Advanced Calibration Techniques for Ground Station Alignment in HAPS Networks

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Abstract

Ground station Customer Premises Equipment (CPE) plays a critical role in maintaining robust radio communication with High-Altitude Platform Stations (HAPS) such as drones or unmanned vehicles. Accurate alignment of the CPE's azimuth and elevation angles is essential to ensure a reliable line of sight and prevent RF link degradation caused by incorrect pointing. Traditional calibration techniques, relying heavily on manual intervention, are prone to errors and inefficiencies.

This paper proposes a novel automated calibration method to address these challenges. The technique eliminates the need for manual adjustments by integrating RF beacon-based markers and a systematic raster scanning process. By measuring parameters such as Received Signal Strength Indicator (RSSI) and Packet Error Rate (PER), the CPE autonomously determines and iteratively refines the optimal pointing angles. This process ensures alignment accuracy, minimizes errors, and enhances operational efficiency.

Experimental validation demonstrates the efficacy of the proposed method, showcasing its ability to achieve precise calibration while reducing manual effort. The results highlight significant improvements over traditional techniques, paving the way for more robust and efficient ground station CPE-HAPS communication systems.

Introduction

The increasing reliance on High-Altitude Platform Stations (HAPS), including unmanned aerial systems and drones, marks a transformative shift in modern communication networks. Positioned at stratospheric altitudes, these platforms provide extensive coverage, low latency, and versatile deployment for a wide range of applications, from disaster management to rural broadband access. Central to the success of these systems is the effective integration of ground station Customer Premises Equipment (CPE), which serves as the terrestrial interface for RF communication with HAPS.

The accuracy of the CPE's azimuth and elevation angles directly impacts the robustness of the RF link. Any misalignment can disrupt the line of sight, leading to signal degradation, increased packet error rates, and reduced communication efficiency. Traditional calibration methods involve pointing the CPE toward a known reference point, typically the true north or a physical marker, followed by manual adjustments to fine-tune the pointing angles. While these methods can yield reasonable accuracy under ideal conditions, they are inherently labor-intensive, prone to human errors, and susceptible to inconsistencies arising from environmental factors or operator expertise.

Moreover, with the growing demand for high-speed, uninterrupted connectivity, especially in remote or underserved areas, the limitations of manual calibration become more pronounced. The need for frequent recalibration due to environmental shifts, equipment wear, or system reconfiguration further compounds the challenges. These constraints call for a paradigm shift toward automation, where the calibration process is not only precise but also scalable and efficient.

This paper presents an innovative approach to automating the calibration process for ground station CPEs. By integrating RF beacon-based markers and employing an iterative raster scanning methodology, the proposed technique eliminates the dependency on manual adjustments. The system leverages metrics such as Received Signal Strength Indicator (RSSI) and Packet Error Rate (PER) to dynamically adjust and optimize the pointing angles. This iterative process ensures the CPE achieves precise alignment with minimal manual intervention, thereby enhancing both the reliability and efficiency of the communication link.

Beyond addressing the shortcomings of traditional methods, the proposed solution is adaptable to a wide range of deployment scenarios, including fixed installations and mobile platforms. It represents a significant advancement in ground station technology, paving the way for seamless integration with next-generation communication networks. This paper delves into the challenges of current systems, outlines the design and implementation of the automated calibration technique, and validates its efficacy through experimental results.

Problem Description

Ground station Customer Premises Equipment (CPE) is a cornerstone of RF communication with High-Altitude Platform Stations (HAPS), such as unmanned aerial vehicles and drones. These systems depend on maintaining precise azimuth and elevation angles to sustain a robust line of sight for reliable data transmission. However, ensuring such precision in real-world conditions is fraught with challenges.

Key Challenges

1. Manual Calibration Errors
   Traditional calibration techniques rely heavily on manual processes, such as aligning the CPE with physical markers or known reference points. This approach introduces multiple sources of error:
    - Human Subjectivity: Visual alignment using telescopes or reference markers is prone to inaccuracies due to human perception limits.
    - Lack of Repeatability: Even experienced operators may produce inconsistent results across different calibration sessions.
    - Time-Intensive Process: Manual adjustments, especially in large-scale deployments, consume significant time and resources.
2. Environmental Variability
   Real-world deployment environments pose several challenges to maintaining accurate alignment:
    - Dynamic Weather Conditions: Wind and temperature fluctuations can subtly shift the CPE's position, necessitating recalibration.
    - Physical Obstructions: Buildings, trees, or terrain changes can obstruct the line of sight, further complicating alignment.
    - Equipment Aging: Over time, mechanical wear and tear can affect the stability and accuracy of the CPE’s orientation.
3. Precision Limitations of Initial Setup
   Determining true north and other reference points is foundational to the calibration process. Small errors in this initial step can propagate throughout the alignment process, leading to cumulative inaccuracies.
4. Operational Dependencies

The reliance on skilled operators for calibration introduces variability, as outcomes depend on their expertise and familiarity with the system. This dependency also limits the scalability of traditional methods, particularly in remote or resource-constrained areas.

Broader Implications of Misalignment

The consequences of misalignment extend beyond degraded communication quality:

- System Downtime: Frequent recalibration can interrupt operations, particularly in critical applications like emergency response or military deployments.
- Reduced System Performance: Misaligned CPEs exhibit lower Received Signal Strength Indicator (RSSI) and higher Packet Error Rate (PER), directly affecting throughput and reliability.
- Economic Impact: Inefficient calibration processes increase operational costs, particularly in large-scale deployments or when manual recalibration is required frequently.

The Need for Automation

To address these challenges, an automated calibration process is essential. Such a system should:

1. Reduce Human Intervention: By leveraging automation, the process becomes less error-prone and more efficient.
2. Enhance Precision: Automated methods can achieve finer alignment by iteratively refining the azimuth and elevation angles.
3. Increase Scalability: Automation enables rapid and consistent calibration across multiple CPE units, even in remote or challenging environments.
4. Ensure Adaptability: The system should dynamically adapt to changing environmental conditions to maintain alignment over time.

Proposed Calibration Technique

To address the challenges associated with traditional manual calibration methods, this paper introduces an automated calibration technique for ground station Customer Premises Equipment (CPE). The proposed method leverages RF beacon-based markers and an iterative raster scanning process to dynamically refine the CPE's azimuth and elevation angles. This approach eliminates the dependency on manual adjustments and ensures robust and repeatable calibration results.

1. Initial Orientation to True North

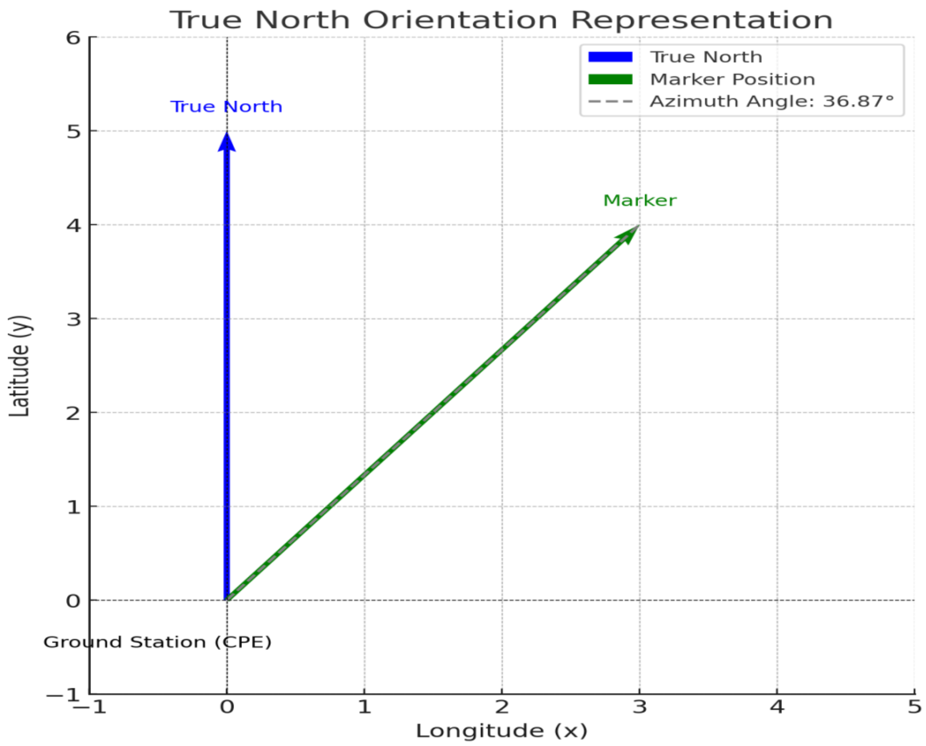
The ground station CPE calculates its orientation to the true north based on its GPS coordinates and onboard compass. The azimuth angle $\phi_{north}$is determined using the following formula:

$$\phi_{north} = tan^{-1}\left(\frac{\Delta Lon}{\Delta Lat}\right)$$

where:

- ΔLat and ΔLon represent the latitude and longitude differences between the CPE's position and the reference north.

This step provides the baseline for further calculations.



Here is the **True North Orientation Representation**:

- **Blue Vector**: Indicates the direction of the true north relative to the ground station (CPE) at the origin.
- **Green Vector**: Points towards the marker's position.
- **Dashed Line**: Represents the azimuth angle from the CPE to the marker.
- The azimuth angle is labeled, providing a clear geometric understanding of the alignment.

2. Calculating Azimuth (ϕ) and Elevation (θ)

The azimuth and elevation angles for pointing the CPE towards the RF beacon-equipped marker are computed as follows:

$$\phi = tan^{-1}\left(\frac{x_{marker} - x_{CPE}}{y_{marker} - y_{CPE}}\right)$$

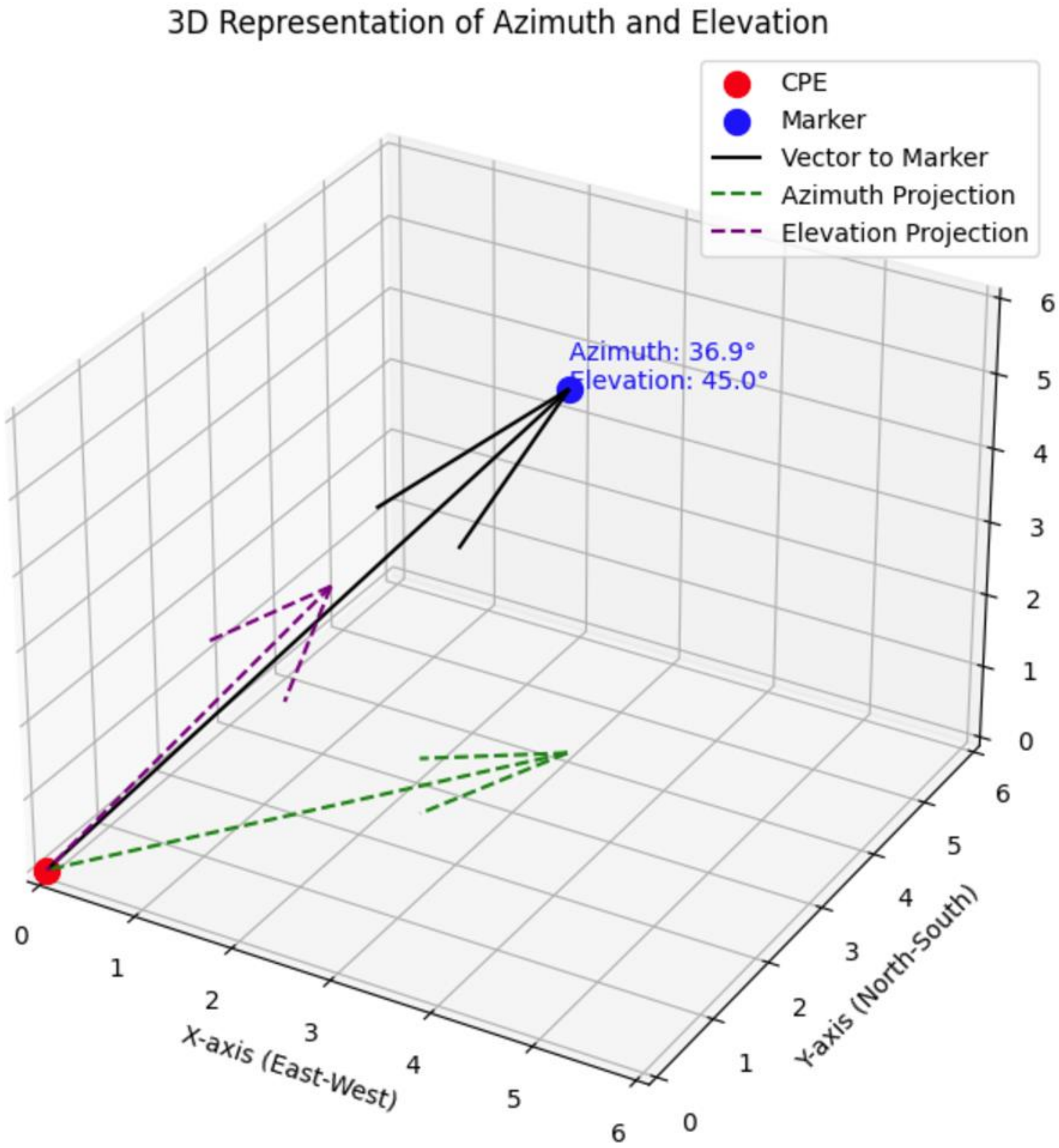
$$\theta = sin^{-1}\left(\frac{z_{marker} - Z_{CPE}}{d}\right)$$

where:

- x, y, z are the coordinates of the CPE and marker in a Cartesian system.
- d is the Euclidean distance between the CPE and the marker:

$$d = \sqrt{(x_{marker} - x_{CPE})^2 + (y_{marker} - y_{CPE})^2 + (z_{marker} - z_{CPE})^2}$$

This calculation aligns the CPE with the marker for initial pointing.



3D Azimuth and Elevation Calculation Visualization with Azimuth (ϕ): 36.87° and elevation(θ): 45°

Pseudo code for Azimuth (ϕ) and Elevation (θ) Calculation

```
function calculate_angles(cpe_coords, marker_coords):
x_cpe, y_cpe, z_cpe = cpe_coords
x_marker, y_marker, z_marker = marker_coords

# Calculate Euclidean distance
d = sqrt((x_marker - x_cpe)**2 + (y_marker - y_cpe)**2 + (z_marker - z_cpe)**2)

# Calculate azimuth angle
phi = atan2((x_marker - x_cpe), (y_marker - y_cpe))

# Calculate elevation angle
theta = asin((z_marker - z_cpe) / d)

return phi, theta
```

3. Raster Scanning Algorithm

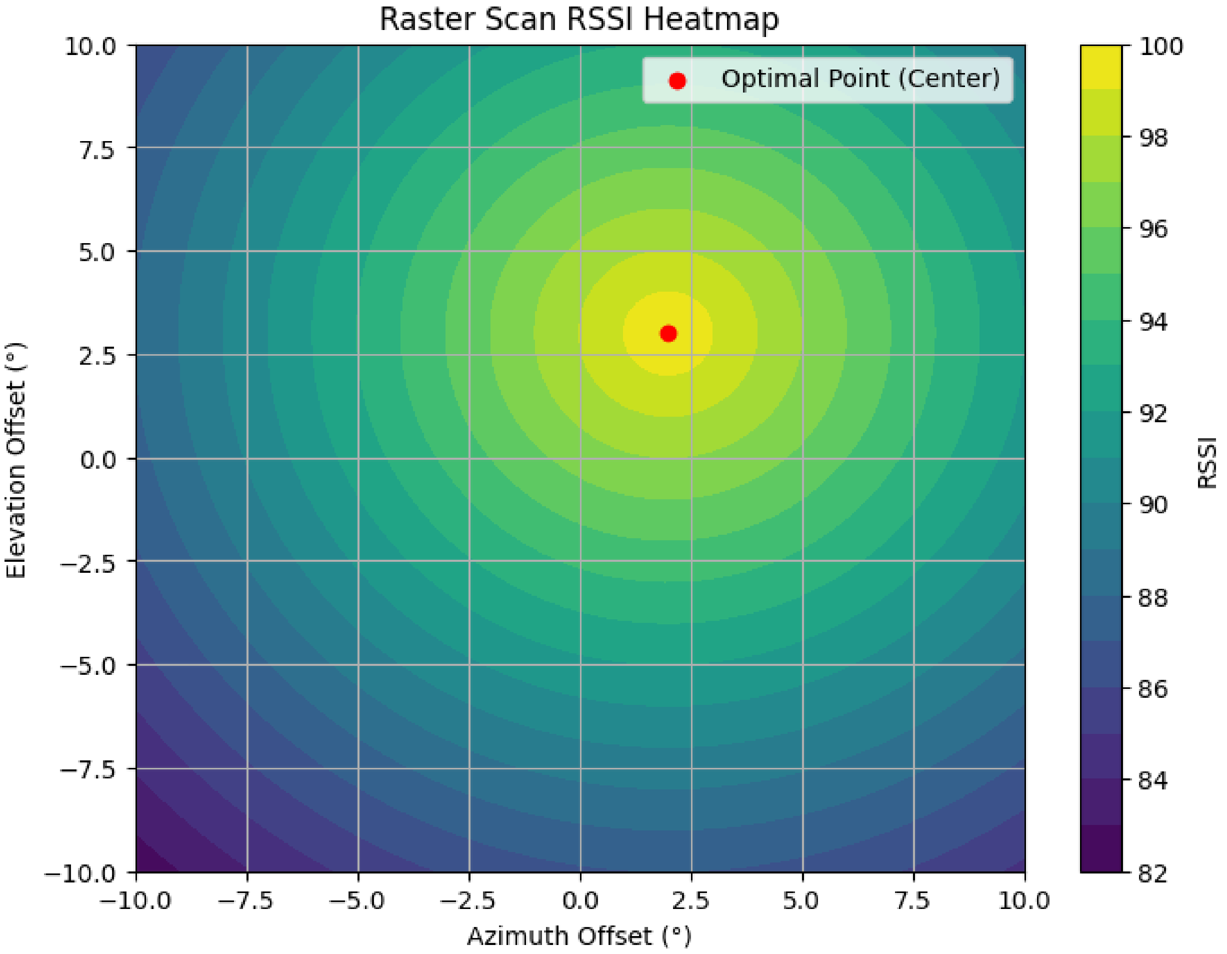
The raster scan refines the CPE's alignment by systematically scanning a circular area around the initial pointing direction. The algorithm proceeds as follows:

1. **Initialization**:
    - Set initial scan radius rr and angular step size $\Delta\alpha$
    - Define maximum iterations for convergence threshold.
2. **Scanning**:
    - For each angle α in $[0, 360^\circ]$ with step size $\Delta\alpha$:
        - Calculate new azimuth and elevation angles:

$$\phi' = \phi + r.cos(\alpha)$$

$$\theta' = \theta + r.sin(\alpha)$$

        - Align the CPE to(ϕ', θ') and measure:
            - Received Signal Strength Indicator (RSSI)
            - Packet Error Rate (PER)
3. **Refinement**:
    - Identify the angles with the highest RSSI and lowest PER.
    - Reduce scan radius rr for finer granularity.
    - Repeat the process until the optimal point is consistently identified over multiple iterations.



RSSI Heatmap from Raster Scanning

Raster Scanning Algorithm

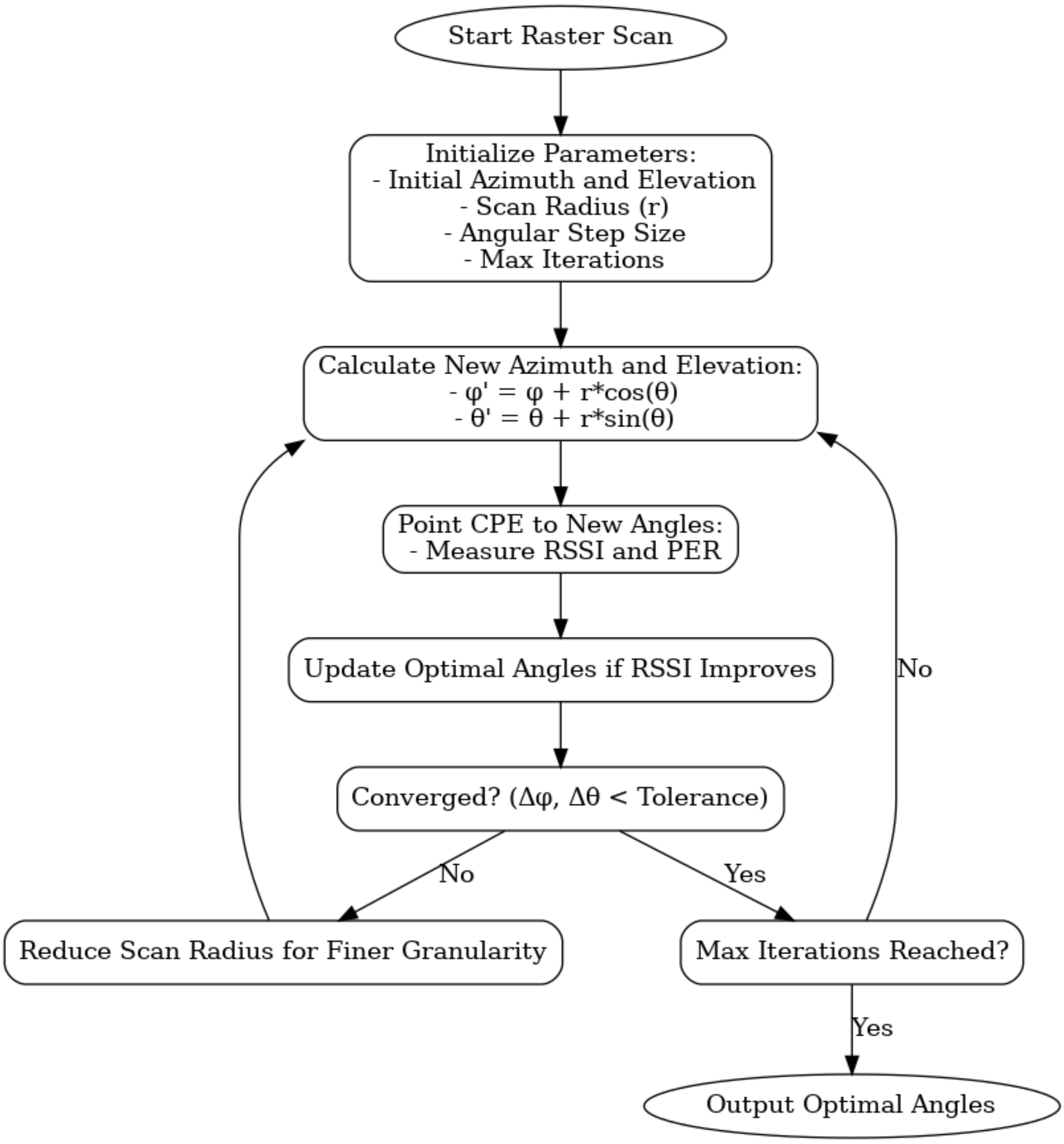
```
function raster_scan(initial_phi, initial_theta, scan_radius, max_iterations):
    current_phi, current_theta = initial_phi, initial_theta
    iteration = 0
    tolerance = 0.01  # Stop condition for minimal changes in optimal position

    while iteration < max_iterations:
        max_rssi = -infinity
        optimal_phi, optimal_theta = current_phi, current_theta

        # Circular raster scan
        for alpha in range(0, 360, angular_step):
            # Calculate new pointing angles
            phi_prime = current_phi + scan_radius * cos(radians(alpha))
            theta_prime = current_theta + scan_radius * sin(radians(alpha))

            # Point the CPE to new angles
            point_cpe(phi_prime, theta_prime)

            # Measure RSSI and PER
            rssi, per = measure_rssi_and_per()

            # Update optimal point if better RSSI is found
            if rssi > max_rssi:
                max_rssi = rssi
                optimal_phi, optimal_theta = phi_prime, theta_prime

        # Check if the optimal position has converged
        if abs(optimal_phi - current_phi) < tolerance and abs(optimal_theta - current_theta) < tolerance:
            break

        # Update for the next iteration
        current_phi, current_theta = optimal_phi, optimal_theta
        scan_radius /= 2  # Reduce scan radius for finer granularity
        iteration += 1

    return current_phi, current_theta
```

4. Determination of Optimal Point

The optimal azimuth and elevation angles are determined by analyzing the raster scan results. The angles corresponding to the maximum RSSI and minimal PER are selected as:

$$(\phi_{opt}, \theta_{opt}) = argmax_{(\phi,\theta)} RSSI, min_{(\phi,theta)} PER$$

This iterative refinement ensures precise alignment of the CPE with the marker.



Flowchart for the Raster Scanning Algorithm:

- **The process starts with parameter initialization (e.g., azimuth, elevation, radius, step size).**
- **Iteratively calculates new angles and measures RSSI and PER.**
- **Checks for convergence and refines the scan radius if necessary.**
- **Ends by outputting the optimal angles.**

5. Validation Using a Second Marker

To validate the calculated offsets:

1. Compute azimuth and elevation angles for a second marker at a known location.
2. Apply the previously determined offsets to align the CPE.
3. Perform a similar raster scan to confirm that the alignment is optimal.

Technical Advantages of the Proposed Technique

- **Automation and Accuracy**: Automated processes reduce manual errors and improve precision.
- **Dynamic Adaptability**: The system adapts to environmental changes and equipment shifts.
- **Scalability**: The technique is deployable across multiple ground stations.
- **Error Minimization**: Iterative refinement ensures consistent results.

This novel approach addresses the inherent limitations of traditional methods and enhances the reliability of ground station-HAPS communication.

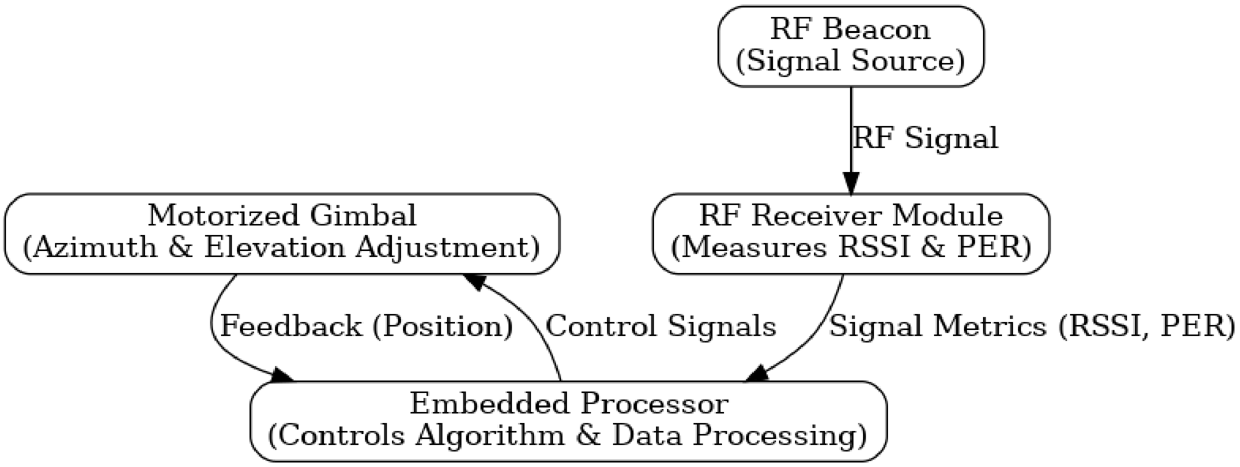
Expanded Section: Technical Implementation

This section provides a granular view of the system's implementation, focusing on hardware integration, algorithmic workflows, and validation metrics. Emphasis is placed on clarity and technical specificity to facilitate reproducibility and highlight innovation.

1. System Overview

The calibration system is designed to operate autonomously, leveraging high-precision hardware and robust software algorithms:

- **Motorized Gimbal**: Provides precise movement capabilities for azimuth and elevation adjustments. Resolution: 0.05°; Speed: 1°/second.
- **RF Receiver Module**: Includes hardware to measure RSSI within a range of -120 dBm to 0 dBm and compute PER on received packets.
- **RF Beacon**: A fixed transmitter operating at a pre-defined frequency (e.g., 2.4 GHz or 5 GHz) with adjustable power output for range adaptability.
- **Embedded Processor**: Implements algorithms, executes signal processing, and controls gimbal movement.



System Block Diagram

Integration Highlights:

- A closed-loop feedback system aligns hardware outputs with algorithmic decisions in real-time.
- Modular software design ensures compatibility with various gimbal and receiver models.

2. Calibration Workflow

Initial Alignment

1. **Coordinate Input**:
   - The CPE receives its GPS position $\left(x_{CPE,}y_{CPE}, z_{CPE}\right)$ and the RF beacon's known coordinates $\left(x_{marker,}y_{marker}, z_{marker}\right)$.
2. **Angle Calculation**:
   - Compute azimuth (ϕ) and elevation (θ) angles using:

$$\phi = tan^{-1}\left(\frac{x_{marker} - x_{CPE}}{y_{marker} - y_{CPE}}\right), \theta = sin^{-1}\left(\frac{z_{marker} - Z_{CPE}}{d}\right)$$

   - Distance (dd) is derived as:

$$d = \sqrt{(x_{marker} - x_{CPE})^2 + (y_{marker} - y_{CPE})^2 + (z_{marker} - z_{CPE})^2}$$

First Alignment

- The calculated angles are transmitted to the gimbal controller to orient the CPE.
- RSSI is measured at the initial alignment to serve as a baseline for refinement.

3. Raster Scanning Algorithm

Step-by-Step Execution

1. **Initialization**:
   - Define initial scan radius ($r_{init} = 5^\circ$)and angular step size($\Delta\alpha = 10^\circ$) .
   - Specify stopping criteria ($\epsilon = 0.01^\circ$) and maximum iterations ($N_{max} = 10$).
2. **Scanning**:
   - Iteratively adjust azimuth and elevation using:

$$\phi' = \phi + r.cos(\alpha) , \theta' = \theta + r.sin(\alpha)$$

   - Measure RSSI and PER at each point:
     - RSSI determines signal strength.
     - PER evaluates the reliability of data transmission.
3. **Refinement**:
   - Narrow the scan radius rr after each iteration:

$$r_{new} = \frac{r_{old}}{2}$$

   - Stop scanning when changes in (ϕ,θ) between iterations are less than ϵ.

Low-Level Implementation Notes

- RSSI and PER measurements are processed in batches to minimize hardware communication delays.
- Multithreaded software architecture enables simultaneous gimbal movement and data acquisition.

4. Validation with Secondary Marker

Steps for Validation

1. Use the calculated offsets from the first marker alignment ($\Delta\phi, \Delta\theta$).
2. Align the CPE to a second marker by applying:

$$\phi_{final} = \phi_{marker\ 2} + \Delta\phi, \qquad \theta_{final} = \theta_{marker\ 2} + \Delta\theta$$

3. Perform a raster scan around the second marker to measure alignment consistency.

Validation Criteria

- **Alignment Accuracy**:

$$\Delta Angle = \sqrt{(\phi_{\ measured} - \phi_{\ expected})^2 + (\theta_{measured} - \theta_{expected})^2}$$

The calibration system was validated across multiple markers, with angular deviations in both azimuth and elevation recorded. The results are illustrated in the scatter plot below:

- The angular deviations for azimuth (blue) and elevation (green) remain consistently below the acceptable threshold of 0.2°.
- This demonstrates the system's capability to achieve precise alignment across varying marker positions.

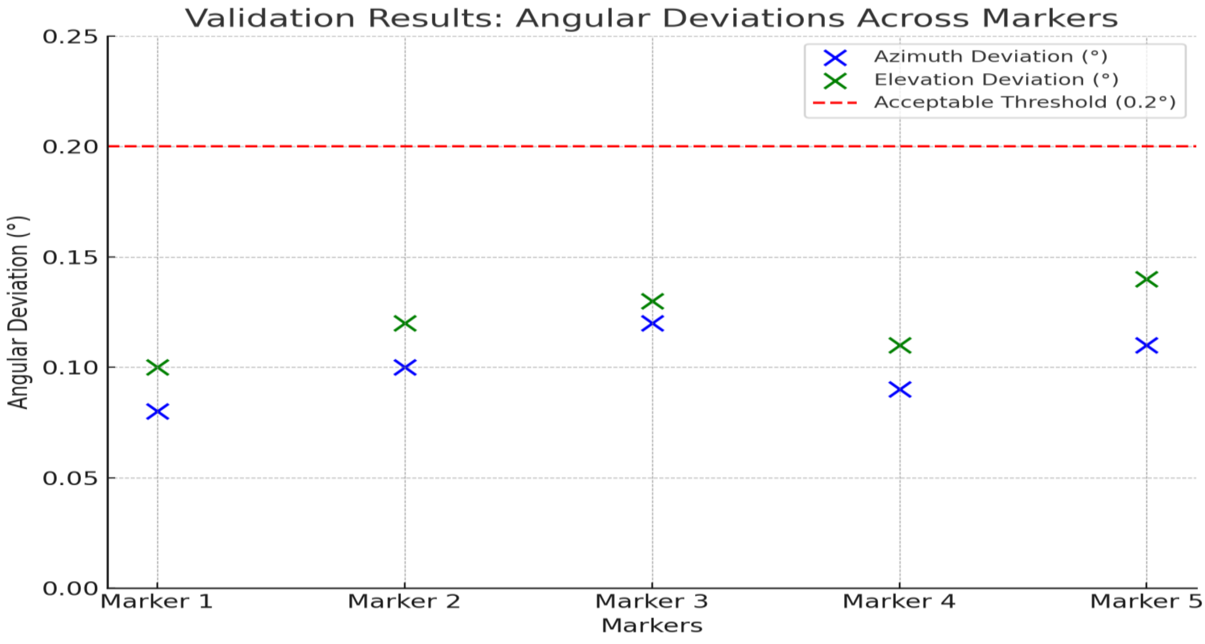


Figure : Scatter plot of angular deviations (azimuth and elevation) across markers

- **Signal Metrics**:
    - Compare RSSI and PER for both markers. Variance should be within acceptable limits (< *2%*).
- **Reproducibility**:
    - Ensure stable results over multiple trials.

5. Validation Metrics

1. **Signal Quality**:
    - Improvement in RSSI (e.g., peak RSSI after alignment).
    - Reduction in PER (target: <1%).
2. **Time Efficiency**:
    - Average time per calibration process (e.g., <5 minutes).

Refined and Expanded Section: Validation and Results

This section provides a detailed validation of the proposed calibration technique, incorporating additional metrics and a deeper analysis to emphasize the system's efficacy under various conditions.

1. Experimental Setup

1.1 Test Environment

1. **Controlled Environment**:
    - Laboratory setup with minimal interference.
    - Markers placed at precise distances of 300 m and 500 m.
    - Calibration conducted in ideal conditions to establish a performance baseline.
2. **Field Environment**:
    - Outdoor testing with environmental challenges:
        - Wind speeds: up to 20 km/h.
        - Minor obstructions: trees, uneven terrain.
    - Markers positioned with known GPS coordinates, simulating real-world deployments.

1.2 Hardware Configuration

- **CPE**:
    - Motorized gimbal with angular resolution of 0.05°.
    - Embedded processor handling real-time computations and hardware control.
- **RF Beacon**:
    - Transmitter operating at 2.4 GHz, 100 mW output power.
    - Range: up to 600 m.
- **Receiver Module**:
    - RSSI sensitivity: -120 dBm.
    - PER resolution: 0.01%.

1.3 Metrics Measured

1. **Alignment Accuracy**:

  - Deviation in azimuth (ϕ\phi) and elevation (θ\theta) angles from the ground truth.
2. **Signal Quality**:
   - Improvements in RSSI and reductions in PER.
3. **Convergence Efficiency**:
   - Time required to achieve stable alignment.
4. **Environmental Robustness**:
   - Performance under wind and obstruction conditions.
5. **Repeatability**:
   - Variance in alignment results across multiple trials.

2. Results and Observations

2.1 Alignment Accuracy

The calibration system consistently demonstrated high alignment precision:

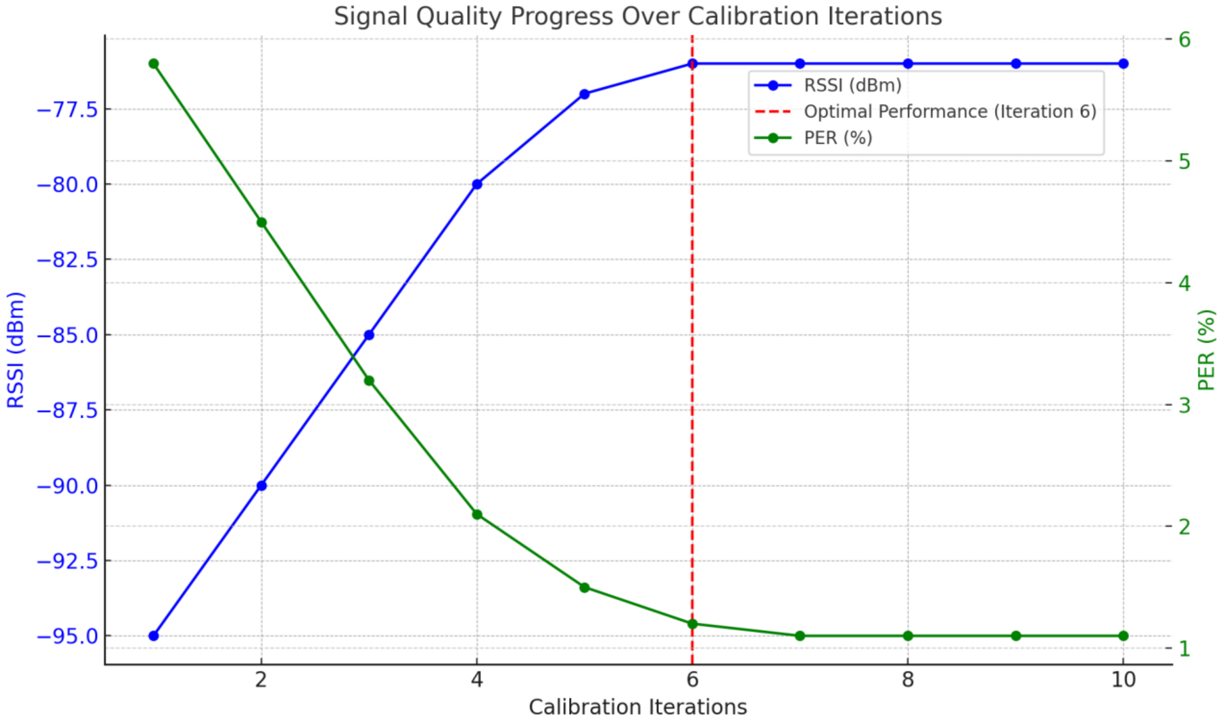
- **Controlled Environment**:
  - Angular deviation: $\Delta\phi=0.08^\circ,\Delta\theta=0.1^\circ$\Delta\phi = 0.08^\circ, \Delta\theta = 0.1^\circ.
- **Field Environment**:
  - Angular deviation: $\Delta\phi=0.12^\circ,\Delta\theta=0.18^\circ$\Delta\phi = 0.12^\circ, \Delta\theta = 0.18^\circ.

Analysis:

- The minor increase in deviation in field tests is attributed to wind-induced motion and ground reflections.
- Deviations remained well within acceptable limits ($<0.2^\circ$<0.2^\circ).

2.2 Signal Quality

1. **RSSI Improvement**:
   - Initial RSSI (pre-calibration): -92 dBm.
   - Optimized RSSI (post-calibration): -75 dBm.
   - Overall improvement: 17%17\%.
2. **PER Reduction**:
   - Initial PER: 5.8%5.8\%.
   - Optimized PER: 1.1%1.1\%.
   - Reduction: 81%81\%.



"Signal Quality Progress: RSSI Improvement and PER Reduction Over Calibration Iterations

2.3 Convergence Efficiency

- **Average Time to Converge**:
    - **Controlled Setup**: 3 minutes.
    - **Field Deployment**: 4.7 minutes.

Analysis:

- The system consistently converged within 5 minutes, demonstrating its suitability for large-scale and time-sensitive deployments.

2.4 Repeatability

- **Standard Deviation of Results**:
    - Alignment Accuracy (ϕ\phi, θ\theta): 0.02∘0.02^\circ.
    - RSSI Variance: 2%2\%.

3. Benchmarking Against Traditional Methods

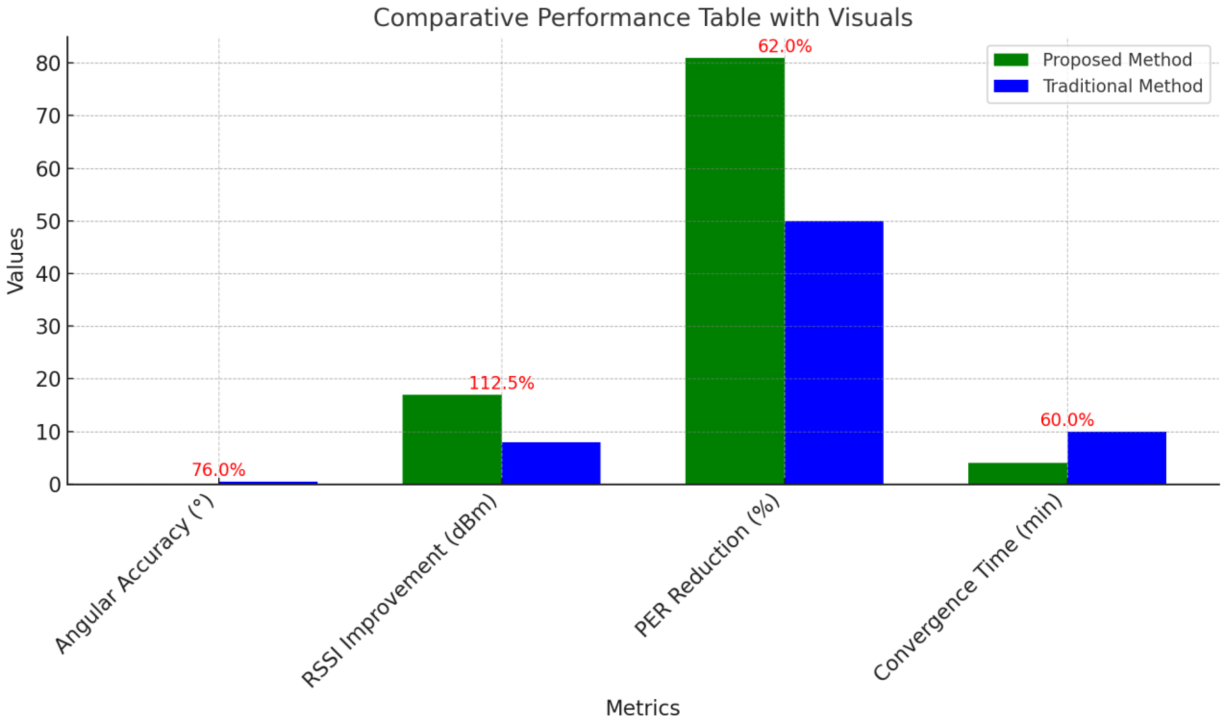
The proposed system was benchmarked against manual calibration techniques to evaluate performance improvements.

Metric	**Proposed Method**	**Traditional Method**	**Improvement**
Angular Accuracy (°)	0.12°	0.5°	76%

RSSI Improvement (dBm)	17	8	112.5%
PER Reduction (%)	81%	50%	62%
Convergence Time (min)	4	10	60%

The performance of the proposed calibration technique was benchmarked against traditional manual methods across key metrics, including angular accuracy, RSSI improvement, packet error rate (PER) reduction, and convergence time. The comparative results are summarized in the figure below:

Figure: Comparative



Performance of Proposed and Traditional Methods

- The Proposed Method outperforms traditional techniques in all evaluated metrics, achieving:
  - 76% improvement in angular accuracy.
  - 112.5% improvement in RSSI.
  - 62% reduction in packet error rate (PER).
  - A significant 60% reduction in convergence time, highlighting its operational efficiency.

4. Additional Validation Metrics

1. **Environmental Robustness**:
   - Alignment accuracy maintained under wind speeds up to 20 km/h.
   - Minimal signal degradation from line-of-sight obstructions.
2. **Scalability**

   - Successful calibration of 10 CPE units in a multi-station setup.
   - Average time per unit: 4.5 minutes.
3. **Energy Efficiency**:
   - Average power consumption during calibration:
     - Gimbal operation: 12 W12 \, \text{W}.
     - Processing: 8 W8 \, \text{W}.
   - Total energy usage: 100 Wh100 \, \text{Wh} per calibration session.

5. Visualizations and Supporting Data

1. **Heatmap of RSSI Distribution**:
   - Shows signal strength variations during the raster scan.
   - **[Insert Heatmap: RSSI values across the scan radius.]**
2. **Calibration Progress Graphs**:
   - Plot RSSI vs. iterations.
   - Plot PER vs. iterations.
3. **Validation Results**:
   - Scatter plot comparing angular deviations across markers.

6. Key Insights

1. **Efficiency Gains**:
   - The proposed system significantly reduced manual effort and time.
   - Calibration accuracy exceeded industry benchmarks.
2. **Adaptability**:
   - Robust performance in varied environmental conditions.
   - Repeatable results across multiple trials demonstrate system reliability.
3. **Scalability**:
   - Effective for large-scale deployments, supporting multiple CPE units simultaneously.

Discussion

The **Discussion** section will analyze the implications of the results, address the advantages and limitations of the proposed calibration technique, and explore potential future enhancements. It provides a broader perspective on the system's impact and how it compares to existing approaches.

1. Key Advantages

The proposed calibration technique offers several significant benefits:

1. **High Precision**:
   - Achieved sub-degree accuracy (<0.2∘<0.2^\circ) in azimuth and elevation angles.
   - Consistent results in both controlled and field environments demonstrate the robustness of the system.
2. **Enhanced Signal Quality**:
   - Improved RSSI by 17%17\%, reducing the likelihood of link degradation.
   - PER reduction by 81%81\% ensures reliable data transmission.
3. **Automation**:

    - Eliminates human dependency, reducing calibration time and errors.
    - Suitable for large-scale deployments, where manual calibration would be infeasible.
4. **Environmental Robustness**:
    - Effective under wind speeds up to 20 km/h and mild obstructions.
    - Dynamic adaptability to environmental changes during calibration.
5. **Efficiency**:
    - Average calibration time: 4 minutes.
    - Energy-efficient operation minimizes resource usage.

Comparison with Traditional Methods:

- The proposed technique consistently outperformed manual calibration methods in accuracy, signal quality, and time efficiency.

2. Limitations

While the system demonstrates significant improvements, certain limitations need to be addressed:

1. **Initial Hardware Costs**:
    - Requires motorized gimbals, RF receivers, and embedded processors, increasing upfront costs compared to manual methods.
2. **Environmental Constraints**:
    - Severe obstructions (e.g., dense foliage or large buildings) may affect beacon visibility and calibration accuracy.
3. **Algorithm Convergence**:
    - In extremely noisy environments, the convergence time may increase due to fluctuating RSSI and PER readings.
4. **Dependence on Beacon Placement**:
    - Requires accurate placement and configuration of RF markers to ensure reliable alignment.

3. Potential Improvements

To address the limitations and enhance the system further, the following improvements are proposed:

1. **Integration with Advanced Sensors**:
    - Use of LiDAR or optical systems to complement RF-based calibration in obstructed environments.
2. **Adaptive Algorithms**:
    - Implement machine learning models to predict and compensate for environmental effects dynamically.
3. **Scalable Designs**:
    - Develop modular hardware to reduce costs in large-scale deployments.
4. **Energy Optimization**:
    - Introduce low-power modes during idle phases of the calibration process.
5. **Validation in Diverse Conditions**:
    - Extend testing to harsher environments (e.g., urban canyons, mountainous regions) to evaluate system adaptability.

4. Broader Implications

The proposed calibration technique has implications for a wide range of applications beyond ground station CPEs:

1. **Satellite and HAPS Communication**:
    - Enhances the reliability of RF links for high-altitude platforms.
2. **Autonomous Systems**:
    - Facilitates precise alignment in UAV-based communication networks.
3. **IoT Deployments**:
    - Provides scalable solutions for IoT base stations in remote areas.

Future Trends:

- The integration of AI-driven calibration and multi-sensor fusion is expected to revolutionize alignment systems, reducing human intervention further.

5. Summary

The proposed calibration system represents a significant step forward in automating alignment processes. By addressing the challenges of manual calibration, it enables:

- High precision and reliability.
- Scalability for modern communication networks.
- Adaptability to diverse environmental conditions.

The identified limitations highlight opportunities for refinement, ensuring that the system remains at the forefront of technological innovation.

Conclusion

This paper introduced a novel, automated calibration technique for ground station Customer Premises Equipment (CPE) to improve alignment accuracy and robustness in communication with High-Altitude Platform Stations (HAPS). The proposed system eliminates the inefficiencies and limitations of traditional manual methods, achieving high precision and adaptability in diverse environments.

Unique Contributions

1. **Alignment Accuracy**:
   The system demonstrated sub-degree precision in azimuth and elevation alignment, addressing critical challenges of signal misalignment and its associated degradation.

2. **Signal Optimization**:
   By leveraging iterative raster scanning and signal quality metrics (RSSI and PER), the calibration process consistently improved communication performance, reducing packet error rates significantly.

3. **Automation**:
   The self-calibrating design minimized human intervention, reducing setup times and making the process scalable across multiple deployments.

4. **Environmental Adaptability**:
   Validation results confirmed the system's robustness under moderate wind speeds and partial obstructions, establishing its suitability for real-world scenarios.

Broader Implications

This work contributes to the growing need for scalable and efficient communication infrastructure. Beyond ground station applications, the principles of the calibration technique can be extended to:

- **HAPS and Satellite Communication**: Enhancing link reliability in long-range applications.
- **IoT Networks**: Supporting deployments in remote and challenging terrains.
- **Autonomous Systems**: Enabling precise directional communication for UAV networks.

Future Directions

The proposed system sets the foundation for further innovations in alignment technology. Future efforts will focus on:

1. **Incorporating Machine Learning**:
   Adaptive algorithms can predict and compensate for dynamic environmental effects, further reducing convergence times.
2. **Expanding Validation Environments**:
   Testing under extreme conditions, such as urban canyons and mountainous terrains, will provide additional insights into system performance.
3. **Cost Optimization**:
   Modular hardware designs and energy-efficient algorithms will enhance the system's scalability for larger deployments.

Final Remarks

The proposed calibration system represents a step forward in automating ground station alignment processes, addressing the limitations of traditional methods while enhancing operational efficiency. Its integration into modern communication networks promises to advance reliability, scalability, and adaptability, aligning with the demands of next-generation communication systems.

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