Performance Evaluation of Wi-Fi Halow - IEEE 802.11ah in Malaysia Settings

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***Abstract*—Wi-Fi HaLow (IEEE 802.11ah) is an emerging wireless communication standard designed to address the growing demand for long-range, low-power connectivity in Internet of Things (IoT) applications. Operating in the sub-1 GHz frequency band, it offers extended coverage, improved penetration through obstacles, and better energy efficiency compared to conventional Wi-Fi. Given its potential for deployment in diverse environments, particularly in developing regions with mixed urban-rural geographies, this study evaluates the real-world performance of Wi-Fi HaLow in Malaysia, a tropical outdoor setting. A testbed was developed using Raspberry Pi 4B devices integrated with AHPI7292S modules based on the Newracom NRC7292 chipset. Operating at 924 MHz, in compliance with Malaysia's ISM band allocation, experiments were conducted across two geographical profiles within Universiti Kebangsaan Malaysia (UKM), a built-up road corridor and a relatively open river path. Key performance indicators such as Round Trip Time (RTT), Received Signal Strength Indicator (RSSI), and data rate were measured at varying distances and during different times of day (daytime and nighttime). The results demonstrate superior performance in open environments, such as riversides, with RSSI and data rate remaining relatively stable beyond 200 m. In contrast, signal quality deteriorated more rapidly along obstructed roadways. CloudRF simulations further confirmed these trends, applying diffraction-based propagation models with terrain and clutter data. The findings highlight Wi-Fi HaLow's suitability for low-power IoT applications in semi-urban and rural tropical settings. While this study provides first insights into geographical and temporal performance factors, it acknowledges the need to integrate atmospheric parameters in future work.**

***Index Terms*—component, formatting, style, styling, insert.**

I. Introduction

The Internet of Things (IoT) refers to a network of interconnected devices-sensors, processors, transceivers, and actuators that communicate both with each other and with the broader internet. As IoT networks grow in complexity and scale, emerging technologies and communication methods have evolved to meet increasing demands for connectivity and data handling [1]. These wireless technologies, within the IoT context, are often classified by their range and energy efficiency into short-range and wide-area solutions.

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Short-range IoT technologies, such as Bluetooth Low Energy (BLE) and Radio Frequency Identification (RFID), are typically deployed in Personal Area Networks (PANs) and Local Area Networks (LANs) [2]. While they offer low power consumption and sufficient throughput for localized applications, their limited range necessitates hierarchical or multihop architectures to extend coverage, often introducing complexity and reducing robustness. These technologies remain critical for applications like wearables, smart homes, and industrial automation.

In contrast, Wide-Area IoT solutions, including Low-Power Wide-Area Networks (LPWANs) and cellular-based IoT (e.g., NB-IoT, LTE-M), cater to use cases requiring long-range communication and scalability, such as environmental monitoring and smart agriculture. Operating in sub-GHz frequency bands, notable LPWAN technologies like LoRa, SIGFOX, and Wi-Fi HaLow achieve extended coverage while maintaining energy efficiency, albeit at the cost of lower data rates.

Wi-Fi HaLow (IEEE 802.11ah) distinguishes itself among LPWANs by offering moderate-to-high data throughput alongside long-range, low-power communication. Designed for IoT, it provides robust propagation characteristics with communication distances reaching up to 1 km in obstructed environments and 3 km in open areas. Theoretically, data rates range from 150 kbps to 15 Mbps within 1 km, tapering to approximately 1 Mbps at 3 km [3], [4]. Yet, empirical studies have revealed notable discrepancies, with throughput falling below 1 Mbps even at shorter ranges [5].

Compared to NB-IoT and LoRa, Wi-Fi HaLow delivers superior bandwidth, making it attractive for data-intensive IoT applications [6], [7]. However, there is a paucity of studies evaluating its resilience in diverse environmental conditions, particularly in tropical climates where high humidity, dense vegetation, and temperature variations could impact wireless performance. Previous research on sub-1 GHz networks such as LoRa has suggested RSSI fluctuations with temperature and propagation challenges in complex terrains [8], [9], but comparable studies for Wi-Fi HaLow remain scarce.

This study addresses this gap by empirically evaluating Wi-Fi HaLow's performance in tropical climates. Focusing on metrics such as Round-Trip Time (RTT), Received Signal

Strength Indicator (RSSI), and data rate, it investigates how environmental factors influence the protocol's real-world behavior. The resulting insights aim to guide optimized deployment strategies and assess Wi-Fi HaLow's suitability for IoT applications in challenging climatic and geographical contexts.

The remainder of this paper is organized as follows: Section 2 outlines the research methodology, Section 3 presents and discusses the results, and Section 4 concludes with perspectives for future research.

II. Methodology

This section will elaborate on the hardware configuration for the drive test and the software simulation using CloudRF.

A. Hardware Configuration

To assess the performance of Wi-Fi HaLow in Malaysia environmental conditions, a custom experimental setup was developed that consists of two Raspberry Pi 4B units that are paired with two AHPI7292S HAT modules (Fig. 1). The detailed specifications for both the access point (AP) or the transmitter and the station (STA), or the end node configurations are provided in Table I.

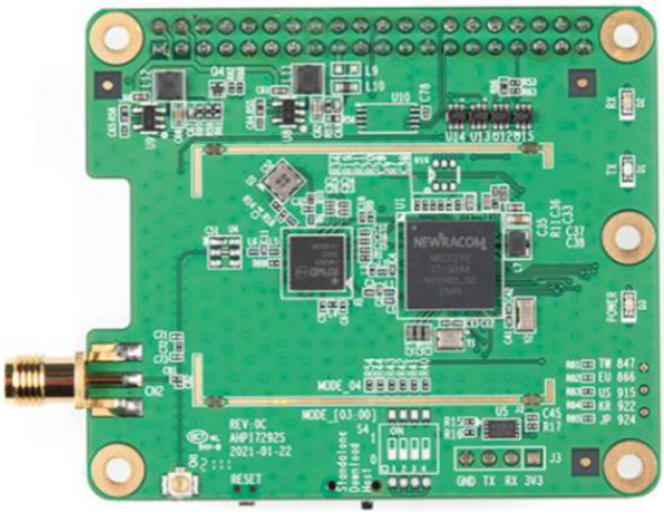

Fig. 1. The AHPI7292S HAT module that can be integrated with Raspberry Pi 4B.

TABLE I
SPECIFICATION OF THE POINT TO POINT WI-FI HALOW DEVICES

Specification	Value
Transmitted Power (dBm)	23
Antenna Gain (dBi)	2
EIRP (dBm)	25
Bandwidth (MHz)	2
Carrier Frequency (MHz)	924

The AHPI7292S module integrates the Newracom™ NRC7292 chipset, enabling support for IEEE 802.11ah (Wi-Fi HaLow) communication in the sub-1 GHz ISM band. This module is capable of operating with channel bandwidths of 1 MHz, 2 MHz, or 4 MHz, which correspond to data throughput ranging from 150 kbps to 15 Mbps. It can be deployed either as a standalone device or as a hosted peripheral via SPI or UART interfaces. In this study, each module was configured to operate in a distinct network role, either as the AP or the STA, enabling point-to-point communication testing.

In accordance with national spectrum regulations established by the Malaysian Communications and Multimedia Commission (MCMC), Wi-Fi HaLow operations in Malaysia are permitted within the 916–924 MHz band. For this study, the transmission frequency was set to 924 MHz, classified under JP allocation guidelines [10]. The selection aligns with practices similar to other sub-GHz low-power wide-area network (LPWAN) technologies such as LoRa and Sigfox, ensuring regulatory compliance while maintaining reliable connectivity.

Wi-Fi HaLow employs a range of modulation and transmission schemes to enhance link robustness and spectral efficiency across varying environmental conditions. At lower data rates, Binary Phase Shift Keying (BPSK) is utilized to ensure high resilience against noise and interference. For moderate throughput, Quadrature Phase Shift Keying (QPSK) provides a balance between data rate and signal stability. Higher-order modulation schemes such as 16-QAM and 64-QAM offer increased spectral efficiency but are more susceptible to noise, making them more suitable for short-range or low-interference deployments. To further improve transmission efficiency in challenging environments, Wi-Fi HaLow implements Orthogonal Frequency Division Multiplexing (OFDM). OFDM partitions the transmission spectrum into multiple orthogonal subcarriers, enabling parallel data transmission and significantly mitigating intersymbol interference (ISI), especially in multipath and obstructed settings.

The modulation scheme selection in Wi-Fi HaLow is adaptive and influenced by key factors such as link distance, propagation environment, and signal-to-noise ratio (SNR). For the terrain and environmental conditions of this study, characterized by hilly topography and structural obstructions within the Universiti Kebangsaan Malaysia (UKM) campus, lower-order modulation schemes were prioritized. Accordingly, BPSK and QPSK were chosen to ensure reliable communication performance under non-line-of-sight (NLOS) conditions. The network data, such as RTT, RSSI, and data rate, are obtained from the commands *ping*, *iwconfig*, and *iperf3*, respectively.

The experiment was carried out within the campus of Universiti Kebangsaan Malaysia (UKM), Bangi, utilizing two paths (Road and Riverside) which are positioned in parallel geographically as illustrated in Fig. 2. Measurements were taken during both daytime and nighttime to assess the impact of temporal variations on the performance of the Wi-Fi HaLow network.

B. Simulation using CloudRF

To simulate the propagation behavior and coverage performance of Wi-Fi HaLow (IEEE 802.11ah), CloudRF was used as the radio planning tool due to its support for terrain-aware

Fig. 2. Map of the two areas in consideration for the drive test. Blue signals refer to the roadside, centred on the university's mosque and red to the riverside, starting from the bridge.

propagation modeling and sub-GHz frequency bands. The simulation was configured to mimic the hardware configuration with a central frequency of 924 MHz, corresponding to the upper limit of the allowed ISM band in Malaysia for Wi-Fi HaLow deployments. A channel bandwidth of 2 MHz was selected to reflect a conservative data rate scenario suitable for long-range, low-power IoT applications. The transmission power was set to 25 dBm EIRP (500 mW), adhering to Malaysian Communications and Multimedia Commission (MCMC) regulations. An omnidirectional antenna with a gain of 2 dBi and a height of 4 meters and 1.5 meters was assigned to both the AP (transmitter) and STA (receiver), which approximates the deployment using Raspberry Pi and AHPI7292S HAT modules. The receiver sensitivity threshold was set based on the modulation type BPSK/QPSK, yielding an approximate threshold of -95 dBm for link reception.

The simulation employed the ITU-R P.1546 propagation model, which is appropriate for the 924 MHz frequency in an outdoor, suburban terrain like the UKM campus. Terrain data with 30-meter resolution was used to account for the hilly landscape and structural obstructions. The environment was classified as "light urban" to approximate moderate building clutter and foliage. The simulation area was defined over a 2-kilometer radius from the access point, enabling an assessment of both line-of-sight (LOS) and non-line-of-sight (NLOS) coverage zones.

Burlington diffraction effects were enabled to estimate signal degradation over terrain edges, particularly important in the campus's elevated and sloped areas. The output metrics included coverage heatmaps, Received Signal Strength Indicator (RSSI) levels, and Signal-to-Noise Ratio (SNR) distribution, which served to evaluate the practical viability of Wi-Fi HaLow deployment in similar tropical terrain environments.

III. Results and Discussion

This section presents the analysis of Wi-Fi HaLow performance based on both simulation and empirical testing. First, signal coverage and path loss were estimated using CloudRF to model expected behavior in the test environments. The results are then compared with real-world measurements obtained from drive tests conducted along roadside and river paths, followed by an evaluation of the impact of temporal variation through daytime and nighttime assessments.

A. CloudRF Simulation

The Fig. 3 and 4 illustrates the simulated signal coverage of Wi-Fi HaLow (IEEE 802.11ah) using the CloudRF platform, conducted over the hilly and semi-urban environment of UKM. Two separate APs noted as the transmitter instances (Tx) and the black icon are shown in the image, each representing the different propagation scenarios (Road and Riverside).

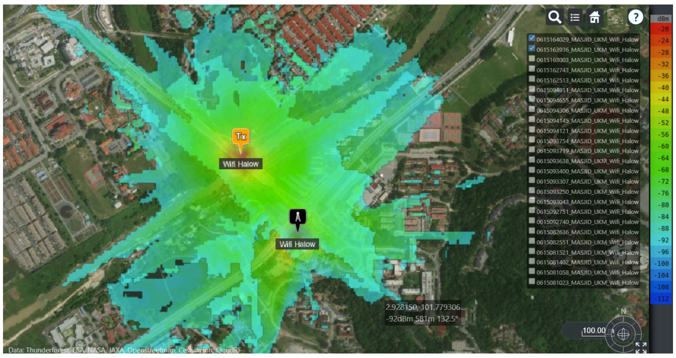

Fig. 3. Simulation results using CloudRF from the mosque and the bridge without diffraction.

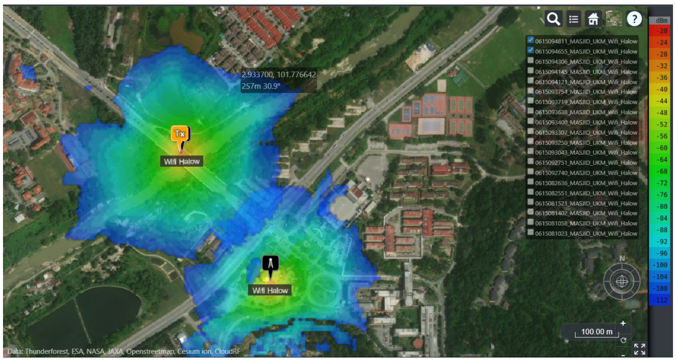

Fig. 4. Simulation results using CloudRF from the mosque and the bridge with Burlington diffraction.

In Fig. 3, the center-left portion of the image, the first transmitter is placed near an open, elevated area (bridge) within the UKM campus. It exhibits a strong signal footprint, indicated by warmer colors (green to yellow), with Received Signal Strength Indicator (RSSI) levels ranging between -40 dBm to -72 dBm, suggesting robust coverage and higher probability of successful communication. The propagation extends uniformly in multiple directions, except where obstructed by denser terrain or building clusters.

The second transmitter, located toward the central-south of the image, operates in a more obstructed area surrounded by vegetation and built-up zones. The coverage from this transmitter is more directional and attenuated, as seen in the increased presence of cyan and light blue tones representing RSSI levels of -80 dBm to -96 dBm and below. These levels, though still within the sensitivity threshold of typical BPSK/QPSK receivers, imply lower link margin and potential degradation in throughput under environmental noise or interference.

In Fig. 4, the coverage prediction is generated with the Burlington diffraction model enabled. Compared to the previous scenario without diffraction, the signal footprint becomes less optimistic and more representative of real-world conditions. The transmitter located at the elevated bridge shows reduced coverage in certain areas, particularly behind terrain obstructions and building structures. Instead of sharp "all-or-nothing" cutoffs, the coverage transitions more gradually, with shadowed regions showing attenuated but still detectable RSSI levels (around –85 dBm to –100 dBm, shown in light to dark blue). This suggests that diffraction allows some signal bending beyond obstacles, though at the cost of weaker link margins.

Similarly, the transmitter situated in the central-south area (mosque) displays a narrower footprint when diffraction is considered. The presence of vegetation and terrain features introduces additional losses, reducing the extent of high-quality coverage (green/yellow zones). However, low-rate IoT communication could still be maintained in certain obstructed regions due to the resilience of Wi-Fi HaLow's narrowband BPSK/QPSK modes.

Overall, incorporating the Burlington diffraction model produces a more conservative and realistic estimation of coverage, highlighting the significant impact of environmental clutter and emphasizing the importance of accurate propagation modeling for planning robust Wi-Fi HaLow deployments. The differences in signal dispersion reflect the influence of terrain elevation, line-of-sight (LOS) availability, and local clutter, highlighting the importance of empirical propagation modeling in the planning and deployment of Wi-Fi HaLow networks.

B. *Road and River Drive Test Results*

Fig. 5 shows the Received Signal Strength Indicator (RSSI) as the distance increased between the AP and STA in both paths. The empirical RSSI values are plotted using red (roadway) and blue (river) markers, while their respective signal attenuation fitted models are represented with solid (roadway) and dashed (river) lines. The RSSI values are expressed in decibels-milliwatts (dBm), with more negative values indicating weaker signal strength.

From the plot, it is evident that the signal attenuation over the river path is significantly lower compared to the road path at similar distances. The river model flattens more rapidly, indicating better signal preservation due to reduced obstruction and more favorable LOS conditions across the open water. In contrast, the road model shows a steeper decline in signal strength, particularly within the first 200 meters, suggesting that buildings, vehicles, trees, and other urban obstructions contribute to greater signal degradation in that environment.

Notably, at distances beyond 400 meters, the river path still maintains RSSI values around -80 to -90 dBm, while the roadway signal dips closer to -100 dBm or lower, potentially nearing the sensitivity limit of the receiver. These trends reinforce the hypothesis that Wi-Fi HaLow exhibits superior performance in open and reflective environments, such as rivers, due to reduced multipath fading and diffraction losses.

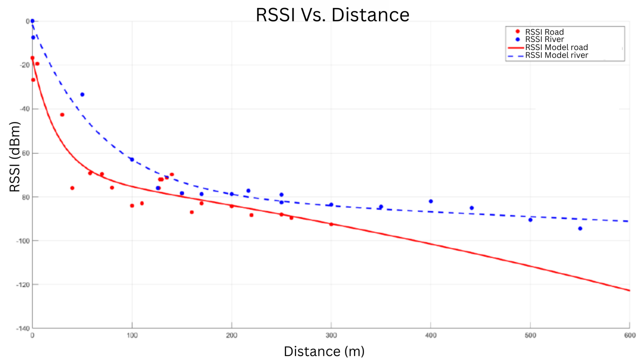

Fig. 5. RSSI vs. Distance for propagation on both location of transmitter.

The next Fig. 6 illustrates the relationship between data rate (Mbps) and distance (meters) for Wi-Fi HaLow signal transmission across the two different paths. The empirical measurements are plotted as red (roadway) and blue (riverside) data points, with corresponding fitted model curves shown in solid and dashed lines, respectively.

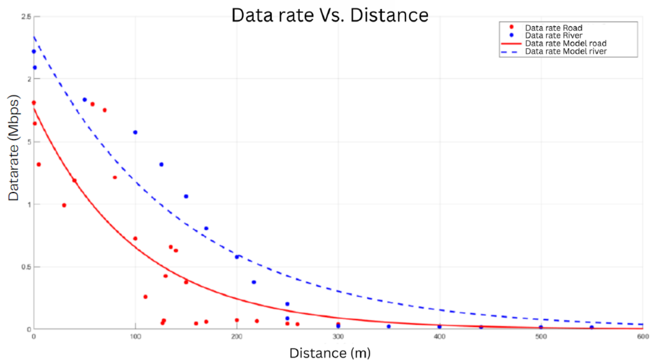

Fig. 6. Datarate vs. Distance for propagation on both location of the transmitter.

The chart clearly shows that the data rate decreases exponentially with increasing distance from the transmitter. This decline is more pronounced in the roadway scenario, where again due to obstacles such as buildings, vehicles, and vegetation that contribute to higher signal attenuation and multipath effects, resulting in a steeper drop in achievable throughput. In contrast, the river path demonstrates a smoother and slower decline, suggesting a more stable channel condition with fewer obstructions, enabling better signal integrity and higher modulation efficiency over extended distances.

At shorter ranges (below 100 meters), both environments maintain data rates above 1 Mbps. However, beyond 200 meters, the river path consistently outperforms the roadway path, retaining usable throughput up to 500 meters, whereas the road path often drops below 0.5 Mbps or experiences near-zero throughput. These results align with expectations from the physical characteristics of sub-GHz Wi-Fi HaLow, which benefits from lower free-space path loss and better penetration, but remains sensitive to diffraction and reflection in cluttered environments.

This comparison underscores the importance of environment-aware deployment strategies for Wi-Fi HaLow in IoT applications, particularly when balancing range and data rate performance for use cases such as smart agriculture, campus sensing, or urban monitoring.

C. Comparison of Day and Night-time Transmission

Additional analysis was conducted to compare the performance of Wi-Fi HaLow between daytime and nighttime measurements. Fig 7 shows the RSSI as the distance increased between the AP and STA. The daytime measurements (dashed blue line) show a stronger signal retention, maintaining connectivity beyond 300 m, whereas the nighttime measurements (red line) indicate earlier signal degradation, with the connection dropping off near 300 m. Equations 1 and 2 represent the regression models for daytime and nighttime data, respectively.

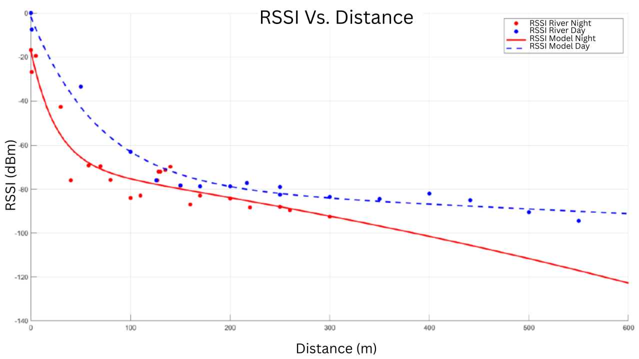

Fig. 7. zRSSI vs. Distance for propagation in the day and night.

$$RSSI_{day}(x) = -77.08e^{0.2876.10^{-3}x} + 58.07e^{-0.01601x} \quad (1)$$

$$RSSI_{night}(x) = -77.92e^{0.5733.10^{-3}x} + 58.07e^{-0.01601x} \quad (2)$$

The daytime model achieved an R^2 value of 0.9797 and RMSE of 4.1482, demonstrating a strong fit with minimal error. In contrast, the nighttime model yielded an R^2 of 0.9586 and RMSE of 5.6304, suggesting greater variability. This variation at night may be attributed to increased environmental noise, temperature inversions, or changes in atmospheric conditions affecting signal propagation. Overall, the results highlight that Wi-Fi HaLow performance is influenced not only by distance but also by temporal factors, which must be considered in real-world IoT deployments.

Finally, in Fig. 8, the relationship between round-trip time (RTT) and distance is illustrated for both daytime and nighttime measurements. RTT represents the delay experienced by a packet travelling from the transmitter to the receiver and back, and is a critical indicator of latency performance in IoT networks. At short ranges (¡100 m), RTT values remain low for both conditions, generally below 20 ms, indicating stable and responsive links. However, as distance increases, the nighttime measurements (red) exhibit a sharp rise in RTT, with values exceeding 100 ms beyond 250 m and reaching over 200 ms at the farthest tested points. This suggests higher attenuation, increased retransmissions, or interference effects during nighttime propagation, contributing to longer delays.

By contrast, daytime measurements (blue) show much more consistent RTT performance across the tested distances, remaining within 10–30 ms even at ranges above 300 m. The corresponding fitted models reinforce these trends: the daytime RTT remains nearly flat with distance, while the nighttime model shows an exponential increase. This divergence indicates that Wi-Fi HaLow links are more stable and latency-efficient during the day, while nighttime conditions introduce variability and delay.

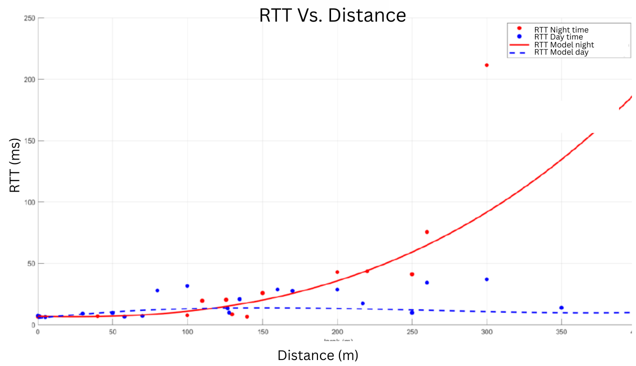

Fig. 8. RTT vs. Distance for propagation in the day and night.

IV. Conclusion and Perspective

In this study, a custom-built test devices was developed to evaluate the performance of Wi-Fi HaLow (IEEE 802.11ah) in terms of round-trip time (RTT), received signal strength indicator (RSSI), and achievable data rate. Measurements were conducted at two distinct locations characterized by differing geographical and environment features, and at two different times of day—daytime and nighttime. The results indicate that Wi-Fi HaLow performs more consistently in open environments, such as across river surfaces, as opposed to obstructed paths like roadways bordered by buildings or vegetation. Additionally, better performance was observed during daytime conditions, suggesting a potential influence of temporal environmental factors.

However, the current evaluation only provides a partial perspective on the environmental impact on network performance due to limited measurement data and as the temporal and spatial variations explored do not comprehensively account for atmospheric dynamics or obstructive elements. To address this limitation, future work should incorporate more test drives and atmospheric parameters—such as temperature, humidity, and barometric pressure, as well as the presence and density of physical obstructions like trees, walls, or vehicles. This expanded approach would enable a more holistic understanding of Wi-Fi HaLow's performance under realistic tropical environmental conditions, thereby informing robust deployment strategies for sub-GHz IoT networks in similar climates.

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