}(\mathrm{t})]$$

The covariance matrix is decomposed as

$$R_{xx} = U_s \Lambda_s \mathrm{U}_{\mathrm{s}}^{\mathrm{H}} + U_n \Lambda_n \mathrm{U}_{\mathrm{n}}^{\mathrm{H}}$$

Where

U_s= Signal Subspace

U_n= Noise Subspace

B. MUSIC Spectrum

The MIUSIC pseudo-spectrum is expressed as

$$P_{MUSIC}(\theta) = \frac{1}{a^H(\theta)U_n U_n^H a(\theta)}$$

The peaks indicate estimated arrival directions.

C. Adaptive Beamforming

Beamformer weights are computed as

$$w = \frac{R^{-1}a(\theta)}{a^H(\theta)R^{-1}\mathrm{a}(\theta)}$$

This improves interference rejection and enhances desired signal reception.

V. MACHINE LEARNING ENHANCEMENT

The Machine Learning enhancement incorporates a Deep Neural Network (DNN) that is integrated into the APAN processor. The Input features include Covariance Matrix, Phase Difference, Signal Amplitude, Doppler Shift and UAV Velocity. The Output parameters include Azimuth Angle, Elevation Angle, Confidence Score and Network Structure.

The distribution of neurons per layer is as tabulated in Table 1.

Table 1. Neurons per layer in DNN integrated into APAN processor

Layer	Neurons
Input	128
Hidden-1	256
Hidden-2	128
Hidden-3	64
Output	2

VI. SIMULATION SETUP

The simulation setup is employed using in MATLAB R2025a platform with Phased Array Toolbox and Deep Learning Toolbox. Several parameters like carrier frequency, number of array elements, UAV speed, SNR range, sources, snapshot number and sampling frequency have been considered for the modeling as tabulated in Table 2.

Table 2. Values of simulation parameters

Parameter	Value
Carrier Frequency	2.4 GHz
Array Elements	8
UAV Speed	10–40 m/s
SNR Range	−10 to 20 dB
Sources	2–5
Snapshot Number	1000
Sampling Frequency	20 MHz

VII. RESULTS AND DISCUSSION

A. RMSE Performance

The Root Mean Square Error performance using APAN have been calculated for different SNR values and result have been compared with the values achieved using MUSIC and ESPRIT algorithms as tabulated in Table 3.

Table 3. RMSE Performance Comparison Chart

SNR (dB)	MUSIC	ESPRIT	APAN
-10	11.8°	10.4°	5.2°
-5	8.3°	7.6°	3.6°
0	6.2°	5.8°	2.1°
5	4.1°	3.8°	1.4°
10	2.8°	2.5°	0.9°

B. Detection Probability

The detection probability have been calculated for the DOA estimation using APAN and compared with that of MUSIC and ESPRIT algorithms as shown in Table 4.

Table 4. Detection Probability for different algorithms

Algorithm	Probability
MUSIC	89%
ESPRIT	91%
APAN	98%

The proposed DOA estimation using APAN technique showcases improved performance characteristics with low SNR values and better UAV mobility.

VIII. COMPUTATIONAL COMPLEXITY

The complexity of MUSIC is $O(N^3)$. The APAN framework reduces repeated spectral searches through neural-network-assisted prediction. Overall complexity becomes $O(N^2)$ for practical UAV implementations.

X. CONCLUSION

The paper presents APAN based DOA estimation technique for UAV communication platforms. The proposed method inculcates the adaptive antenna processing, subspace based signal estimation, and deep learning to improve localization accuracy and reliability of communication. Simulation results show significant improvements in RMSE SNR, detection probability and robustness over MUSIC and ESPRIT algorithms. In future RIS assisted APAN systems will be focused upon with federated learning for UAV swarms and real time FPGA implementation techniques.

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