

Design and Validation of a Low-Cost 5G UAV-SDR Narrowband Channel Sounding System

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Abstract—This paper presents the design and experimental validation of a low-cost UAV-based narrowband channel sounding system using a Software-Defined Radio (SDR). The platform integrates RF signal acquisition with Global Navigation Satellite System (GNSS) positioning and Inertial Measurement Unit (IMU) data, enabling synchronized Received Signal Strength Indicator (RSSI) measurements and antenna orientation estimation at 3.5 GHz. Experimental results validate the proposed multi-sensor architecture and demonstrate its suitability for orientation-dependent air-to-ground channel characterization. Moreover, the measured RSSI exhibits good agreement with the Free-Space Path Loss and Two-Ray propagation models, confirming the reliability and flexibility of the proposed platform for air-to-ground propagation measurements.

Keywords—Channel sounding, UAV, SDR, RSSI, 5G.

I. INTRODUCTION

The widespread deployment of fifth-generation (5G) networks in the sub-6 GHz band poses significant challenges for network planning, particularly in Air-to-Ground (A2G) communications [1]. Wireless communications involving Unmanned Aerial Vehicles (UAVs) are strongly influenced by multipath effects, ground reflections, and variations in link geometry [2]. Consequently, the reliability of these communications depends on channel models that consider the particularities of altitude and link geometry dynamics [3].

Although classic propagation models, such as Free-Space Path Loss (FSPL) and the Two-Ray (2-Ray) model [4], are widely adopted as reference approaches for A2G links, previous studies indicate that these models may not accurately capture the effects observed in real-world environments, particularly in scenarios with mobility, multipath, and geometric variations [3]. Furthermore, the acquisition of accurate empirical data still often relies on specialized RF instrumentation and robust synchronization mechanisms between RF measurements and UAV telemetry.

In this context, Software-Defined Radio (SDR) emerged as a promising alternative for channel sounding and wireless

communications due to its flexibility, reconfigurability, and cost-effectiveness [5]. The integration of SDRs into small aerial platforms allows access to In-phase and Quadrature (IQ) samples and the dynamic adjustment of communication parameters [6], both of which are essential for accurate channel characterization and modeling [7]. Nevertheless, ensuring measurement reliability requires the integration of Inertial Measurement Unit (IMU) and Global Navigation Satellite System (GNSS) data, enabling the precise correlation between RF measurements and the UAV's position and orientation.

This work proposes a narrowband channel sounding system operating at 3.5 GHz, based on a LimeSDR Mini embedded in a UAV. The main distinguishing feature of the proposed platform is the synchronized integration between RF measurements, GNSS positioning with Real-Time Kinematic (RTK), and the spatial orientation of the receiving antenna (*yaw*, *pitch*, and *roll*), enabling analyses that account for the angular geometry of the communication link [8]. The main contributions of this work are summarized as follows:

- 1) Development of a portable architecture integrating SDR, Raspberry Pi, and low-cost sensors embedded in a UAV;
- 2) Proposal of a multi-sensor synchronization methodology for channel characterization;
- 3) Integration of antenna angular characterization, GNSS RTK positioning, and orientation via an IMU, allowing a consistent and accurate use of directional antennas;
- 4) Experimental validation of the proposed system through a multi-sensor integration test and comparisons with the FSPL and 2-Ray propagation models.

The remainder of this paper is organized as follows. Section II describes the proposed system, including the receiver architecture, GNSS positioning with RTK, and antenna characterization. Section III presents the measurement campaign and relevant parameters for the experimental tests. Results are then discussed in Section IV. Finally, Section V presents the conclusions and perspectives for future work.

II. SYSTEM DESCRIPTION

This section presents the proposed narrowband channel sounding system and its main components. First, the receiver architecture embedded in the UAV is described, including the SDR, GNSS RTK module, IMU, and data synchronization strategy. Then, the operation of the RTK positioning system and the antenna characterization procedure are discussed, highlighting how these elements contribute to the analysis and interpretation of the measured propagation data.

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A. Receiver architecture

The choice of components for the sounding was carefully evaluated to allow the system to be embedded in small UAVs. Thus, the selection and configuration of the hardware used were strongly conditioned by the need to minimize the final weight of the prototype while maintaining technical characteristics suitable for scientific research applications.

Accordingly, the proposed receiver system includes:

- LimeSDR Mini v2.4 SDR module for RF acquisition;
- Raspberry Pi 5 for peripheral orchestration, processing, and data storage;
- Waveshare LC29H Dual-band GNSS module with RTK support for precise georeferencing of samples;
- Adafruit BNO055 IMU module for recording the spatial orientation of the UAV;
- ZTE MF920U 4G Modem to provide internet access during flight;
- 4.66 dBi patch antenna at 3.5 GHz;
- Power Bank i2GO 5000 mAh to power the system.

Fig. 1(a) presents a schematic diagram of the receiver system, while Fig. 1(b) shows the physical implementation of the integrated platform, whose total weight was approximately 442 grams. A 4-mm acrylic sheet was used as a structural base, along with screws, velcro, and double-sided adhesive tape for securing the modules safely and with low weight. The power bank used proved sufficient to power the system for more than

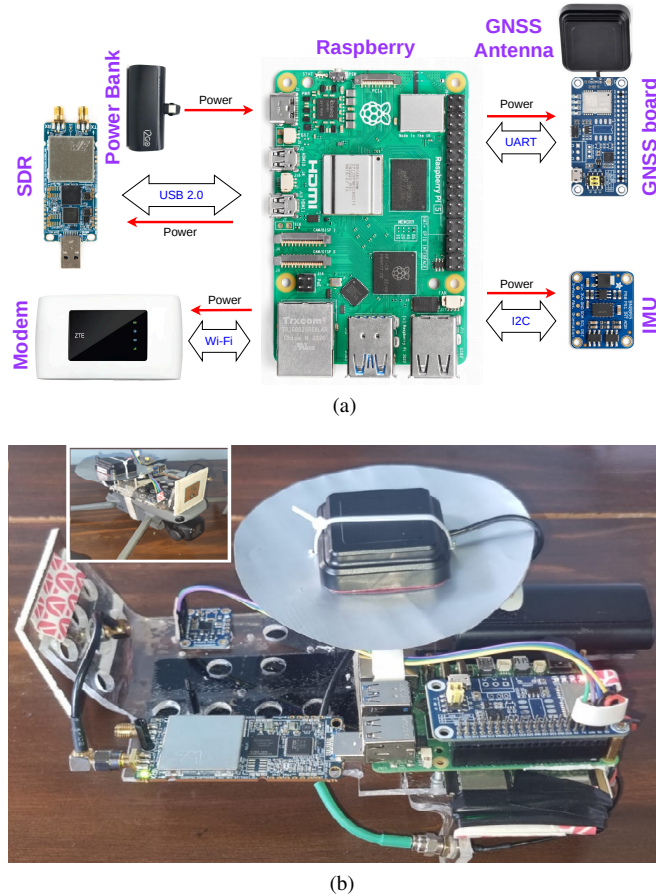


Fig. 1. The receiver system, showing (a) a schematic diagram with a summary of the communication protocols between peripherals and the Raspberry Pi, and (b) a picture of the platform mounted on the acrylic base.

120 minutes, meaning the duration of the experiments was limited mainly by the flight autonomy of the UAV.

1) *LimeSDR*: The SDR is connected to the Raspberry Pi through a USB 2.0 interface, allowing continuous acquisition of complex IQ samples in baseband. Although the module supports USB 3.0 operation, the USB 2.0 interface was chosen due to the reduction of electromagnetic interference observed experimentally on the embedded GNSS module. During preliminary tests, it was found that USB 3.0 operation significantly degraded the quality of GNSS positioning, even with attempts to shield its coaxial cable, possibly due to electromagnetic interference generated by high-speed USB operation, as previously reported in similar contexts [9]. However, for the configurations used, the 2.0 port is sufficient.

RF acquisition is performed through a GNU Radio flowchart executed on the Raspberry Pi. The IQ samples received by the LimeSDR are converted to the frequency domain using FFT, and the power spectral density is subsequently calculated. The Received Signal Strength Indicator (RSSI) is estimated from the spectral peak in a narrow window centered on the Continuous-Wave (CW) carrier frequency. A preliminary calibration step of the LimeSDR was performed using a signal generator, a spectrum analyzer, a power divider, cables, and connectors. By simultaneously injecting the same signal into both receivers (the spectrum analyzer and the SDR) through the power divider, it was possible to define gain and offset parameters to compensate for the difference between the power measured by the spectrum analyzer and that measured by the LimeSDR. Due to the inherent flexibility of SDRs, other forms of acquisition are also under study for future work, including IQ sample capture for channel estimation, as discussed in [7].

2) *GNSS*: The LC29H GNSS module is connected to the Raspberry Pi via a Universal Asynchronous Receiver-Transmitter (UART) serial interface, which records positioning data with a 1 Hz update rate. The receiver provides messages compliant with the National Marine Electronics Association (NMEA) 0183 standard, containing latitude, longitude, altitude, RTK solution quality, and the number of tracked satellites, in addition to saving raw GNSS observation data. RTK corrections are received via the *Networked Transport of RTCM via Internet Protocol* (NTRIP) using a Wi-Fi connection with the embedded 4G modem. Additionally, a second LC29H module in the Base version is installed at the transmitter antenna position to continuously record GNSS observations at a fixed position. A brief presentation of the operation of GNSS RTK is shown in Section II-B.

3) *IMU*: The BNO055 module is connected to the Raspberry Pi via the I²C bus and operated in Nine Degrees of Freedom (NDOF) mode, performing embedded sensor fusion. The system continuously records the UAV orientation angles (*yaw*, *pitch*, and *roll*) and calibration levels. *Yaw* indicates the direction relative to magnetic North, while *pitch* and *roll* represent elevation and lateral inclinations, respectively. These angles are used to estimate the effective gain of the UAV antenna according to its orientation relative to the transmitter.

Due to the sensitivity of the BNO055 magnetometer to changes in the surrounding magnetic field, calibration was performed before each experiment [10]. For validation, the

UAV was manually oriented at 0° , 90° , 180° , and 270° . Fig. 2 shows an example of the validation process where the yaw follows the applied rotation, while pitch indicates a small inclination and roll remains close to 0° due to the geometry of the UAV and the mounting of the module on the acrylic base.

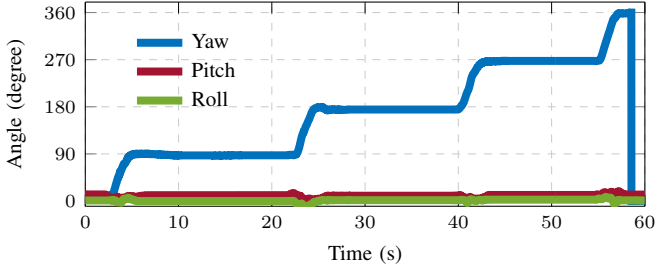


Fig. 2. Example of validation of the IMU calibration before the experiments.

4) *Data Synchronization*: Data from the different modules are recorded in three independent CSV files: RF spectral data, IMU orientation data, and GNSS/RTK data. Each subsystem records independent *timestamps* with millisecond resolution, allowing for temporal alignment during post-processing.

The different modules operate at different update rates. The IMU module performs acquisition at a frequency of approximately 80 Hz, RF spectral data are recorded at approximately 100 Hz, while the GNSS RTK module typically provides updates at 1 Hz. For data synchronization, it was decided to use the IMU records as the primary temporal reference (*master timeline*) due to the need to correctly associate the UAV's orientation with the spectral samples acquired by the SDR. GNSS data were temporally aligned through linear interpolation of geographic coordinates and altitude, while RF spectral data were associated with IMU samples using a nearest neighbor temporal strategy (*nearest neighbor*). The reduced update rate of the GNSS module can be partially compensated through temporal interpolation associated with proper planning of the measurement campaign. In particular, trajectories with approximately constant speeds or segmented acquisitions at predefined positions contribute to reducing spatial inconsistencies between synchronized samples.

B. GNSS Positioning with RTK

Conventional GNSS positioning presents errors on the order of meters due to atmospheric effects and satellite inaccuracies [11], which can compromise the correlation between propagation data and link geometry. To mitigate this problem, the RTK technique was used, which allows for centimeter precision through differential carrier phase processing [12].

In this work, the GNSS receiver operates in *rover* mode, receiving corrections via NTRIP from the infrastructure of the Brazilian Institute of Geography and Statistics (IBGE) through a 4G connection. An IBGE's base station, located at Fluminense Federal University (UFF), was used due to its proximity to the experimental area.

In scenarios without connectivity, the system operates in a hybrid mode: a GNSS module at the transmitter position acts as a base, while the embedded rover records its observations. Subsequently, post-processed kinematics (PPK) is applied to reconstruct the trajectory with centimeter precision

[12]. This approach ensures operational robustness in different environments. The LC29H base module can be used to enable RTK mode without IBGE service. However, this approach would require a dedicated link between the base and the rover, introducing unnecessary complexity.

An example of the RTK correction effect can be observed in Fig. 3. The green samples indicate a fixed RTK solution, associated with centimeter-level precision. Float RTK samples represent an intermediate solution, still of good quality, but without full ambiguity resolution. In standalone mode, shown in red, no differential corrections are applied, possibly due to loss of 4G connectivity, and the position is estimated only from the receiver's own observations. During the flight, the UAV altitude was intended to remain approximately constant. In particular, between 1000 and 2000 m of horizontal distance, the UAV was maintained at an altitude close to 24 m. Within this range, several standalone solutions occurred, and the estimated altitude presents significant drift relative to the expected value, introducing errors that may compromise data analysis depending on the precision required by the experiment. In this case, the PPK solution (black dots) was used to reconstruct the UAV trajectory with centimeter-level precision.

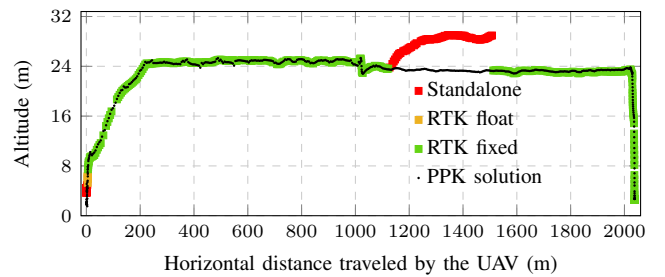


Fig. 3. Effect of correction data link loss on UAV height estimation.

C. Antenna Characterization

Identical patch antennas were used at both the transmitter and receiver, operating in the 3.5 GHz band. These antennas were designed and manufactured at the UFF laboratory, and their gains were experimentally measured at approximately 4.66 dBi at 3.5 GHz. Additionally, the losses of the coaxial cables used in the transmitter and receiver were also characterized for subsequent power calculations in theoretical models.

To evaluate the angular behavior of the antennas, a characterization process of the radiation pattern in two dimensions (2D) was carried out. For this, an experimental structure equipped with two stepper motors was used, allowing for controlled positioning of the antenna under test in the azimuth and elevation axes. No anechoic chamber was available for the measurement, so an open area was selected to mitigate unwanted reflections.

During the procedure, the received power was recorded for different angular combinations, allowing the acquisition of the antenna's relative radiation pattern shown in Fig. 4. The angular characterization of the antennas, associated with orientation information provided by the IMU and the precise geometry of the link obtained through GNSS RTK, provides additional parameters for the analysis and interpretation of the spectral data measured during the experiments.

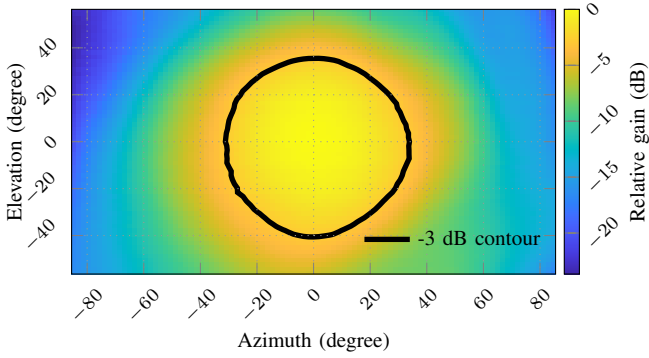


Fig. 4. Measured 2D radiation pattern of the patch antenna used in the transmitter and receiver.

III. MEASUREMENT CAMPAIGN

This section describes the measurement campaign carried out to validate the proposed channel sounding platform and the experimental configurations adopted during the tests. Two types of tests were performed to validate the receiver as a whole. The first test aimed to evaluate the integration of antenna characterization, IMU, and GNSS positioning. The second one consisted of comparing the behavior of the measured RSSI with consolidated theoretical models. In summary, in both measurement campaigns, the system operated with a 3.5 GHz CW signal and a transmitter output power of -14.31 dBm. Both the transmitter and receiver employed patch antennas with 4.66 dBi measured gain, while the total cable and connector loss was approximately 4.5 dB. The LimeSDR gain was set to 10 dB, and an additional empirically determined 8 dB offset was applied to compensate for internal losses and scaling effects introduced by FFT-based RSSI estimation. The measured noise floor within the analyzed spectral window was approximately -90 dBm.

A. Multi-Sensor Data Integration Test

This test aimed to evaluate whether the integration among IMU, antenna characterization, and precise positioning via GNSS allows for refining the obtained spectral data. The experiment was conducted in a flat area, and the transmitter and receiver were positioned on pedestals at 1.3 m from the ground, with a separation of 10.3 m and boresights aligned. The position, height, and orientation of the transmitter antenna were recorded for post-processing. The receiver pedestal allowed rotation only in yaw, keeping the antenna level. Reference angles of 0° (boresight), $+45^\circ$, and -45° were defined and marked on the pedestal for easier visualization and handling, as shown in Fig. 5.

During acquisition, the receiving platform was manually rotated between these angles, with brief pauses at each position. From the perspective of the transmitting antenna, the receiver always remained aligned with its boresight; therefore, it is expected that the calculation of the estimated relative gain in post-processing results in a gain close to 0 dB over time. The transmitter antenna gain was estimated from the angle between the known and fixed transmitter boresight vector and the receiver direction, whose position was obtained from the receiver GNSS module based on its geographic coordinates

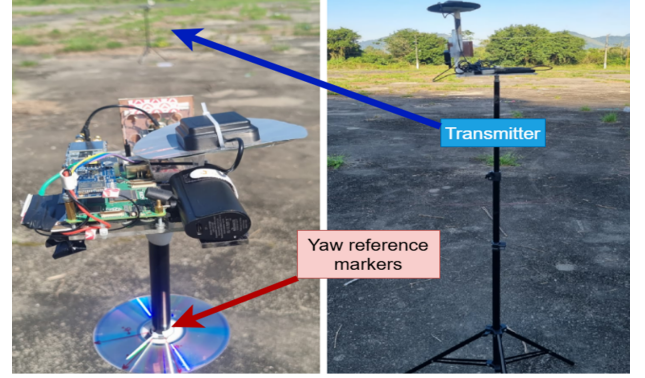


Fig. 5. Experimental setup during the measurement campaign, showing the transmitter and receiver platforms.

and altitude. The resulting angle was then associated with the previously characterized radiation pattern.

To calculate the relative gain of the receiving antenna, the angle between the boresight vector and the transmitter's direction is considered, as well as the orientation provided by the IMU. In this controlled test, only the yaw significantly influences the estimated gain. The implemented post-processing code already considers pitch variations associated with the height difference between the transmitter and receiver and the UAV tilt, which, in this experiment, is negligible due to the geometry adopted to facilitate data interpretation. The effect of roll, related to polarization misalignment between antennas, was not implemented. From the antenna characterization, the -3 dB point of polarization mismatch is reached at approximately $\pm 45^\circ$ of roll, while empirical measurements indicated a UAV roll variation within $\pm 28^\circ$. Therefore, its influence was considered negligible for the present experiments.

B. Large-Scale Fading and Propagation Model Validation

In this experiment, conducted in the same open area described in Section III-A, the objective was to evaluate whether the observed channel fading follows the behavior predicted by propagation models widely described in the literature, such as the FSPL and 2-Ray models [4]. The flight plan consisted of an approximately 70 m straight-line radial trajectory toward the transmitter, while maintaining the UAV at approximately the same height as the transmitter antenna (about 1.5 m above ground level) and keeping the antennas aligned to minimize the influence of antenna directivity on the results. Post-processing filtering was performed to select RF samples corresponding to distances between 10 and 70 m from the transmitter using synchronized GNSS and IMU data, and the resulting measurements were then compared with the FSPL and 2-Ray theoretical models.

IV. EXPERIMENTAL RESULTS

This section presents the experimental results obtained with the proposed platform, first evaluating the effects of antenna orientation on the received signal and then comparing the measured RSSI with theoretical propagation models.

A. Data Integration Validation

Fig. 6 presents the measured RSSI (left axis) and the estimated relative gains of the transmitting and receiving antennas

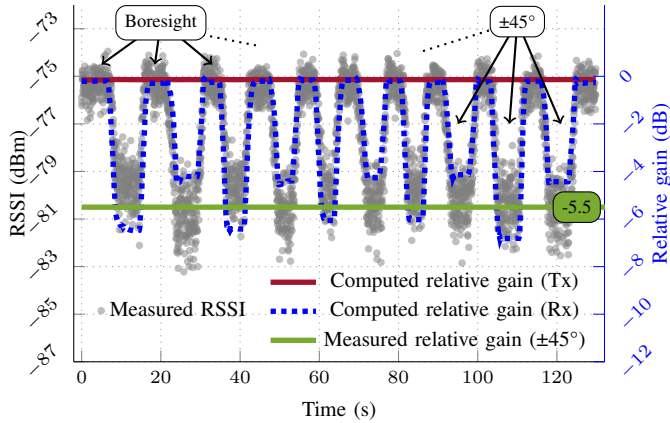


Fig. 6. Antenna gain variation due to misalignment on RSSI over time.

(right axis) during the controlled yaw variation experiment. Based on the measured radiation pattern, a misalignment of $\pm 45^\circ$ at elevation 0° results in a reduction in antenna gain of approximately -5.5 dB, and this effect is consistently observed in the measured RSSI when the misalignment reaches $\pm 45^\circ$. The computed transmitter antenna gain remained close to 0 dB, as expected, while the estimated receiving antenna gain adequately reproduces both the temporal behavior of the signal and the depth of the fading. Small discrepancies between the alternating relative gain minima were attributed to initial experimental misalignment or deviations in the module's yaw measurement. A more careful evaluation of the results suggests that applying a correction of approximately -5° to the yaw column of the dataset makes the estimated gain minima more uniform and consistent with the antenna radiation pattern, approaching the expected value of approximately -5.5 dB for both $\pm 45^\circ$ misalignment conditions. These results indicate that the integration between IMU, GNSS, and antenna characterization is suitable for analyses dependent on UAV orientation.

B. Large-Scale Fading and Propagation Model

Fig. 7 presents the measured RSSI (left axis) along the planned flight path, as well as the expected RSSI based on the FSPL and 2-Ray models. The corresponding UAV altitude is also shown on the right axis. It is observed that the UAV height shows small variations around the planned altitude, since maintaining a precise and constant UAV altitude during flight is difficult. The first three fades of the measured RSSI show good agreement with the 2-Ray model, while the fourth fade was not observed due to the SDR noise floor. The small discrepancies in the fade positions are likely due to UAV altitude variations during flight. Nevertheless, the results indicate that the receiver setup operated properly onboard the UAV, demonstrating its reliability for measurements in other environments.

V. CONCLUSION

This work presented a narrowband channel sounding system based on an SDR embedded in a UAV, integrating RF measurements, GNSS positioning with RTK, and IMU-based orientation data. The proposed architecture demonstrated the feasibility of a low-cost and flexible platform for empirical

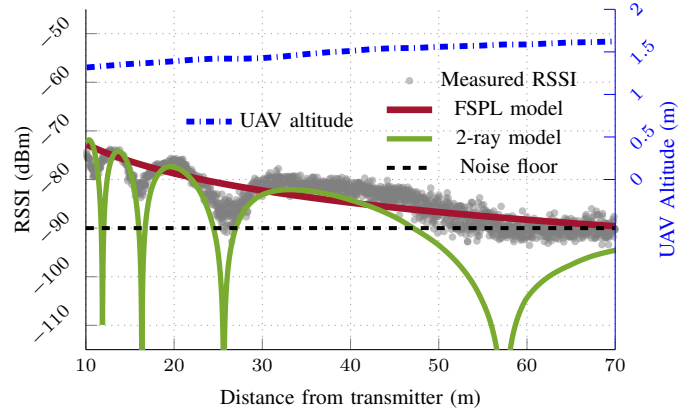


Fig. 7. Measured RSSI and propagation model comparison

channel characterization. Experimental results showed that the integration of antenna radiation characterization with precise positioning and UAV orientation is an effective approach for analyzing the impact of angular misalignment on the received signal. This capability enables a more detailed interpretation of propagation effects, especially when directional antennas are employed. Furthermore, the large-scale analysis indicated good agreement between the measured RSSI and theoretical propagation models, particularly the two-ray model, supporting its applicability to broader channel sounding campaigns in other environments.

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