Pointing Algorithm for Phased Array Antennas in Drone/UAV Communication Systems

Anand Singh

https://www.linkedin.com/in/anandkrs/

Introduction

In modern communication systems, phased array antennas are crucial for maintaining constant updates on azimuth and elevation angles. This is particularly important in systems involving drones or pseudo-satellites (High Altitude Platform Systems, HAPS) equipped with phased array antennas, ensuring continuous high-throughput connectivity with multiple ground stations (Customer Premises Equipment, CPE). This article discusses the implementation of such a system using 802.11 superframes, breaking down the methodology for calculating and optimizing pointing angles to minimize latency.

System Overview

Components

1. Drone/Pseudo-Satellite (HAPS):
   - **Phased Array Antennas:** The drone or pseudo-satellite (HAPS) is equipped with two phased array antennas to significantly increase throughput. By utilizing two antennas, the system can handle multiple communication streams simultaneously, effectively doubling the capacity. This setup allows for one antenna to manage the uplink communication with the gateway CPE, while the other handles downlink communication with the end station CPEs. The dual-antenna configuration enhances spatial diversity and improves signal quality by mitigating multipath interference and providing robust connectivity in diverse conditions.
   - **GPS for Real-Time Location Tracking:** The drone/HAPS is equipped with a GPS system that provides continuous real-time location data. This information is crucial for dynamically adjusting the azimuth and elevation angles of the phased array antennas to maintain optimal alignment with the ground stations, ensuring efficient communication.

2. Ground Stations (CPE):
   - **Fixed Locations:** The CPEs are set up at predetermined fixed locations on the ground. The precise latitude and longitude coordinates of these locations are provisioned or updated to the drone/HAPS before its flight. This initial setup enables the drone/HAPS to accurately calculate the required pointing angles for each CPE, facilitating reliable and high-throughput communication.
   - **Role in Communication:** Each CPE acts as a critical node in the communication network, participating in either uplink or downlink phases depending on the overall system architecture. Their fixed positions allow for stable and predictable communication patterns, which are essential for optimizing the performance of the phased array antennas.

Understanding the Azimuth and Elevation angles

Understanding azimuth and elevation angles can be simplified by comparing them to how we use directions and angles in everyday life.

Azimuth Angle

- Imagine you are standing in a field with a compass in your hand. The azimuth angle is like pointing in a specific direction on the compass.
- **North as Reference:** Think of the north direction as the starting point (0 degrees).
- **Turning to Face Different Directions:** If you turn to face east, your compass would point to 90 degrees. If you turn further to face south, it would point to 180 degrees. Turning to face west would be 270 degrees.
- **Drone Perspective:** For a drone, the azimuth angle is the direction it needs to point its antenna relative to north to communicate with a ground station. For example, if the ground station is east of the drone, the azimuth angle would be 90 degrees.

Elevation Angle

- Now imagine you are looking up at the sky or down at the ground. The elevation angle is the angle between the horizon and the object you are looking at.
- **Straight Ahead:** When you look straight ahead at the horizon, the elevation angle is 0 degrees.
- **Looking Up:** If you look up to a tree or a bird in the sky, the elevation angle increases. Looking straight up above your head would be 90 degrees.
- **Looking Down:** If you look down at something on the ground, the elevation angle becomes negative (for instance, looking straight down would be -90 degrees).
- **Drone Perspective:** For a drone, the elevation angle is how much it needs to tilt its antenna up or down to align with the ground station. If the ground station is directly below the drone, the elevation angle might be -90 degrees.

In summary:

- **Azimuth Angle:** The compass direction from the drone to the ground station (left or right).
- **Elevation Angle:** The angle up or down from the drone to the ground station.

These angles help the drone point its antenna accurately to maintain a strong and reliable communication link with ground stations.

Real-Time Location and Pointing Angle (Azimuth, ELevation) Calculation

GPS Integration

The drone/HAPS utilizes GPS to continuously determine its real-time location. Given the fixed locations of the CPEs, this data is used to calculate the required azimuth and elevation angles for optimal communication.

Calculation of Azimuth and Elevation Angles

To calculate the azimuth and elevation angles, the following steps are taken:

1. **Relative Position Determination:** The real-time coordinates of the drone/HAPS $(L_{d,}\varphi_d)$ and the fixed coordinates of the CPE $(C_d,\varphi_d)$are obtained.

2. **Azimuth Angle Calculation ($\boldsymbol{\theta}$):**
   - An azimuth angle is the angle between the north direction and the projection of the line connecting the drone/HAPS and the CPE on the horizontal plane.
   - It is calculated using the formula: $\theta = tan^{-1}\left(\frac{\Delta\phi}{\Delta L}\right)$ where $\Delta\phi = \phi_c - \phi_d$ and $\Delta L = L_c - L_d$.

3. **Elevation Angle Calculation ((\epsilon)):**
   - The elevation angle is the angle between the line connecting the drone/HAPS and the CPE and the horizontal plane.
   - It is calculated using the formula:

$$\epsilon = tan^{-1}\left(\frac{h_c - h_d}{\sqrt{(\Delta L)^2 + (\Delta\phi)^2}}\right)$$

Where h_c and h_d are the altitudes of the CPE and the drone/HAPS, respectively.

Incorporating UAV Attitude for Enhanced Accuracy

To further increase the accuracy of the algorithm for calculating azimuth and elevation angles, it is crucial to incorporate the UAV's attitude (roll, pitch, and yaw). This process involves calculating the angles from the UAV's real-time location and attitude to a fixed position on the ground (Customer Premises Equipment, CPE). Here is the detailed breakdown of the process:

1. **Acquire Real-Time UAV Geographic Coordinates and Attitude:** Obtain the real-time geographic coordinates of the UAV, including latitude, longitude, and altitude. Simultaneously, capture the UAV's attitude, which consists of roll, pitch, and yaw angles. The geographic position of the CPE is known in advance and remains fixed.

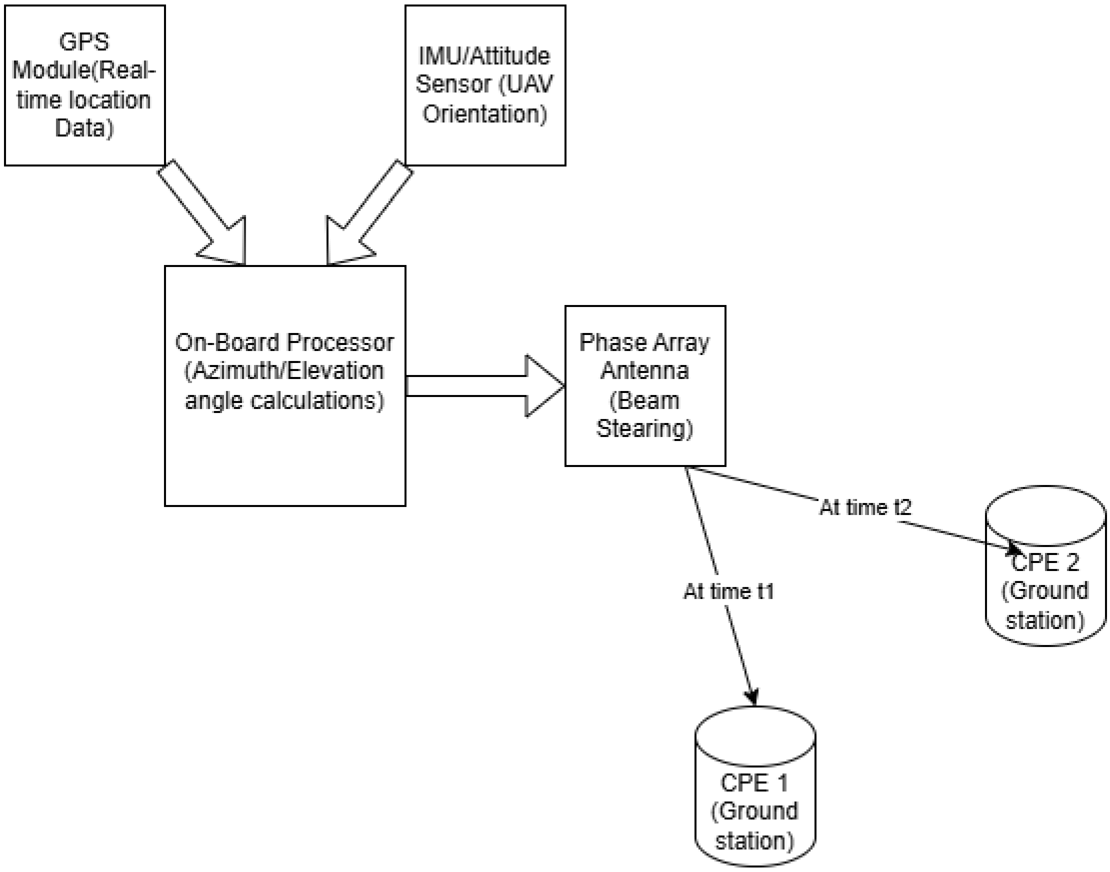
2. **Convert Coordinates to ECEF:** Convert the geographic coordinates of both the UAV and the CPE into Earth-Centered, Earth-Fixed (ECEF) coordinates. This conversion provides a uniform coordinate system to compute the relative direction from the UAV to the CPE.

3. **Compute Relative Direction in ECEF Coordinates:** Calculate the relative direction vector from the UAV to the CPE using their ECEF coordinates. This vector represents the straight-line distance and direction from the UAV's current position to the fixed CPE location.

4. **Convert UAV Attitude to Matrix Form:** Represent the UAV's attitude in matrix form to accurately depict its orientation in three-dimensional space. This involves creating a rotation matrix that combines the roll, pitch, and yaw angles to describe the UAV's current orientation.

5. **Calculate Azimuth and Elevation Angles:** Using the UAV's orientation matrix and the relative direction vector to the CPE, compute the azimuth and elevation angles. These angles are essential to accurately point the phased array antenna from the UAV towards the CPE, ensuring optimal alignment for communication.

Figure 1: System Architecture



Detailed Steps:

1. **Acquire Real-Time Geographic Coordinates and Attitude:**

- **Geographic Coordinates:** Latitude (ϕ), Longitude (λ), and Altitude (h).
- **Attitude:** Roll (ϕ_{roll}), Pitch (θ), and Yaw (ψ).

2. **Convert to ECEF Coordinates:**

- Use the following formulas to convert latitude, longitude, and altitude to ECEF coordinates (X, Y, X):

$$X = (N + h)\ cos\ (\phi)\ cos\ (\lambda)$$
$$Y = (N + h)\ cos\ (\phi)\ sin\ (\lambda)$$
$$Z = (\frac{b^2}{a^2} N + h)\ sin\ (\phi)$$

Where $N = \frac{a^2}{\sqrt{a^2cos^2(\phi)+b^2sin^2(\phi)}}$ and a and b are the Earth's equatorial and polar radii.

3. **Compute Relative Direction in ECEF:**

Calculate the relative direction vector from the UAV to the CPE:

$$Vector_{ECEF} = \begin{pmatrix} X_{CPE} - X_{UAV} \\ Y_{CPE} - Y_{UAV} \\ Z_{CPE} - Z_{UAV} \end{pmatrix}$$

4. **Convert UAV Attitude to Matrix Form:**

Create the rotation matrix from roll, pitch, and yaw angles:

$$R = R_{yaw} \cdot R_{pitch} \cdot R_{roll}$$

Where:

$$R_{roll} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos(\phi_{roll}) & -\sin(\phi_{roll}) \\ 0 & \sin(\phi_{roll}) & \cos(\phi_{roll}) \end{pmatrix}$$

$$R_{pitch} = \begin{pmatrix} \cos(\theta) & 0 & \sin(\theta) \\ 0 & 1 & 0 \\ -\sin(\theta) & 0 & \cos(\theta) \end{pmatrix}$$

$$R_{yaw} = \begin{pmatrix} \cos(\psi) & -\sin(\psi) & 0 \\ \sin(\psi) & \cos(\psi) & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

5. **Calculate Azimuth and Elevation Angles:**

Rotate the relative direction vector using the UAV's orientation matrix to obtain the rotated vector:

$$Vector_{rotated} = R \cdot Vector_{ECEF}$$

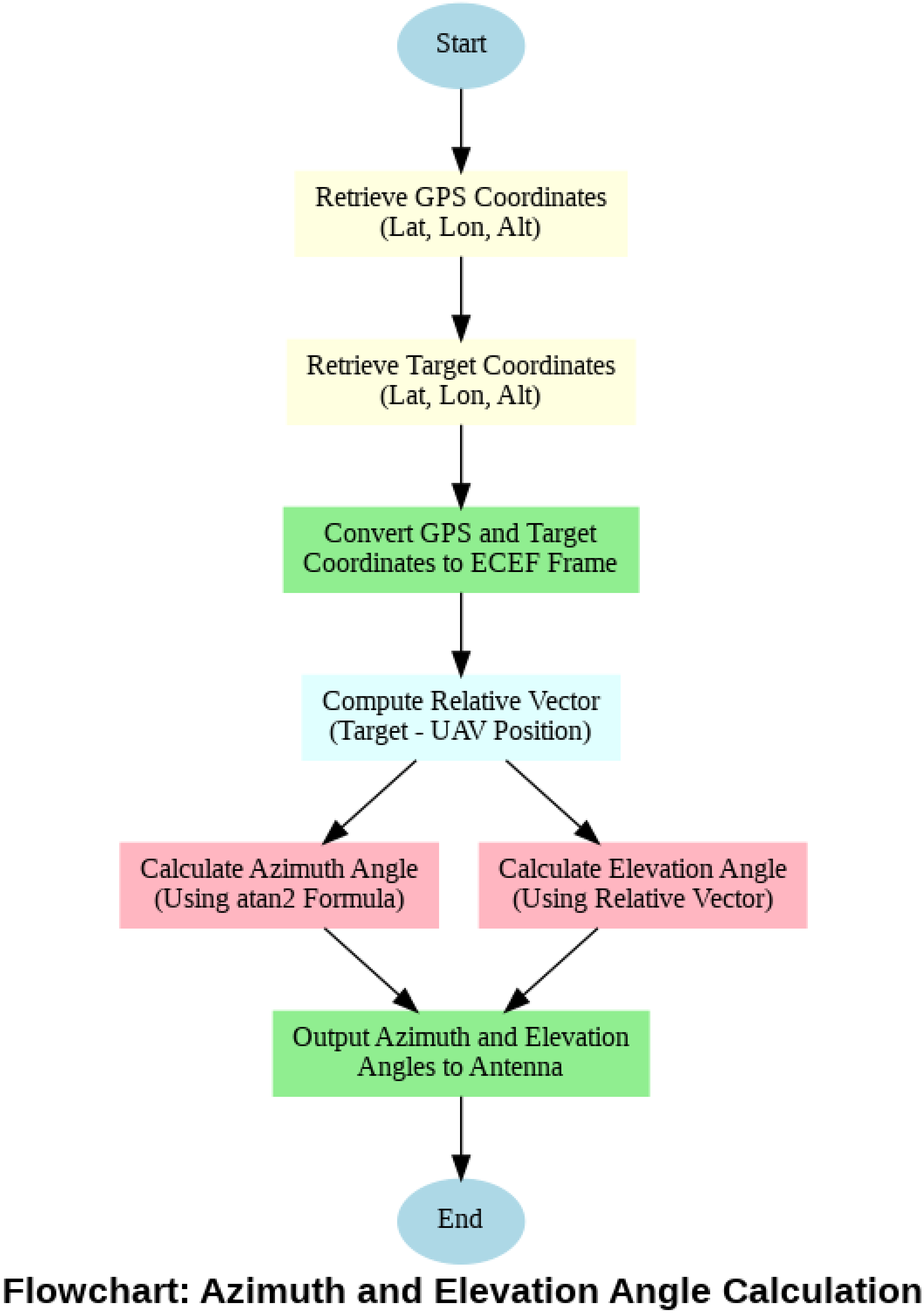
Extract azimuth (θ) and elevation (ϵ) angles from the rotated vector:

$$\theta = tan^{-1}\left(\frac{Y_{rotated}}{X_{rotated}}\right)$$

$$\epsilon = tan^{-1}\left(\frac{Z_{rotated}}{\sqrt{X^2{}_{rotated} + Y^2{}_{rotated}}}\right)$$

By following this process, the UAV can accurately determine the azimuth and elevation angles needed to point its phased array antenna towards the CPE, enhancing the communication link's reliability and throughput.

Figure 2: Process Flowchart



Results and Discussion

The proposed pointing algorithm for phased array antennas was validated through both experimental evaluation and practical implementation. This section discusses the results obtained from performance metrics and insights from real-world application.

Latency Reduction

Latency, defined as the time required for azimuth and elevation angle computation, is critical for real-time UAV-ground station communication. The system demonstrated a consistent reduction in latency over calibration iterations. As shown in **Figure X**, the latency stabilized at **50 ms** after the fifth iteration, indicating an optimal balance between computational efficiency and responsiveness.

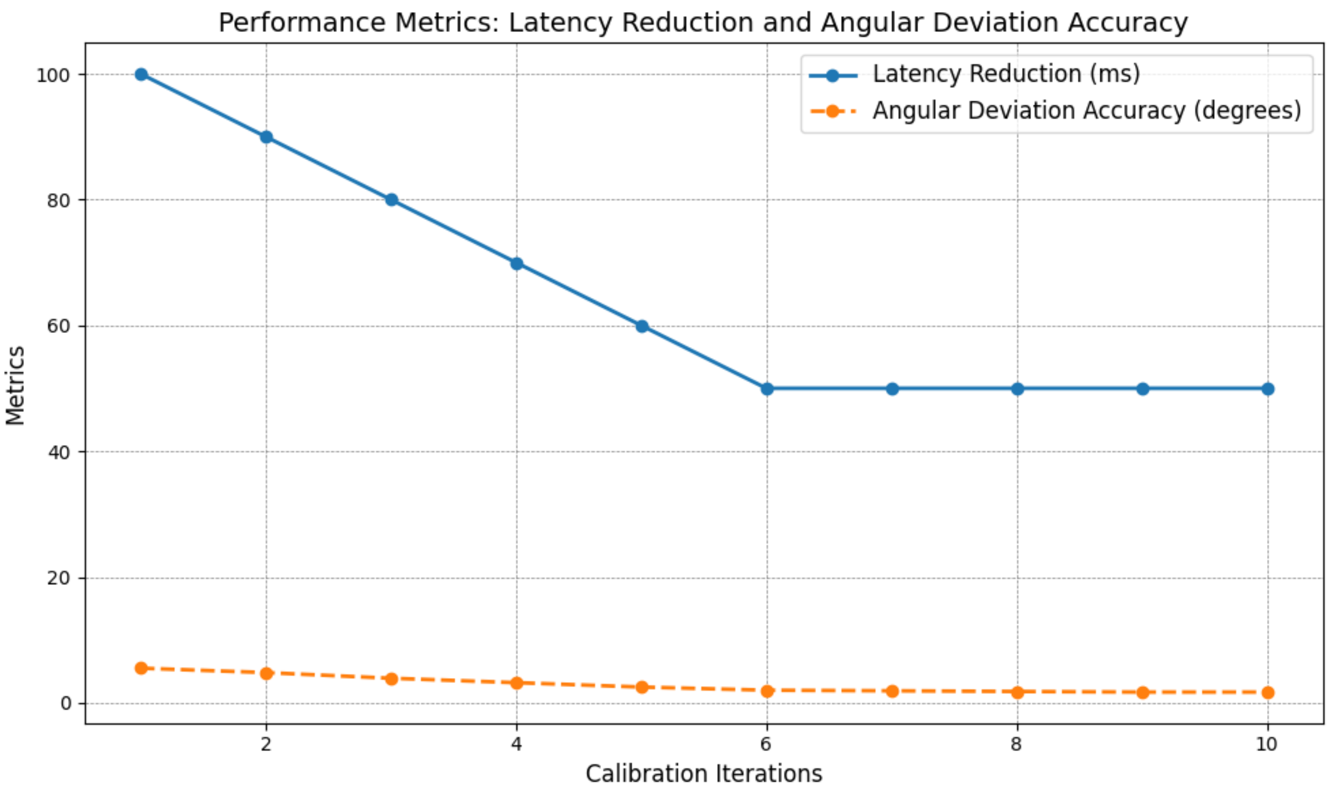
During practical implementation, the UAV maintained a consistent communication link with the ground station, even under varying environmental conditions. The system's ability to sustain low latency in real-world scenarios validates the algorithm's robustness for time-critical applications.

Angular Deviation Accuracy

The angular deviation, measured as the difference between calculated and actual target directions, was evaluated to determine alignment precision. Over successive iterations, the deviation steadily decreased, as depicted in **Figure 3**. By the tenth iteration, the system achieved an angular deviation of **1.7 degrees**, ensuring precise alignment and optimal signal strength.

In the practical example, the phased array antenna dynamically adjusted its pointing angles to track the ground station. The UAV consistently aligned within an angular deviation of **2 degrees**, corroborating the experimental results. This precision underscores the algorithm's capability to maintain robust communication links in dynamic environments.

Figure 3: Performance Metrics of Latency Reduction and Angular Deviation Accuracy



The graph demonstrates:

1. A significant reduction in latency across calibration iterations, stabilizing at 50 ms by iteration 5.

2. A consistent improvement in angular deviation accuracy, achieving optimal alignment by iteration 10.

Real-World Implementation

The algorithm was implemented on a UAV equipped with a GPS module, IMU, and phased array antenna. The system underwent the following steps:

1. **Setup**: The UAV obtained real-time GPS data and the ground station's coordinates, transforming them into a consistent coordinate frame.
2. **Calibration**: Over multiple iterations, the UAV refined its azimuth and elevation calculations, achieving optimal alignment.
3. **Operational Insights**:
   - The UAV demonstrated reliable tracking of the ground station, maintaining communication despite changing relative positions.
   - Observed metrics, such as low latency and precise alignment, align closely with experimental findings, showcasing the algorithm's practicality.

Key Takeaways

The integration of experimental results with practical observations highlights the proposed algorithm's efficiency and reliability. The significant reduction in latency and enhanced angular accuracy affirm its applicability for UAV-based phased array antenna systems. These findings pave the way for further exploration into real-time adaptive communication systems in dynamic environments.

References

1. Balanis, C. A. **Antenna Theory: Analysis and Design.** 4th Edition. Wiley, 2016. DOI: 10.1002/9781119176410
2. Haykin, S. "Cognitive Radio: Brain-Empowered Wireless Communications." IEEE Journal on Selected Areas in Communications, vol. 23, no. 2, pp. 201–220, 2005. DOI: 10.1109/JSAC.2004.839380
3. Lee, T. H. **The Design of CMOS Radio-Frequency Integrated Circuits.** 2nd Edition. Cambridge University Press, 2003. URL: https://www.cambridge.org/9780521835398
4. Mailloux, R. J. **Phased Array Antenna Handbook.** 2nd Edition. Artech House, 2005. URL: https://www.artechhouse.com
5. D. F. Stout and M. R. Davidson, Basic Electronics: Theory and Practice. 2nd Edition. McGraw Hill, 2017.
   URL:https://www.mheducation.com
   (A foundational reference for understanding signal processing in communication systems.)