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16. ABSTRACT

This report is part of AHMCT's research project "Development and Testing of an Unmanned Aerial System (UAS) Cellular & Wi Fi Repeater: Phase 2." The goal of this research is to expand upon the successful UAS aerial repeater that was created in Task 3280. The researchers evaluated several commercial off-the-shelf (COTS) vehicle routers and antennas to improve the ground Wi-Fi network. After the components were selected an easily assembled payload package was designed to mount to the UAS to create a useable communication network.

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Advanced Highway Maintenance and Construction Technology Research Center

Department of Mechanical and Aerospace Engineering
University of California at Davis

Development and Testing of an Uncrewed Aerial System (UAS) Cellular & Wi-Fi Repeater: Phase 2

Evan Sim, Anh Duong, Dave Torick, Kin Yen & Shima Nazari

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April 28th, 2025

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Division of Research, Innovation and System Information

Executive Summary

California Department of Transportation (Caltrans) has many rural use cases where no current network communications exist outside of satellite services. Based on prior research from the Advanced Highway Maintenance and Construction Technology (AHMCT) Research Center, the cellular range of typical sites in rural areas is significantly limited by surrounding terrain and foliage. There is a need to provide enhanced communications availability outside of current cellular offerings without full-fledged investment in satellite equipment. Research performed under Phase 1 of Task 3280, showed that an Uncrewed Aerial Systems (UAS) can elevate a payload into the cellular signal that is typically blocked by terrain and create a Wi-Fi network on the ground for worker communications. Refinement of the UAS payload was necessary to minimize deployment time and reduce the number of components required to establish a usable network. After the payload package was optimized, field trials were conducted to verify the technology's success in various terrain situations with limited to no cellular network coverage. With a temporary Wi-Fi network in construction and emergency response areas, communication can now occur through emails and Wi-Fi calling, increasing efficiency, resource management, and accurate equipment deployment for the first time in some rural districts.

The purpose of this document is to provide the results from the field trials, analyze the performance of the UAS aerial repeater system, and provide recommendations.

Problem, Need, and Purpose of Research

Caltrans identified a need to improve communication in rural areas due to limited coverage. In response, the AHMCT team redesigned and tested the UAS system to enhance communication capabilities. During Phase 2, the team focused on making the system lighter and easier to assemble. Additionally, they evaluated various cellular and Wi-Fi antennas to optimize performance, selecting the best-performing and most compact designs. Once the UAS system was optimized, the team mapped signal performance along Highways 299 and 70 to identify potential testing locations. The goal of this research was to assess the performance of the second-generation design from Phase 2 compared to the Phase 1 system.

Overview of the Work and Methodology

The AHMCT team divided the tasks as follows:

1. **Project management:** Organize meetings with the project panel to ensure the tasks are on track.
2. **Review of commercial off-the-shelf (COTS) products:** Compare the performance of COTS cellular and Wi-Fi antennas. Further details of the selection process are outlined in the Interim Report – Task 2, with the complete information available in Appendix A.
3. **Develop and optimize a second-generation payload package:** Optimize the performance of the UAS system. Further details of the development process are outlined in the Interim Report – Task 3, with the complete information available in Appendix B.
4. **Cellular mapping and selection of field trial locations:** Map out cellular signal (long term evolution [LTE] signal) performance along Highways 299 and 70, then use these results to select field trial locations. Further details of the mapping process are outlined in the Interim Report – Task 4, with the complete information available in Appendix C.
5. **Field trials and survey of the outcomes:** Test the UAS system at selected locations and report results. Further details of the testing process are outlined in the Interim Report – Task 5, with the complete information available in Appendix D.

Major Results and Recommendations

Major results:

- The UAS system extends the cell signal range, provided that a cell tower signal is within approximately 10 miles and the location is within the signal sector.
- There was no need for the drone to ascend to 350 feet Above Ground Level (AGL) to send emails or use Voiceover Internet Protocol (VoIP) if there is no broadband shadow; these tasks were successfully carried out at both 0 and 200 feet AGL.
- Having a strong cellular antenna and a reliable modem helps improve signal without the need to deploy the drone
    - Taking flight was required to acquire a signal in only two instances: Once when the UAS was deployed on Highway 299 and once when deployed on Highway 70.

Recommendation:

- From the research, the UAS system has minimal gain in providing a communication network for users. Therefore, utilizing a Sierra Wireless MP70 modem and Proxicast antennas, or any high-performance modem and antenna pairing, can create a usable network in many situations when mounted to a vehicle.

- Future work should focus on a Starlink network system instead of a UAS-based network system.

Table of Contents

Acronyms and Abbreviations

Acronym	Definition
AGL	Above the ground
AHMCT	Advanced Highway Maintenance and Construction Technology Research Center
Caltrans	California Department of Transportation
COTS	Commercial Off–The-Shelf
FCC	Federal Communications Commission
LEO	Low Earth Orbit
LTE	Long Term Evolution
UAS	Unmanned Aerial System
UASRE	Uncrewed Aerial Systems Repeater
VOIP	Voiceover Internet Protocol
WiFi	Wireless Fidelity

Acknowledgments

The authors thank the California Department of Transportation (Caltrans) for their support, in particular Jeremiah Pearce with the Office of ITS Engineering and Support in District 3 and Andre Chavez and Sean Campbell with the Division of Research, Innovation and System Information. The authors acknowledge the dedicated efforts of the AHMCT team who have made this work possible.

Chapter 1: Introduction

Problem

Enhancing network connectivity and ensuring reliable cellular coverage in work zones and emergency response areas are important to guarantee the safety of operations and facilitate prompt responses to emergencies. However, the geographical features of the surrounding terrain, such as hills, can significantly impede cellular signals, leading to potential communication gaps. Unmanned aerial systems (UAS) have emerged as a promising solution to this challenge due to their ability to carry specialized payloads and operate at elevated heights. By leveraging UAS technology, it is feasible to establish a network infrastructure that can receive signals from a higher vantage point, thereby extending cellular coverage to users on the ground within the operation area.

Objectives

Throughout Phase 2 of the project, the AHMCT team aimed to expand upon the UAS aerial repeater created as part of the first phase of the project (Task 3280.) The main focuses are as follow:

1. Research and procure commercially available Wi-Fi routers and antennas
2. Design a weather-proof drone-level payload package to enclose the router and antennas
3. Develop test plan
4. Evaluate one router/antenna configuration that is suitable for Caltrans' operations
5. Optimize Wi-Fi connection seen at ground level

Of the above goals, the AHMCT team first researched high-performance commercial off-the-shelf (COTS) components to identify the most suitable modems, cellular systems, and wireless fidelity (Wi-Fi) antennas for the UAS system. Once the optimal parts were selected, the team designed the system with a focus on rapid assembly in the field.

As part of optimizing the Wi-Fi connection seen at ground level, the team tested the system along California Highways 299 and 70. These locations were chosen as they are areas where cell signal improvement was possible and due to safety considerations such as the launching location needed to be 25 feet from the road.

Scope

The AHMCT team performed the following tasks to determine whether a UAS system is effective in establishing a network:

1. **Task 1 – Managing project:** The AHMCT team worked closely with the project panel to ensure test deployments were safe and effective.
2. **Task 2 – Review of COTS products:** The goal of this task was gathering information, identifying, and documenting the COTS long term evolution (LTE) modems and antennas that fit Caltrans' needs. Viable test candidates were procured and tested to determine the most suitable parts for a UAS system.
3. **Task 3 – Develop and optimize second-generation payload package:** Designed for deployment in remote regions of California, the updated payload package addresses and overcomes connectivity limitations posed by challenging terrain. Key design considerations included ensuring ease of installation, reliability, and optimal signal performance.
4. **Task 4 – Cellular mapping and section of field trial location(s):** Highways 299 and 70 were chosen for testing locations as they are rural routes on which Caltrans District 2 normally have operations. The testing locations were chosen because they were in proximity of the Federal Communications Commission (FCC) projected broadband, in regions where there are minimal to no cellular coverage, and there were at least 25 feet from the edge of a roadway to fly the UAS system.
5. **Task 5 – Field trials and survey of the outcomes:** The AHMCT team deployed the UAS system in designated locations (determined from the previous task). After sufficient data were collected from the UAS system, the team processed the information and provided the results.

Background

The research in this report is the continuation of Task 3280. In this report, the AHMCT team focused on developing the UAS system for design and performance. During Task 3280, a UAS-based aerial repeater was implemented to extend the usable wireless communication capabilities in the rural environments tested. The equipment preserved from this phase of the project include the DJI Matrice 300 RTK drone and Sierra Wireless MP70 wireless modem, both of which showed success for meeting the goals described in the Objectives section.

To address these goals, the AHMCT team sought to further develop the payload package developed in Phase 1 of the project. The system was designed with the aim of creating a ground Wi-Fi network for Caltrans employees in construction zones and emergency response. The AHMCT team used the findings from the first phase of the project to guide a more robust design for the system, which was a result of the following:

1. A more rigorous design phase compared to Phase 1, leading to a robust payload design that withstands the expected field conditions
2. Several test sessions throughout the project to optimize Wi-Fi antenna choices
3. Using test conditions which better reflect the conditions in which the system will be deployed

Research Methodology

The AHMCT team followed these steps for the research:

1. **Research and Procurement of COTS**: Identify and procure high-performance, lightweight Wi-Fi and cellular antennas.
2. **UAS Package Optimization**: Design a UAS that minimizes assembly time while ensuring maximum lightweight efficiency.
3. **Cellular Signal Mapping on Highways 299 and 70**: Collect cellular signal data along these highways to identify optimal testing locations that are both safe and have potential for signal improvement.
4. **UAS System Performance Evaluation**: Conduct testing at designated locations and report results.

Overview of Research Results and Benefits

Table 1.1: Key deliverables

Task	Deliverable	Note
2	Interim report summarizing Review of Commercial Off-the-Shelf (COTS) Products	Appendix A and Task 2 Overview
3	Interim report summarizing Develop and Optimize Second Generation Payload Package	Appendix B and Task 3 Overview
4	Interim report summarizing Cellular Mapping and Selection of Field Trial Locations	Appendix C and Task 4 Overview
5	Interim report summarizing Field Trials and Survey of the Outcomes	Appendix D and Task 5 Overview

Task	Deliverable	Note
6	Final report	This report

The following conclusions for the UAS repeater system were made from the above results:

- The system extends the signal range, provided that a cell tower signal is within approximately 10 miles and the location is within the signal sector.
- There was no need for the drone to ascend to 350 feet Above Ground Level (AGL) to send emails or use Voiceover Internet Protocol (VoIP) if there is no broadband shadow; these tasks were successfully carried out at both 0 and 200 feet AGL.
- Having a strong cellular antenna and a reliable modem helps improve signal without the need to deploy the drone.
    - The UAS was only deployed one time on Highway 299 and one time on Highway 70 to fly to create a usable network.

The benefits of utilizing the UAS system are:

1. **Enhanced LTE Signal Strength**: Improve the strength of the LTE signal when a cellular tower is within 10 miles.
2. **LTE Signal Hotspot Creation**: In some cases, the UAS can generate an LTE signal hotspot in areas where no LTE signal is available.

Chapter 2: Project Tasks

Task 2 Overview: Review of Commercial Off-the-Shelf (COTS) Products

The AHMCT team focused on researching and procuring high-performance, lightweight COTS antennas and modems. Previous project reports presented detailed information on the uncrewed aerial systems repeater (UASRE) system concept of operation and reviewed several viable candidates. This literature review focuses on new products that were not available during the previous project timeframe. The results provided a basis for selecting and procuring suitable LTE modems and antennas for subsequent testing and evaluation. The final system configuration was determined based on the component testing results. Refer to Appendix A for a comprehensive report.

Task 3 Overview: Develop and Optimize Second Generation Payload Package

The AHMCT team focused on integrating the high-performance, lightweight COTS products procured in Task 2 into the UAS system. Designed for deployment in remote regions of California, the updated payload package addresses and overcomes connectivity limitations posed by terrain. Key design considerations included ensuring ease of installation, reliability, and optimal signal performance. Additionally, the system was designed for quick and easy assembly, requiring minimal hardware and tools. Refer to Appendix B to view a comprehensive report.

Task 4 Overview: Cellular Mapping and Selection of Field Trial Locations

The AHMCT team conducted LTE (or cellular) signal mapping on Highways 299 and 70. After performing three trials on each highway, the team used the mapping results to select field trial locations. The selected field trial locations were required to meet the following criteria:

- At least 25 feet of clearance from the edge of the roadway.
- Sufficient space for the pilot to back up and maintain visibility of the UAS system at all times.
- Proximity to the projected FCC national broadband map. The map displays where services are available as reported by providers.
- Located in segments with minimal to no signal coverage (based on the results of cellular mapping).
- Preferably within 10 miles of the projected cellular towers.

The AHMCT team drove to the chosen locations to conduct the UAS system field trials. Refer to Appendix C for a comprehensive report.

Task 5 Overview: Field Trials and Survey of the Outcomes

The AHMCT team processed the collected data and concluded the following:

- The UAS system can extend the signal range in certain cases, provided a cell tower is within approximately 10 miles.
- No measurable difference was obtained by the UAS system at altitudes higher than 200 ft.

- In many instances, the UAS system can capture a usable signal without deployment. The combination of a high-performance LTE antenna and a reliable modem can improve the signal on the ground.

The AHMCT team concluded that the UAS system offers minimal benefits for California Department of Transportation's (Caltrans) rural operations. Therefore, satellite-based system is recommended as a broadband telecommunications alternative over the UAS-based system. Further research with low-earth orbit (LEO) satellite communication is also recommended. Refer to Appendix D to view a comprehensive report.

Chapter 3: Deployment and Implementation

The UAS system was deployed for two days of testing, and the results indicate that the system is not suitable for Caltrans' rural operations. The following sections explain why the UAS system is not recommended for implementation.

Problems and Issues that Affected Product Deployment

Personnel Requirements: A minimum of two Caltrans personnel is required per shift during drone deployment, one of whom must be a certified Part 107 pilot. According to Federal Aviation Administration (FAA) regulations as of April 2025, any non-recreational UAS operation requires a Part 107–certified pilot, unless the drone is below 150 feet AGL and tethered. However, Caltrans mandates the use of a Part 107–certified pilot and a visual observer for all drone operations, regardless of altitude or whether the drone is tethered. Given Caltrans safety standards, the terrain, the potential for strong gusts, and the UAS's optimal performance often at approximately 200 feet AGL, a visual observer is required.

Deployment Location and Direction Limitations: The UAS system performs optimally within 10 miles of a cellular tower. Caltrans personnel should remain within 10 miles of a cellular tower and ensure the drone captures a usable LTE signal (by checking if their phones are able to send emails and conduct calls). About 10 minutes are required for drone deployment and for the payload package to stabilize and provide usable signal. Each time the personnel relocate, this process must be repeated. Additionally, a safe deployment area must have a shoulder that is at least 25 feet wide and 100 feet long to allow the pilot to maintain a clear line of sight of the UAS. All these factors may limit the system effectiveness in rural areas.

Limited LTE Signal Gain: The UAS system successfully detected usable LTE signals on the ground due to its strong cellular antenna (Proxicast) and reliable modem (Sierra Wireless 70). During testing on Highways 299 and 70, the UAS only needed to ascend twice out of eleven trial runs to capture a usable LTE signal. Therefore, Caltrans personnel are more likely to obtain a usable LTE signal with a higher gain antenna and/or a higher sensitivity modem mounted on their vehicles as opposed to relying on the UAS for signal capture.

Short Flight Durations: Each UAS deployment requires two (2) batteries, providing approximately 30 minutes of flight time. With eight (8) batteries stored in the charging case, the UAS system can operate for a total of about two hours. Although the UAS system was tested with a third party tethered system,

the tether was not implemented.

Outcome from Noted Problems and Issues

Given the limitations listed above, the AHMCT team and the project panel agreed that organizing a UAS workshop to train Caltrans personnel would not be practical.

Moving forward, the AHMCT team recommends that the UAS system will be supplemented by improving modems and antennas on the ground based on the results of the UAS system testing.

Other Considerations

Based on the current technology market, the AHMCT team recommend prioritizing a Low Earth Orbit (LEO) satellite broadband over a UAS-based network system for rural operations. The setup of commercially available LEO satellite broadband is straightforward and does not require a certified drone pilot. For example, Caltrans has already deployed the Starlink satellite broadband in recent years with positive results.

Chapter 4: Conclusions and Future Research

Conclusions

The UAS system can improve LTE signal under the condition that it is within 10 miles of a cellular tower and inside a signal sector. However, field trial results indicate that deploying the UAS system was not always necessary to detect usable LTE signals. In many cases, a high-performance cellular antenna and a reliable modem were sufficient to enhance LTE signal on the ground, eliminating the need for flying the UAS system.

The UAS system offers minimal benefits for Caltrans's rural operations. The system is complex to deploy due to several limitations, including personnel requirements, restricted deployment locations, limited LTE signal gain, and short flight durations. It would be challenging for Caltrans to consistently have a certified Part 107 pilot available for every shift. The UAS system requires at least two personnel (one pilot and one visual observer) for deployment, which is not ideal for operations in rural areas where personnel resources are limited.

Should deployment be necessary, the AHMCT team has outlined recommendations in the following section to ensure safe and effective operation.

Recommendations

Based on the results, the AHMCT team provides the following recommendations for the effective utilization of the UAS system:

- **Recommendation:** For optimal performance, the UAS system should be located within approximately 10 miles of a cellular tower.
  - On Highway 299, the UAS system failed to capture a usable signal in two out of five test runs when flown between 200 and 400 feet AGL, due to the test sites being more than 10 miles from the nearest cellular tower. Without proximity to a tower, the system's performance is significantly reduced.
  - Similarly, on Highway 70, the UAS system failed to capture a usable signal when flown at 200 feet AGL, as the test site was more than 10 miles from the nearest cellular tower. The UAS system did not fly higher than 200 feet AGL due to a helicopter drill taking place at the time.

- **Recommendation:** The UAS system should be operated under the supervision of a certified Part 107 pilot throughout the entire flight.
    - Terrain conditions can produce potentially strong gusts of wind. Therefore, it is highly recommended to supervise the UAS system at all times to ensure the UAS system does not crash into the path of traffic.
    - The limited space between the shoulder and the road also poses challenges that require careful monitoring.
- **Recommendation:** To ensure uninterrupted operation during a 2-hour mission, a minimum of eight backup batteries should be available.
    - During the test runs, the UAS system required two batteries to operate for 30 minutes, emphasizing the need for additional batteries to extend mission duration.

The AHMCT team **does not recommend deploying the UAS system if the Wi-Fi clients:**

- Can reliably obtain a usable LTE signal on the ground when connecting to the UAS system.
    - The Wi-Fi clients should be able to place a phone call to verify signal availability. The results show that utilizing a Sierra Wireless MP70 modem and Proxicast antennas can provide a usable network that enables the user to send emails and perform VoIP on the ground in many situations.
- Does not meet safety requirements.
    - The user must be able to observe the UAS system at all times.
    - The deployment area must have sufficient clearance on the shoulder to safely deploy and land the system outside of the clear zone next to the roadway.

Future Research

The AHMCT team plans to propose improving the system signal on the ground rather than relying on the UAS system. Given the need to meet high-performance and lightweight requirements, the selection of suitable antennas and modems is limited. However, the team can now explore and procure more advanced components for the LTE hotspot without the constraint of the UAS weight limitations.

Additionally, the team can investigate the availability of satellite networks in the market. In recent years, the Starlink satellite hotspot has been a leading candidate for Caltrans, with successful deployments already observed in the field. The team can further assess Starlink's performance in more rural areas to validate its capabilities at various locations and determine if it could be a more effective solution for Caltrans' rural operations.

Appendix A: Interim Report for Task 2

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17. KEY WORDS Unmanned Aerial System, Drone, Communications Repeater, LTE Modem, LTE Antenna, Wi-Fi Antenna, MIMO	18. DISTRIBUTION STATEMENT No restrictions. This document is available to the public through the National Technical Information Service, Springfield, Virginia 22161.	
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The research reported herein was performed by the Advanced Highway Maintenance and Construction Technology (AHMCT) Research Center, within the Department of Mechanical and Aerospace Engineering at the University of California – Davis, for the Division of Research, Innovation and System Information (DRISI) at the California Department of Transportation. AHMCT and DRISI work collaboratively to complete valuable research for the California Department of Transportation.

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Advanced Highway Maintenance and Construction Technology Research Center

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Development and Testing of an Unmanned Aerial System (UAS) Cellular & Wi Fi Repeater: Phase 2 - Review of Commercial Off-the-Shelf (COTS) Products

Kin Yen, Anh Duong, Evan Sim, Dave Torick, and Shima Nazari

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List of Acronyms and Abbreviations

Acronym	Definition
AGL	Above the ground
AHMCT	Advanced Highway Maintenance and Construction Technology Research Center
Caltrans	California Department of Transportation
COTS	Commercial Off–The-Shelf
DOT	Department of Transportation
DRISI	Caltrans Division of Research, Innovation and System Information
LTE	Long Term Evolution
MIMO	Multiple-Input and Multiple-Output
UAS	Uncrewed Aerial Systems
UASRE	Uncrewed Aerial Systems Repeater

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Chapter 1: Review of commercial off-the-shelf (COTS) products

Advanced Highway Maintenance and Construction Technology (AHMCT) researchers performed a literature review of commercially available vehicle Long Term Evolution (LTE) modems and antennas that may be suitable for Caltrans operations. Previous project reports presented details of the uncrewed aerial systems repeater (UASRE) system concept of operation and reviewed several viable candidates. This literature review focuses on new products that were not available in the previous project timeframe. The review results provided a basis for selecting and procuring suitable LTE modems and antennas for subsequent testing and evaluation. The final system configuration was based on the components testing result.

Task Objective:

The goal of Task 2 was to gather information, identify, and document the commercially available off-the-shelf LTE modems and antennas that fit Caltrans' needs. Viable test candidates were procured and tested in subsequent tasks.

General Requirements / Considerations

The requirements for the UASRE were provided in the previous project's final reports. In the previous project, a Wi-Fi ground station with external 5dB gain antennas was used to establish a stable high speed Wi-Fi connection with the UASRE. One of the current project objectives is to eliminate the use of Wi-Fi ground station or any modification to Wi-Fi client antenna configurations.

Generally, the primary focus component specifications are weight, size, cost, performance, and availability. At the end of COVID-19 pandemic (early in the project), some products were subjected for long lead time due to the supply chain issues.

The secondary focus component specification is power requirements: voltage input range, current, and power consumption. Larger wire size for higher current and the need for external voltage converter can increase system weight.

Methodology

An extensive product search was carried out in the previous project. In addition, major system and component manufacturers were identified in the previous project. AHMCT researchers revisited previously identified components and the system manufacturers' website to determine if new products were available and suitable for the UASRE system. Google and Amazon product searches were conducted to find suitable Wi-Fi and 4G LTE antennas.

Chapter 2: 4G Long-Term Evolution (LTE) Modem Selection

Requirements

The previous project final report listed detailed requirements for the LTE modem with Wi-Fi. The following are LTE modem selection criteria:

- The product search focused on the LTE modem with built-in Wi-Fi preferably with multiple-input and multiple-output (MIMO) support.
- The DJI M300 provides 24 VDC to power any external devices. Therefore, any LTE modem that does not support 24 VDC power input were rejected.
- For data collection and system evaluation purposes, the LTE modem must be able to provide system operational status data, such as LTD signal strength, network status, GPS location, time, and internal temperature via an application program interface (API).
- Different LTE modems may have a different LTE user equipment (UE) category (CAT) and class definitions. In general, higher UE CAT modems support higher communication speed. UE CAT 8 is the exception to this rule. Detail UE CAT information is available on the internet. Thus, a LTE modem with CAT supporting higher communication speed was preferred.
- Support for 5G and FirstNet features were secondary / lower priority.
- Availability – some viable test candidates were late found to be not available or have a long lead time (over 3 months).

Selected LTE Modem

Modem manufacturers, such as Sierra Wireless, Peplink, and Cradlepoint, websites were reviewed for any new products introduced after the previous project. Web searches were also performed to search for suitable products. In the previous project, the Sierra Wireless MP70 was selected for the LTE modem with Wi-Fi. In addition, AHMCT researchers were successful in pulling performance metrics data from Sierra Wireless MP and RV series LTE modems using a Python program. The modem performance metrics data are vital for data analysis and evaluation of the UASRE system performance. Our new literature review did not find any LTE Modem with Wi-Fi with significant improvement over the existing Sierra Wireless MP70 modem. Thus, the MP70 was selected for the UASRE system.

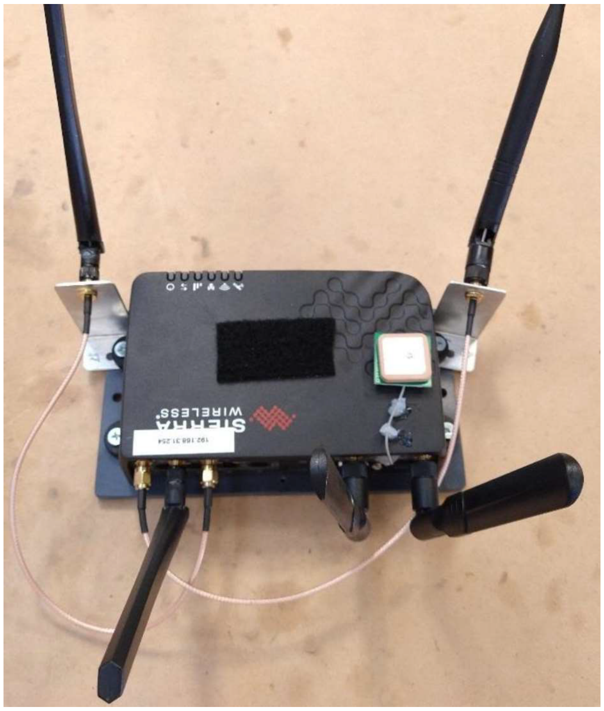

Figure 2.1: Sierra Wireless MP70 modem with Wi-Fi

Some new viable modem candidates (e.g., Sierra Wireless XR60) were announced in the middle of the UASRE system testing/evaluation phase. Thus, they were not considered. The XR60 operating system is different from the RV and MP series and uses a different way to pull performance data from the modem. In addition, 5G is not critical since it is generally not available in rural areas.

Table 2.1: Selected LTE Modems and their specifications comparison table

Make	Model#	Part#	Cost	Size (mm)	Weight	Wi-Fi	LTE	Power
Sierra Wireless	MP70	1104073	$1,099	190x45x 105	1.68 lbs	802.11 b/g/n/ac, 3x3 MIMO, "high output power "	FirstNet, Cat 12 600/150 mps	7-36V
Sierra Wireless	RV55	1104302	$949- $1,043	119x33x 102	0.7lbs / 320g	802.11ac, 2x2 MIMO, 16dbm output	FirstNet, Cat 12 600/150 mps	7-36V "low idle power"
Peplink	Peplink MAX BR1 Pro	MAX-BR1-PRO-GLTE-S-T-PRM	$1199	146.8 x 129 x 29.3	1.28lbs	2.4GHz@19dbm + 5GHz@19dbm 2x2 Wi-Fi 6	1x CAT-20	10-30V, 19W max
Peplink	Transit	MAX-TST-PRO-DUO-LTEA-USR-T-PRM, MAX-TST-5GD-T-PRM	$1,020	160x97x 33.5	1.3lbs / 590g	2.4GHz@19dBm+ 5GHz@21dBM 2x2 Wi-Fi 5, Wi-Fi mesh	FirstNet, ESN, Cat 12, 18, 5G	12-48V, 18W max
Peplink	BR1 Mini	MAX-BR1-MINI-LTEA-W-T-PRM		125.7 x 107 x 35	0.95 lbs / 430g	Simultaneous Dual-Band (2.4GHz / 5GHz) Wi-Fi 5, 2X2 MIMO	Cat6	
Peplink	Transit Duo	MAX-TST-DUO-LTEA-R-T	(quote need) ~$1200	160 x 97 x 33.5	1.3lbs / 590g	2.4GHz@19dBm+ 5GHz@21dBM 2x2 Wi-Fi 5 Wi-Fi mesh	FirstNet, Cat 12	12-48V, 18W max
Peplink	BR1 Pro 5G	MAX-BR1-PRO-5GH-T-PRM	$1,500	147 x 129 x 30	1.28 lbs / 580 g	2.4GHz@24dBm+ 5GHz@26dBM, 2x2 Wi-Fi 6	5G	10-30V, 19W max

Chapter 3:
Wi-Fi Antenna Selection

Requirements

The previous project final report provided detailed Wi-Fi requirements. Based on the previous project finding and experience, new Wi-Fi requirements have been added:

1) The UASRE system must not use any ground station. Previous project requires the use of a Wi-Fi ground station / repeater with high gain Wi-Fi antennas to maintain a stable high speed Wi-Fi connection to the UASRE. Physical ground station setup resulted in additional system setup time.
2) The Wi-Fi coverage requirement was reduced to meet the no ground station requirement. The UASRE must have Wi-Fi coverage for portable Wi-Fi client devices (iPhone and Android phone) directly under the UASRE within a 200 ft radius. The maximum UAS above the ground (AGL) is 350 ft in this use case.

Wi-Fi Antennas Selection

All-in-one LTE, Wi-Fi, and GNSS antennas were not considered due to the new Wi-Fi coverage requirement. In the preliminary UASRE design, the LTE and GNSS antennas will be placed on top of the UAS, and the Wi-Fi antennas are placed below the main body of the UAS and slightly higher than the landing legs in order to provide Wi-Fi signal coverage under the UAS. Therefore, the Wi-Fi, LTE, and GNSS antennas must be separated.

Wi-Fi antennas must be small enough to fit under the UAS body, with a total weight of under 3.5 lbs. The spacing between the UAS landing legs is 380 mm. Any Wi-Fi antennas larger than 380 mm would require modifications of the UAS landing leg. The published antenna weight may not be accurate, since it may include heavy mounting hardware that would not be used for the UASRE.

The researchers' selection of Wi-Fi antennas was primarily focused on the gain and beam pattern (beam angle), because different Wi-Fi antennas exhibit varying RF gain and beam patterns. A narrow directional beam angle delivers a stronger Wi-Fi signal to client devices directly beneath the UASRE. However, as the client device moves away from this central point, the signal strength drops off rapidly. In contrast, a wider beam angle increases the coverage area of the Wi-Fi signal, but at a lower average strength. The antenna gain and beam pattern serve as key factors in narrowing down the pool of candidate antennas for testing and evaluation in the specific UASRE use case conditions.

Web searches were performed to search for suitable Wi-Fi-only antennas in 2.4 and/or 5.8 Ghz frequencies. A data summary table was created with selected viable Wi-Fi antenna specifications. For each Wi-Fi antenna, the table contains information on size, weight, cost, gain, beam angle, RF frequencies, antenna type, and a hyperlink to its specifications. Any Wi-Fi antennas with a weight over 3.5 lbs or dimensions over 320 mm x 320 mm were rejected immediately, and their data were not entered into the Wi-Fi antenna data summary table. The antenna type data consisted of information such as Single, 3x3, or 2x2 MIMO, as well as the antenna design (patch, Yagi, or omni-direction). The Sierra Wireless MP70 Wi-Fi supports 3x3 MIMO diversity antenna configuration. The Patch antenna design is more suitable for the UASRE application than the Yagi antenna design, and the Yagi antenna height presents challenges in mounting the antennas under the UAS body.

For this research, Wi-Fi antenna test candidates were selected from the table for purchase and subsequently evaluated. Details of the Wi-Fi antenna evaluation are provided in Appendix B (Task 3)..

Chapter 4:
LTE Antenna Selection

Requirements

The previous project final report provided detailed LTE requirements. Based on the previous project finding and experience, LTE antennas will be mounted on top of the UAS. The MP70 modem supports a 2x2 MIMO LTE antenna. Thus, UASRE uses either two single LTE antennas or one 2x2 MIMO LTE antenna.

LTE Antennas Selection

Web searches were performed to search for suitable LTE antennas. A data summary table was created with selected viable LTE antenna specifications. The table contains information on Wi-Fi antenna size, weight, cost, gain, frequency range, antenna type, and hyperlink to its specifications. Any LTE antennas with a weight over 2 lbs were rejected immediately, and their data were not entered into the LTE antenna data summary table. The antenna type is either directional or omni-direction.

Directional LTE antennas generally have higher signal gain; however, directional LTE antennas are generally heavier and bulky, and they present challenges in mounting the antennas on the UAS without dramatically changing the UAS center of gravity location. Using directional LTE antennas would require the UAS operator to know the general direction to the closest LTE base station in the field. However, after an extensive search, the AHMCT researchers were unable to find a reliable comprehensive LTE station locations map. Pointing the UAS directional LTE antennas in the field would require the UAS operator to monitor the LTE signal strength information in real-time using a trial-and-error process. Consequently, the system setup time and effort would increase. Therefore, omni-directional LTE antennas are preferred for the UAS.

The LTE antenna test candidates were selected from the table for procurement and subsequent evaluation. Details of the evaluation are provided in the interim report for Task 3.

Appendix B: Interim Report for Task 3

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16. ABSTRACT

This report is part of AHMCT's research project "Development and Testing of an Unmanned Aerial System (UAS) Cellular & Wi Fi Repeater: Phase 2." The goal of this research is to expand upon the successful UAS aerial repeater that was created in Task 3280. The researchers evaluated several commercial off-the-shelf (COTS) vehicle routers and antennas to improve the ground wireless fidelity (Wi-Fi) network. After the components were selected, an easily assembled payload package was designed to mount to the UAS to create a useable communication network. The goal of the research is to evaluate the benefits and drawbacks of the aerial repeater concept through field testing. This document details the development of the second-generation payload package..

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Advanced Highway Maintenance and Construction Technology Research Center

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Development and Testing of an Unmanned Aerial System (UAS) Cellular & Wi Fi Repeater: Phase 2 - Develop and Optimize 2nd Generation Payload Package

Evan Sim, Anh Duong, Kin Yen, Dave Torick, and Shima Nazari

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April 28th, 2025

California Department of Transportation

Division of Research, Innovation and System Information

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List of Acronyms and Abbreviations

Acronym	Definition
AHMCT	Advanced Highway Maintenance and Construction Technology Research Center
Caltrans	California Department of Transportation
DRISI	Caltrans Division of Research, Innovation and System Information
COTS	Commercial Off–The-Shelf
CAD	Computer-aided Design
DOT	Department of Transportation
D1	District 1
GPS	Global Positioning System
N	Network
NNE	North-north-east
PLA	Polylactic Acid
RSSI	Received Signal Strength Indicator
RSRP	Reference Signal Received Power
RSRQ	Reference Signal Received Quality
SINR	Signal-to-Interference plus Noise Ratio
SR	State Route
SMA	Subminiature Version A
VOIP	Voiceover Internet Protocol
Wi-Fi	Wireless Fidelity

Acronym	Definition
3D	3-dimensional

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Chapter 1: Introduction – Field Trials and Analysis

Caltrans has many rural use cases where no current network communications exist outside of satellite services. Based on prior Advanced Highway Maintenance and Construction Technology (AHMCT) research, there currently exists a large cellular network in the rural districts, but the range of typical sites is significantly limited by surrounding terrain and foliage. There is a need to provide enhanced communications availability outside of current cellular offerings, without the requirement of a full-fledged investment in satellite equipment. Research performed under Phase 1 of Task 3280, showed that a UAS can elevate a payload into the cellular signal that is typically blocked by terrain and create a Wi-Fi network on the ground for worker communications. Refinement of the Unmanned Aerial System (UAS) payload is necessary to minimize deployment time and reduce the number of components necessary to establish a useable network. After the payload package has been optimized, It is necessary to conduct field trials to verify the success of the technology in various terrain situations with limited to no cellular network coverage. With a temporary Wi-Fi network in construction and emergency response areas, communication can now occur through emails and Wi-Fi calling, assisting in efficiency, resource management, and accurate equipment deployment for the first time in some rural districts.

The purpose of this report is to provide details on the development of the second-generation payload package seen with the UAS system. The report focuses on how the payload package was designed to maximize Wi-Fi signal at ground level.

Chapter 2:
Summary of Results

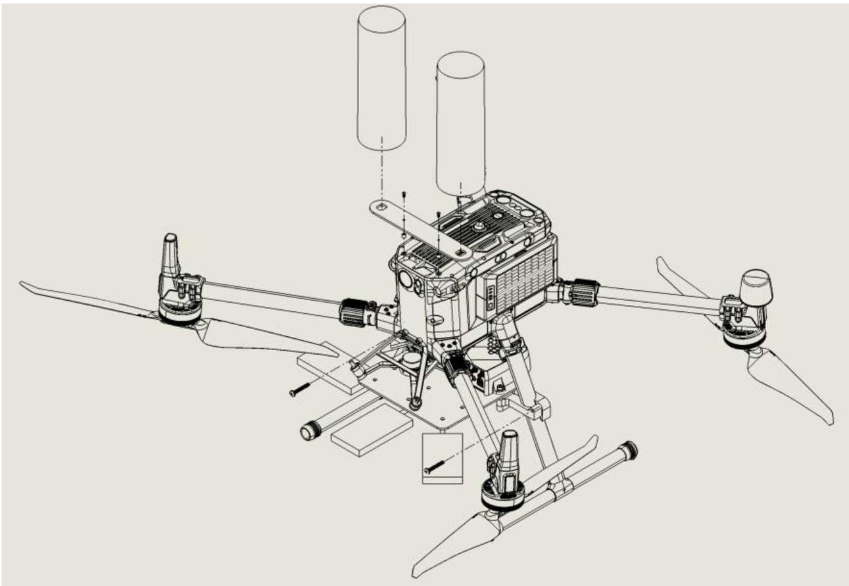


Figure 2.1: Drawing of final payload package in an exploded view

This chapter details the primary objectives of Task 3 and explains how the final payload package design fulfills these requirements.

Designed for deployment in remote regions of California, the updated payload package addresses and overcomes connectivity limitations posed by challenging terrain. Key design considerations included ensuring ease of installation, reliability, and optimal signal performance. The final design met all objectives outlined under Task 3 of the project proposal:

- Procurement of suitable components,
- Development of a second-generation payload package,
- Optimization for enhanced ground-level signal strength.

The final design also aligned with key objectives from the 2020-2024 Caltrans Strategic Plan, particularly:

1. **Safety First** – The system's ease of installation reduces operator exposure to potential hazards, enhancing their safety.
2. **Efficiency and Stewardship –** Simplified deployment ensures rapid setup, improving operational efficiency in the field.

The payload package incorporates:

- 3D-printed mounts with a hinge design and threaded inserts for streamlined setup.
- Custom-cut mounting plates for the modem, power components, and antennas.
- Three (3) APA-M25 8DB Wi-Fi antennas.
- Two (2) modified Proxicast cellular antennas.

Field tests conducted in Caltrans District 1 (D1) demonstrated the improved system's effectiveness:

- The payload withstood forces from takeoff, flight, and landing without failure.
- Full system assembly takes under six minutes.
- The design ensured proper functionality of all integrated components, including the DJI M300, wireless modem, and GPS antenna.
- The selected combination of cellular and Wi-Fi antennas maximized signal strength at ground level.

The following sections detail the system's design process, including COTS component selection, in-house fabrication, and field test results.

Chapter 3: Payload Mount Design

Preliminary Design

In the preliminary stage of the project, the design objective mounting solution was to hold the wireless modem, antennas, and mobile battery. The solution should keep these components fixed on the drone during takeoff, flight, and landing. To achieve this goal, the AHMCT team created the following requirements:

- Solution must not obstruct the downward facing camera on DJI M300.
- Solution must be positioned below the cellular antennas.
- Solution must allow for proper clearance for Wi-Fi antennas.
- Solution must be easy to install.
- Solution must be as light as possible.

The AHMCT team determined the payload capacity of the DJI M300 to be 2.7 kilograms (kgs) using specification sheets offered by the UAS manufacturer. With this maximum mass constraint, as well as the packaging limitations listed above, a leg-mounted solution with an upper antenna mounting plate was identified as the most effective design to execute.

A preliminary sketch for the mounts was first created in SolidWorks based on a pre-existing computer-aided design (CAD) file to ensure that the design would allow for proper clearance for the bottom-facing Wi-Fi antennas. This sketch can be seen in the figure below:

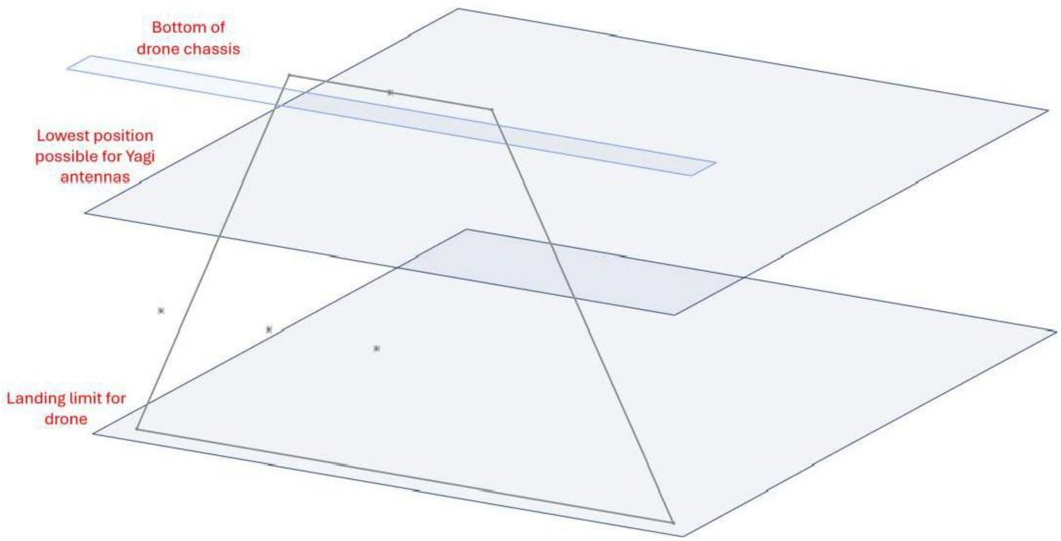


Figure 3.1: Preliminary sketch for packaging items on payload package

The second plane from the top was created particularly for the Yagi Wi-Fi antenna, which extends farther down compared to the other two solutions (this antenna is explored further in Chapter 4 of this report). Preliminary designs for the mounts and mounting plates were created as follows:

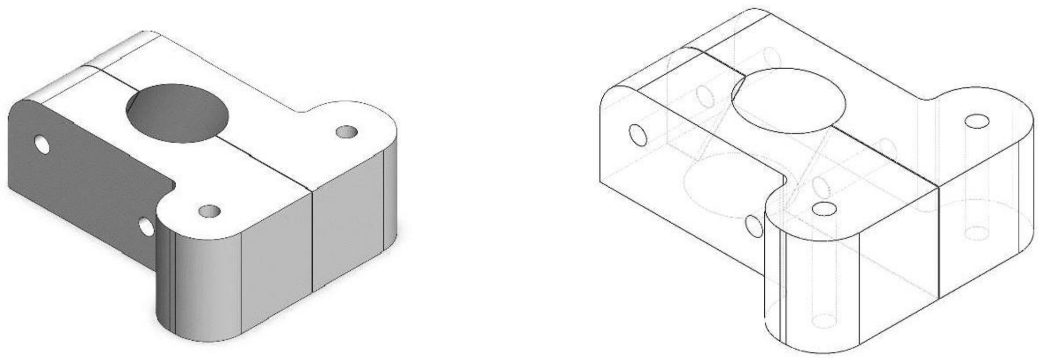


Figure 3.2: Rendering of first-generation 3D-printed mounts designed in CAD software

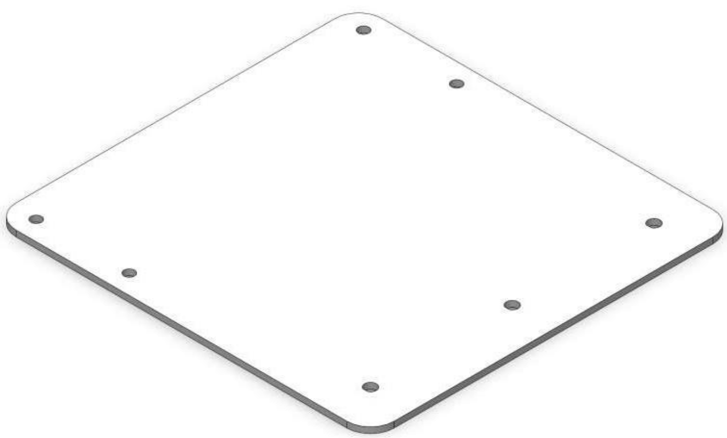


Figure 3.3: Rendering of first-generation modem mounting plate designed in CAD software

The mount design (shown in Figure 3.2) allows for direct attachment of the payload package to the legs of the drone. The mounts were secured using four (4) sets of nuts and bolts. The antenna mounting plate (Figure 3.3) and modem were affixed to the drone using four (4) more sets of nuts and bolts. Prior to fabrication, proper interface for these components was ensured using CAD software measurements.

The mounts seen in Figure 3.2 were created via 3D printing using polylactic acid (PLA) as the material. Polylactic acid was selected due to its material properties under the expected load conditions and its relatively low price. If the part fails during testing, engineers can quickly redesign it and fabricate a replacement at low cost and with high efficiency. The mounting plate was laser-cut from acrylic stock, which was chosen primarily for its rigidity. These two components are shown installed on the DJI M300 in Figure 3.4.

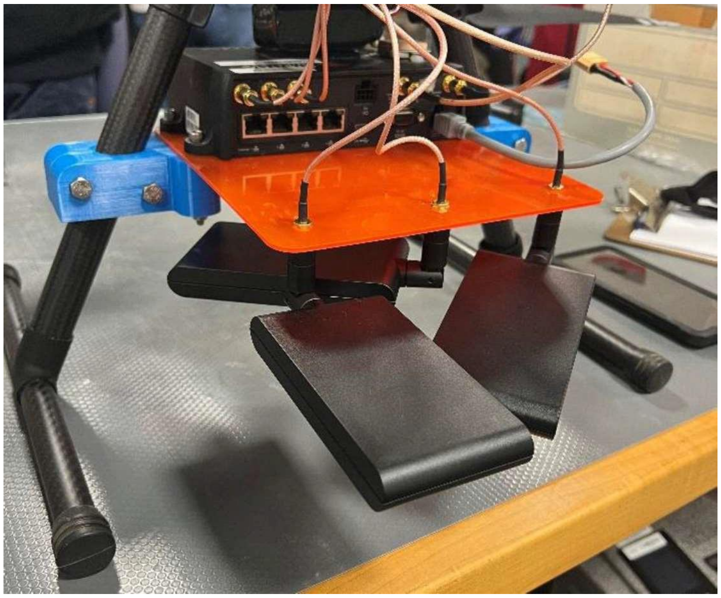


Figure 3.4: 3D-printed mounts and modem plate installed on the DJI M300

A mounting plate was also necessary to install the cellular antennas for the wireless modem. This plate was laser-cut from acrylic and mounted on top of the DJI M300 UAS using fasteners and two pre-existing mounting holes. The final iteration of the design utilizes this plate to hold the GPS antenna as well. The plate holds (2) cellular antennas, as shown in Figure 3.5.

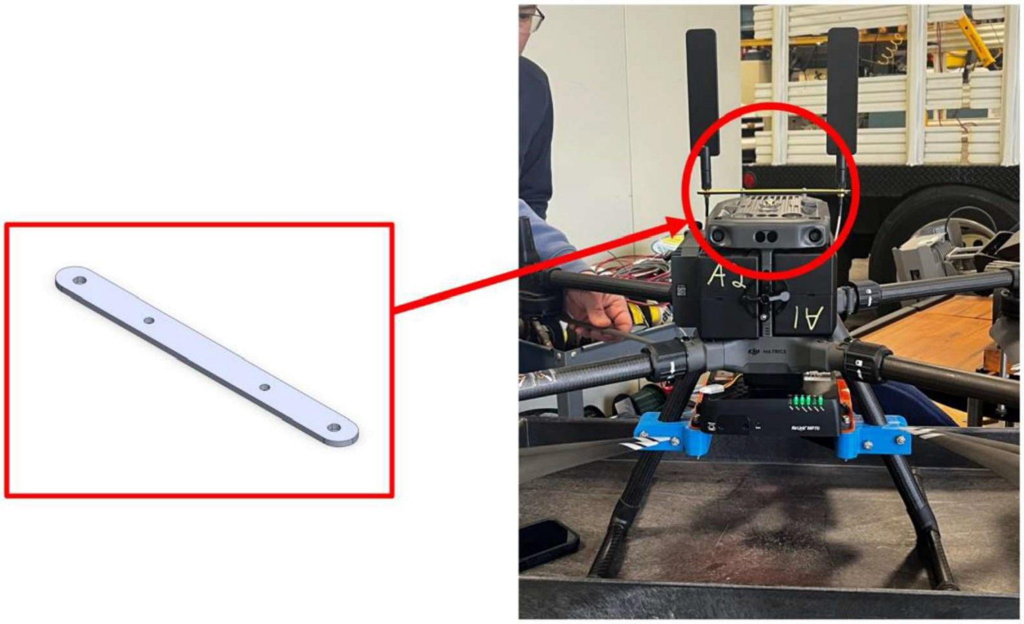


Figure 3.5: First version of cellular antenna mounting plate

Outcomes of Preliminary Design

Every component detailed above was fabricated and installed on the DJI M300 UAS for use in the first testing session for the system, which took place in April 2024. This testing session is described in detail in Chapter 4 of this report. The final mass characteristics were tabulated and are displayed in Table 3.1.

Table 3.1: Components of preliminary payload package design and their masses

Item	Unit Mass (g)	Quantity	Total Mass (g)
3D-Printed Mount	104	2	208
Modem Mounting Plate	122	1	122
Cellular Antenna Mounting Plate	11	1	11
Sierra Wireless Modem	742	1	742
APA Wi-Fi Antennas	58	3	174
Bingfu Cellular Antennas	32	2	64
Portable Battery	220	1	220
Cables	N/A	N/A	50
Hardware	N/A	N/A	100
		Payload Package Total Mass	1,729

Note: g = gram.

Figure 3.6 shows the first-generation payload package mounted onto the DJI M300 and the system being tested outdoors.

Figure 3.6: First-generation payload package mounted onto the DJI M300 and system testing conducted during the April 2024 testing session.

During the April 2024 testing session, all components of the payload assembly functioned correctly and withstood the forces seen during takeoff, flight, and landing. The results from the UAS experiments also revealed opportunities for several improvements to the system, as follows:

- The mass of both the 3D-printed mounts and modem mounting plate should be significantly reduced by creating fillets and removing material from both parts.
- The excessive number of fasteners in the 3D-printed mounts was not optimal. The design should instead use brass-threaded inserts to achieve the necessary clamping force to hold the components together.
- Installation should be simplified. The design of the 3D-printed mounts requires multiple steps for removal, as the two halves of the mounts are fastened with nuts and bolts and must be fully removed to detach the system. Implementing a hinge design will allow the system to remain intact during installation/removal.
- The cellular mounting plate only allowed for mounting antennas equipped with subminiature version A (SMA) adapters. Future iterations of the payload should use antennas equipped with network (N) adapters.
- The mounting plate was not rigid and wobbled when the cellular antennas were attached.

Updated Design

As a result of the April testing session, as well as testing sessions held in July and October, the final design of the payload package included changes. These included changes in COTS and fabricated components. The CAD layout of the system is shown in Figure 3.7.

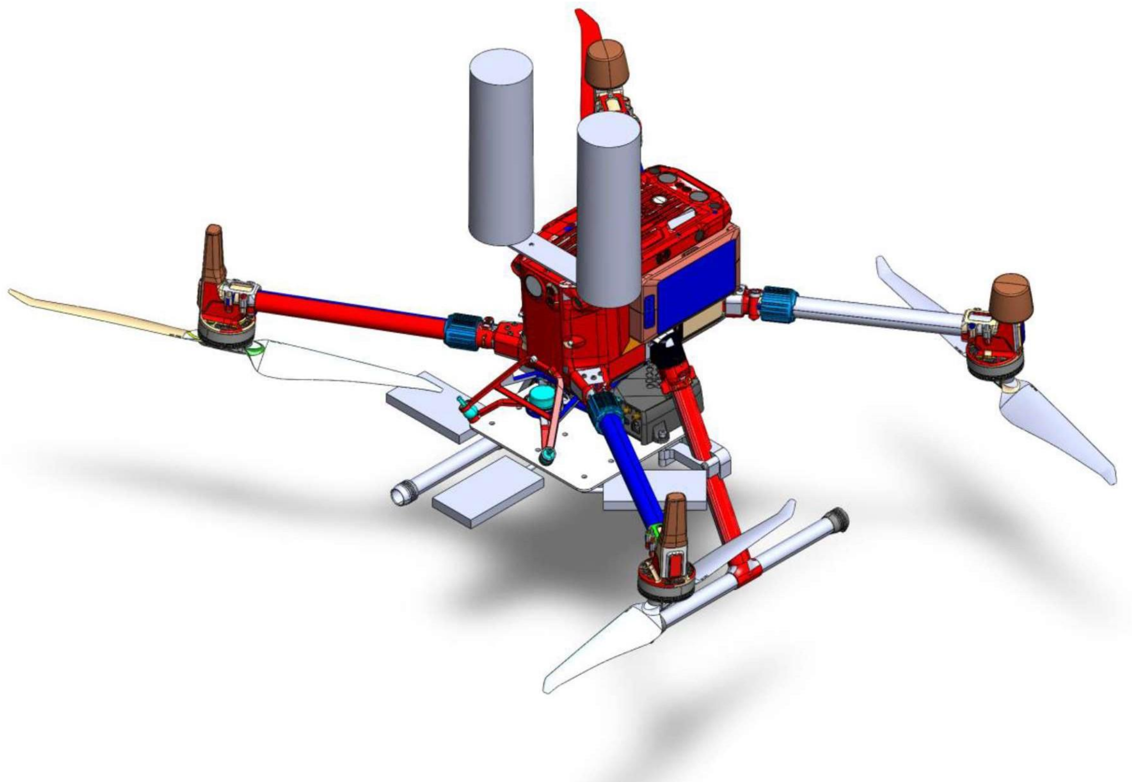


Figure 3.7: CAD layout of updated payload package design

The specific changes the researchers made to the design are described below and are shown in Figures 3.8 through 3.11.

3D-printed mounts

- Introduced a clamp design for ease of installation, so that the front-facing side of the mounts pivot along the bolt that holds the modem in place. This change also allows for the entire system to be kept intact during installation and removal. The operator attaches the antenna cable connections.
- Redesigned the mounts to fit brass-threaded inserts for the M5 bolts. This redesign was used for points where the mounts clamp to the DJI M300 legs and where the modem attaches to mounting plate.
- Removed excess material to decrease mass.

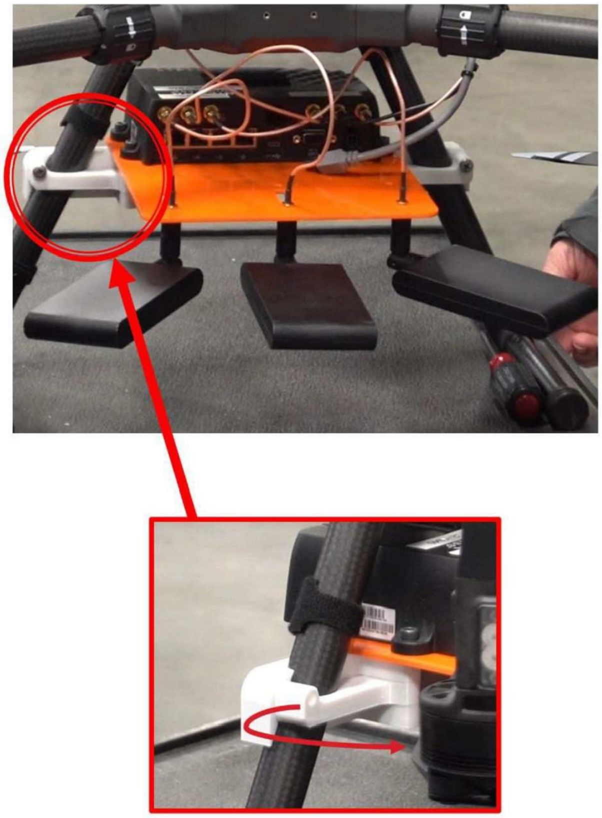


Figure 3.8: Diagram showing how the updated 3D-printed mounts work

Modem Mounting Plate

- A large cutout was made from the center of the mounting plate to lower the mass.
- Included one more row of holes to mount Wi-Fi antennas with SMA adapters.
- Removed the battery to power the modem directly from the drone using a USB-C adapter.

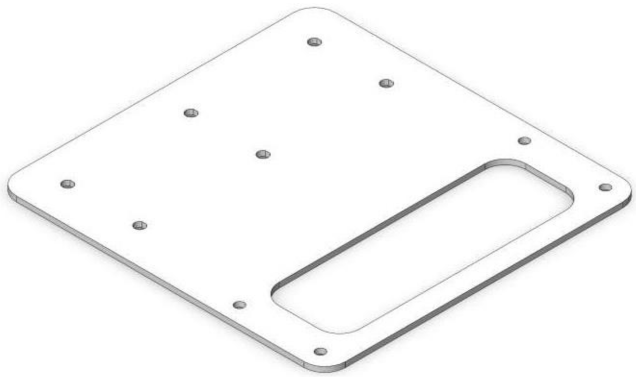


Figure 3.9: CAD of modem mounting plate

Cellular Antenna Mounting Plate

- Created a new mounting plate design that allows for N-adapter antennas to be used with the system.
- The part is made of aluminum to introduce more rigidity.
- The part now includes Velcro patch for attaching GPS antenna.

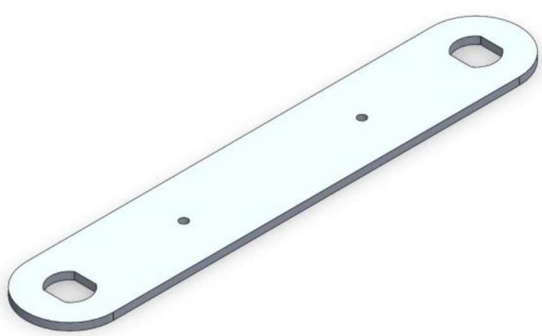


Figure 3.10: CAD of cellular antenna mounting plate

Cellular Antennas

- Proxicast cellular antennas were chosen due to their superior performance compared to the Bingfu antennas. Further details are provided in Chapter 4.
- The antennas were modified to reduce mass. The system will not be operated in wet conditions, so the waterproof casing was removed from the antennas to further decrease mass.

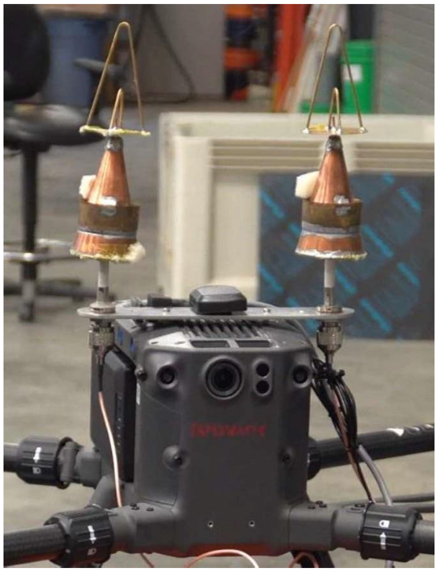


Figure 3.11: Modified Proxicast cellular antennas

Hardware

- The previous design required the use of Phillips-head and hex-head tools for installation. The hardware was changed so that Caltrans operators only need a single Phillips-head screwdriver to install the payload package.

A detailed drawing of the updated design and a bill of materials can be found in Appendix A.

Outcomes of the Updated Design

The final iteration of the payload package design introduced changes that accommodate the new antennas and facilitate the installation process. By simplifying the installation method with an updated mount design and hardware, the time taken to deploy the system in potentially hazardous locations is shortened. Furthermore, by reducing the mass of the payload package, installation is less cumbersome. Both of these improvements contribute to the safety and efficiency goals outlined in Chapter 1.

The improvements in the mass of the payload package are shown in Table 3.2.

Table 3.2: Components of updated payload package design and their mass

Item	Unit Mass (g)	Quantity	Total Mass (g)
3D-Printed Mount	62	2	124
Modem Mounting Plate	116	1	116
Cellular Antenna Mounting Plate	60	1	60
Sierra Wireless Modem	762	1	762
APA Wi-Fi Antennas	58	3	174
Proxicast Cellular Antennas	84	2	168
Cables	186	N/A	186
Fasteners	40	N/A	40
		Payload Package Total Mass	1,630

Deployment Time Study

A time study was conducted to determine the amount of time required to deploy the system from unpacking the DJI M300 until power-up. This time study involved filming and timing the setup of the system using a video camera and a stopwatch. The AHMCT team found that the time taken was less than six (6) minutes. Figure 3.12 displays the steps required for this process.

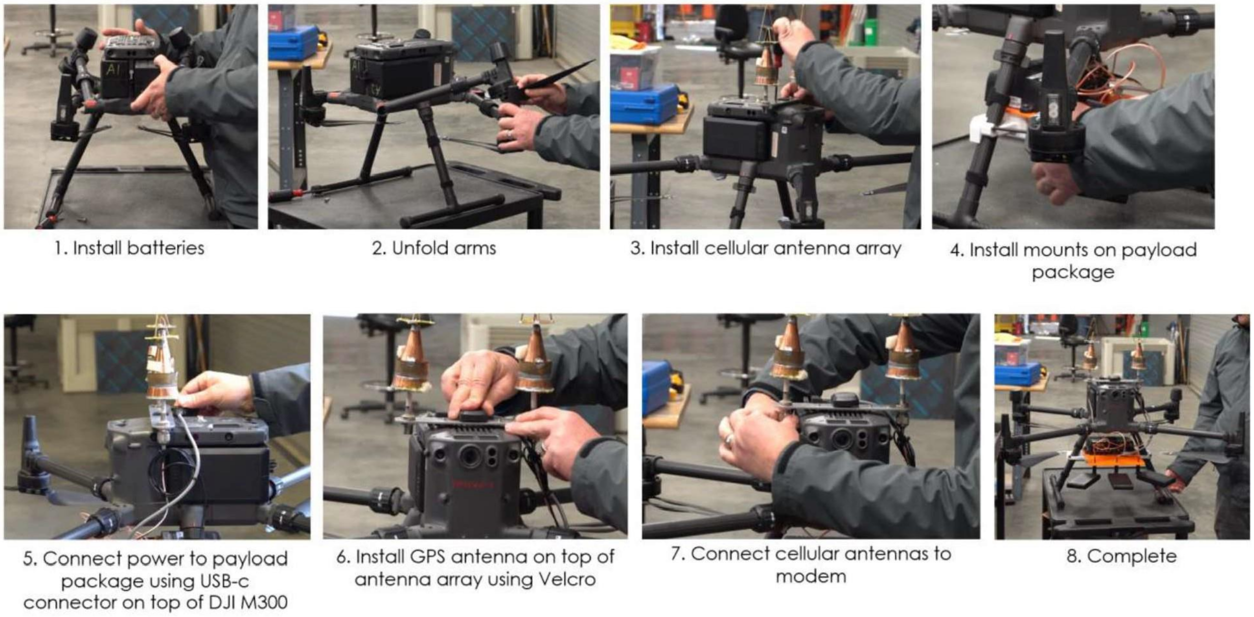


Figure 3.12: Steps involved in mounting the system to the DJI M300

As can be seen in Figure 3.12, the steps to install the system on the DJI M300 drone were such that clearance problems were avoided. Steps such as installing the batteries, cellular antenna array, and mounts were taken before making the wire connections for this reason.

Chapter 4: Antenna Selection

The aerial repeater system makes use of Wi-Fi and cellular antennas to retrieve a signal to which users can connect. Thus, the selection of these antennas was a critical consideration, as they play a vital role in allowing for a consistent and strong signal. Furthermore, the antenna choices varied considerably in their coverage area. The AHMCT team conducted numerous testing sessions to ensure that the antennas selected were best suited for the use cases stated in the project proposal.

To determine the best possible option for both sets of antennas, the AHMCT team first devised a list of parameters that were to be collected during the preliminary testing sessions. The parameters are shown in Table 4.1.

Table 4.1: Parameters tested for Wi-Fi antennas

Parameter	Units
Signal strength (best)	dBm
Signal strength (worst)	dBm
Upload speed	Mbps
Download speed	Mbps
Latency	ms
Retransmission	%
Email Latency	s

Each of the parameters shown in the table are defined below.

- **Download/upload speed:** the rate at which device can download incoming data and send outgoing data, respectively.
- **Signal strength:** the amount of power received by a wireless device from wireless transmitter (antenna).
- **Latency:** the amount of time taken for data packet to travel from a source to a destination and back.
- **Retransmission %:** the percentage of data packets that need to be resent in a network due to errors or packet loss during initial transmission.
- **Email Latency:** the amount of time taken to receive an email while connected to the aerial repeater's wireless modem from an iPhone.

The AHMCT team also determined whether calling via voiceover internet protocol (VOIP) was possible. Of these parameters, upload speed and email latency were determined to be the most important, due to the expected use cases for the system. Namely, the AHMCT team anticipated that Caltrans operators would most likely use the aerial repeater system to contact others via email communication, making both upload speed (for sending emails,) and email latency (for receiving emails,) a critical consideration in the antenna selection process.

Wi-Fi Antenna Testing

April 2024 Testing

The first testing session held by the AHMCT team was intended to inform a decision for which Wi-Fi antennas to utilize. During this time, the first iteration of the payload package was complete and installed on the DJI M300. The testing took place on April 12, 2024, and April 15, 2024, at Woodland-Davis Aeromodellers Field.

In preparation for testing, the AHMCT team developed a test plan in which the vertical and horizontal distances from the system were varied from 0 ft to 350 ft and 0 ft to 200 ft, respectively. These intervals were chosen to ascertain the distance in each direction at which each antenna functions optimally.

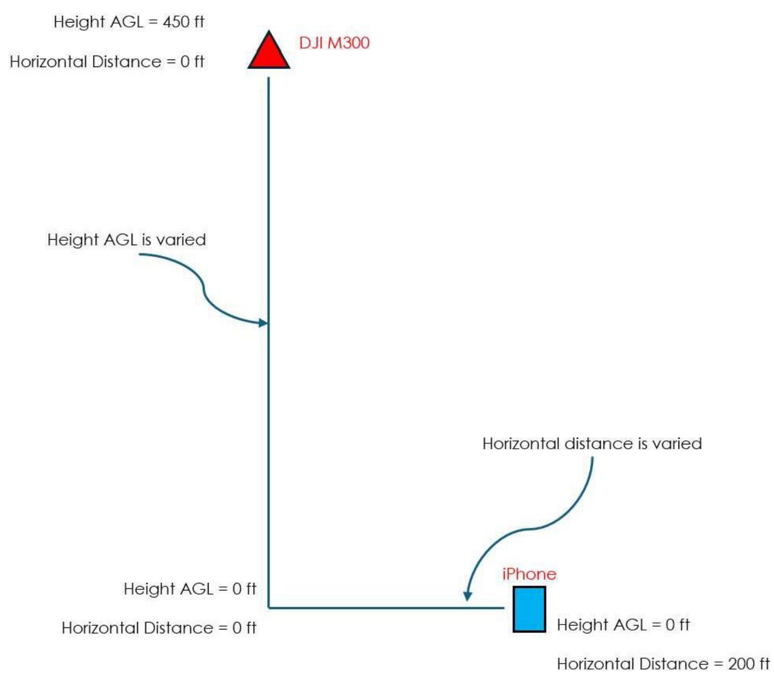


Figure 4.1: Diagram showing positions/distances of drone and iPhone during April testing

The AHMCT team started with three (3) options for the Wi-Fi antennas, shown in Table 4.2.

Table 4.2: Wi-Fi antenna contenders

Antenna	Type	Single Antenna Mass (g)
Bingfu	Omnidirectional	16
APA M25-8DB	Directional panel	58
Yagi	Directional PCB	22

Note: g = gram.

For this testing session, the parameters in Table 4.1 were collected using online internet test tools and applications on an iPhone. An iPhone was specifically used due to its ubiquity amongst Caltrans operators. The parameters were logged manually at each distance for this testing session, but would later be logged automatically and with greater granularity using a Python script.

A complete set of this data can be seen in Appendix B. The AHMCT team determined that the most pertinent data were collected when varying the height AGL at each horizontal extreme. This decision also guided future testing efforts. Data for this particular range can be seen in Figures 4.2 through 4.7.

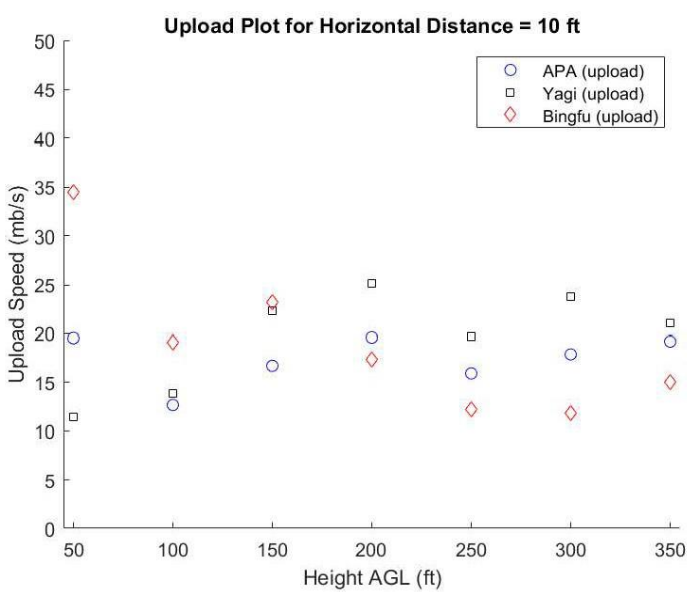


Figure 4.2: Upload speed plot for horizontal distance = 10 ft, varied with height AGL

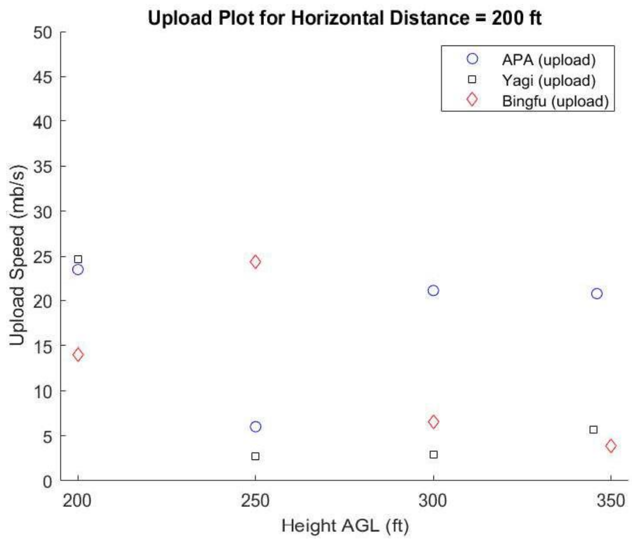


Figure 4.3: Upload speed plot for horizontal distance = 200 ft, varied with height AGL

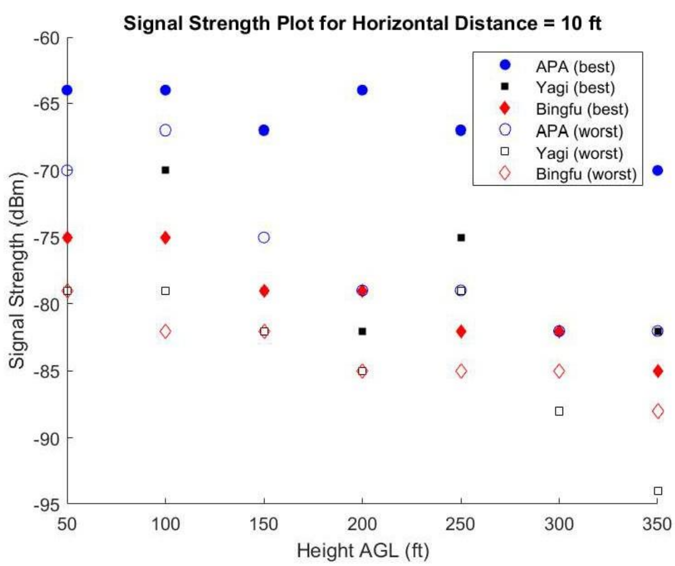


Figure 4.4: Signal strength plot for horizontal distance = 10 ft, varied with height AGL

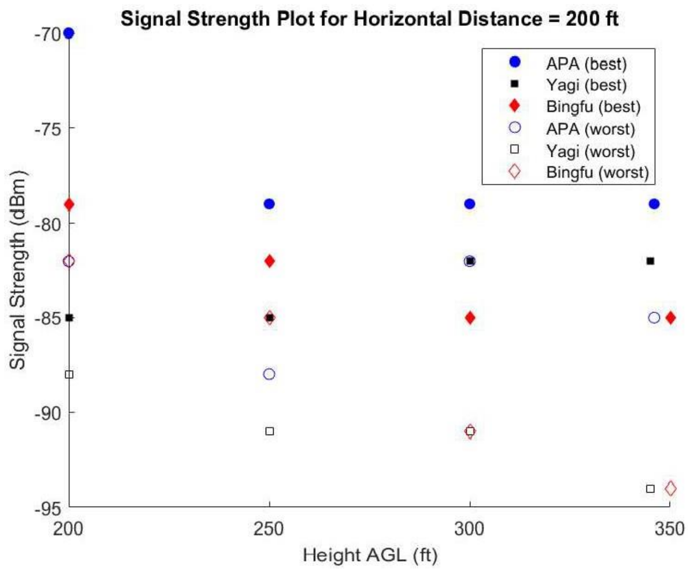


Figure 4.5: Signal strength plot for horizontal distance = 200 ft, varied with height AGL

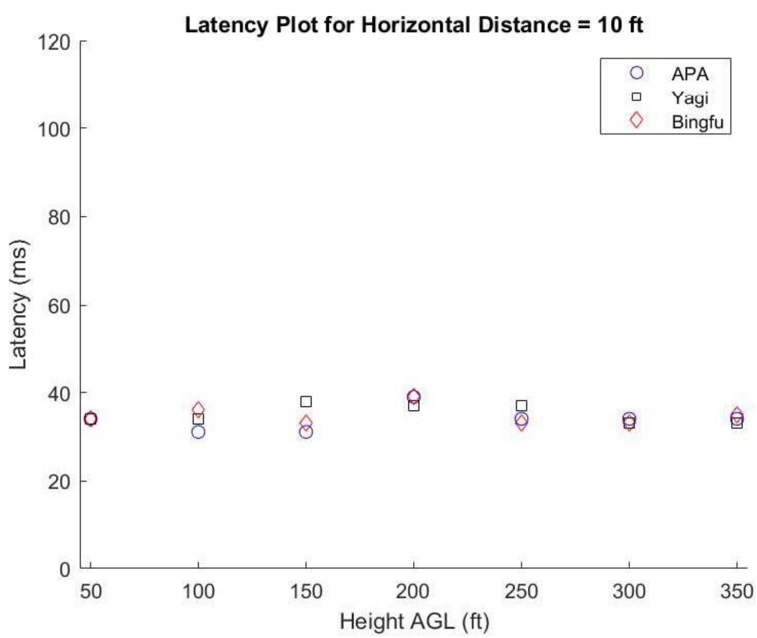


Figure 4.6: Latency plot for horizontal distance = 10 ft, varied with height AGL

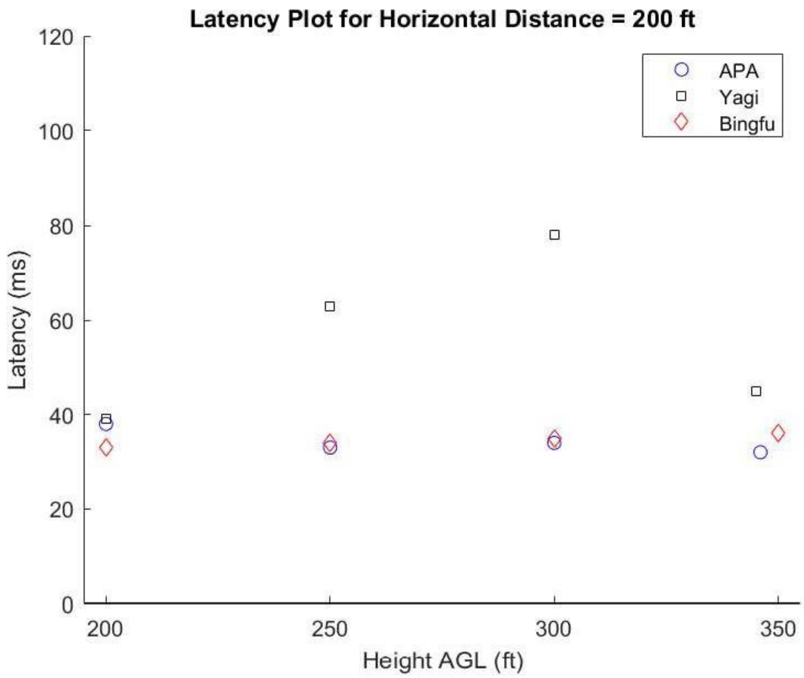


Figure 4.7: Latency plot for horizontal distance = 200 ft, varied with height AGL

Table 4.3 displays the average retransmission percentage and email latency for the three tested Wi-Fi antennas.

Table 4.3: Average retransmission % and email latency for the three Wi-Fi antennas

Variable	APA	Yagi	Bingfu
Average retransmission %	0.29	1.33	0.24
Average email latency (s)	8.53	10.20	7.60

The data shown in Figures 4.2 through 4.7 and Table 4.3 suggest that the APA and Bingfu antennas consistently outperformed the Yagi antennas in each parameter. The Yagi antennas were seen to be less predictable, especially when observing latency at a horizontal distance of 200 ft. Furthermore, while the Yagi provided competitive upload speeds at closer horizontal distances, this was not the case as this distance increased. It also showed poor signal strength at both horizontal distances and a higher average latency/retransmission percent.

However, VOIP and email communication was possible at every distance for all antennas (detailed data can be seen in Appendix B.)

In order to better quantify the parameters observed, the AHMCT team created a decision matrix for these three antenna choices. A weight was given to each parameter of interest; then, a score for each parameter was given to each antenna choice based on its performance observed during the testing session. This decision matrix can be seen in Table 4.4.

Table 4.4: Weighted decision matrix for Wi-Fi antennas

Parameter	**Weight***	**APA**	**Yagi**	**Bingfu**
Upload speed	2	9	6	7
Download speed	1	7	3	8
Signal strength	1	10	4	6
Latency	2	8	6	10
Retransmission %	1	8	6	9
Email Latency	1	8	6	9
Totals	80	67	43	66
	Score	83.8%	53.8%	82.5%
	Rank	**1**	**3**	**2**

Note: Each weight is a multiplier that is included in the total score for each antenna.

The table above indicates that the APA M25-8DB was the best Wi-Fi antenna choice for the system. However, because there was only a 1.3% difference between the APA M25-8DB and the Bingfu antennas, the AHMCT team decided that another testing session would be required to make a firm decision.

July Testing

The AHMCT team returned to Woodland-Davis Aeromodellers Field on July 26, 2024, to perform another testing session (Figure 4.8). The objectives of this testing session were to test the updated ground-based system and to collect data to inform a final decision on the Wi-Fi antenna used.

Figure 4.8: Field test on July 26th, 2024. The picture shows the drone system being deployed and the ground-based system collecting data.

As mentioned in the April testing section, the AHMCT team opted to collect data at a smaller number of distance intervals, shown in Table 4.5.

Table 4.5: Distances tested for Wi-Fi antennas during July session

Horizontal distance tested (ft)	Vertical distances tested (ft)
10	100
10	350
100	100
100	350
200	150
200	350

Three trials were completed for each distance. The same parameters from the April testing session were collected for each distance and were logged manually (a complete set of this data can be seen in Appendix C.) However, during this session, two logging scripts were also run simultaneously to automatically acquire signal level, upload speed, and download speed data. This allowed for plots with greater continuity to be acquired. Figures 4.9 and 4.10 show sample plots that were created using the data collected during this testing session. A complete set of plots can be found in Appendix C.

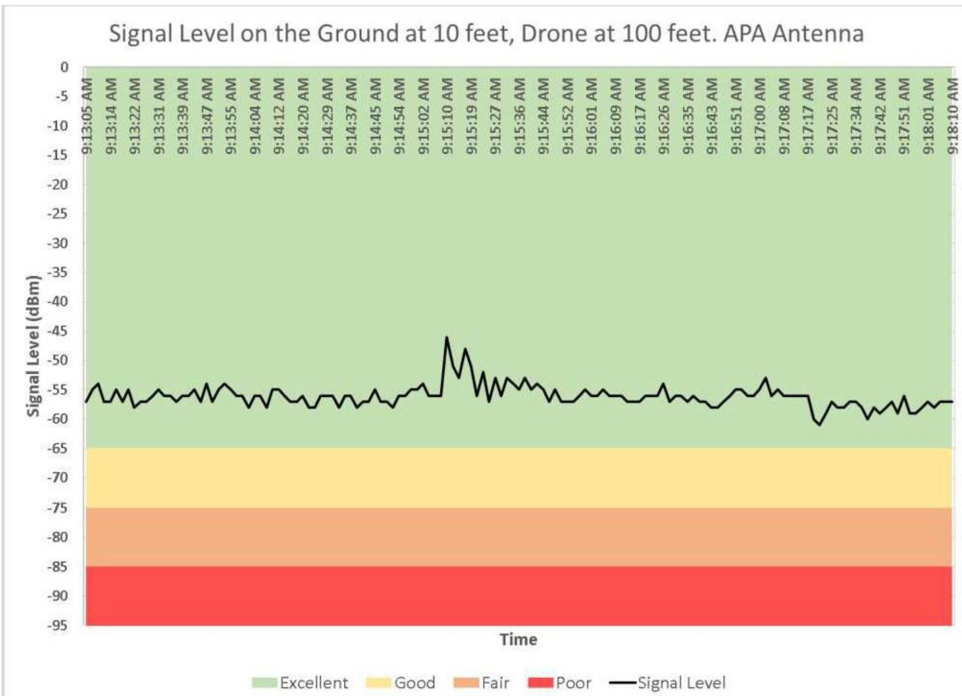


Figure 4.9: Signal level plot for horizontal distance = 10 ft and height AGL = 100 ft varied with time, for APA antenna

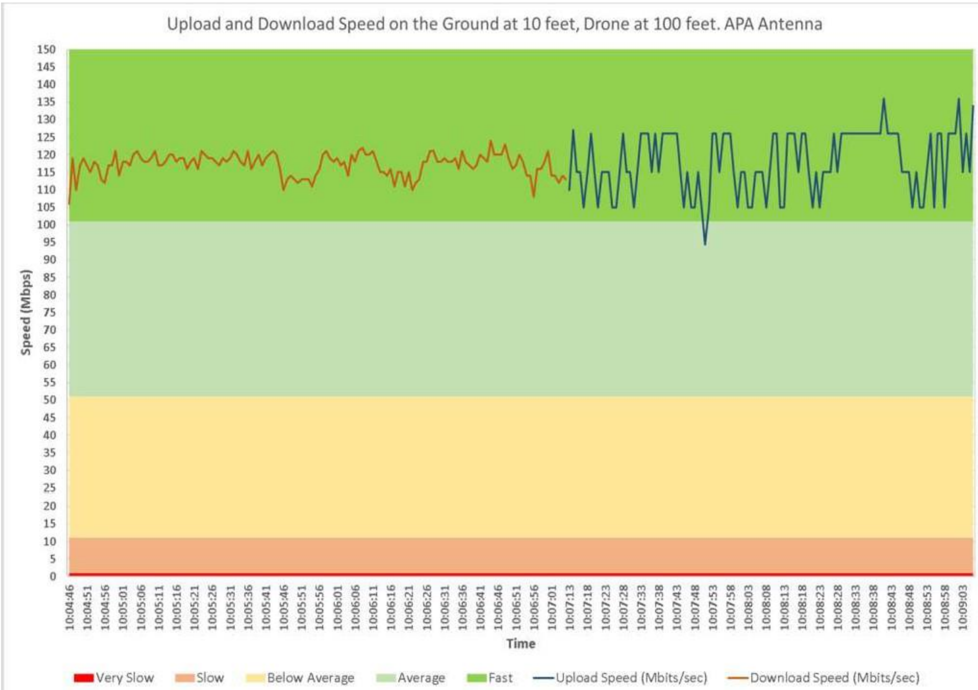


Figure 4.10: Upload/download speed plot for horizontal distance = 10 ft and height AGL = 100 ft varied with time, for APA antenna

The two plots above suggest that of the two antennas, the APA showed the most promising results both in upload speed and signal level. The overall results of the testing, including average values for the desired parameters at each distance, are displayed in Table 4.6.

Table 4.6: Signal level, upload speed, and download speed results from July session

Height / Horizontal Distance	APA Wi-Fi Antenna	Bingfu Wi-Fi Antenna
Height AGL = 100 ft / Horizontal distance = 10 ft	Signal Level -56.1 dBm, Upload 117.9 Mbps, Download 117.2 Mbps	Signal Level -64.1 dBm, Upload 47.3 Mbps, Download 20.4 Mbps
Height AGL = 350 ft / Horizontal distance = 10 ft	Signal Level -67.8 dBm, Upload 65.2 Mbps, Download 84.6 Mbps	Signal Level -78.2 dBm, Upload 0.008 Mbps, Download 0.38 Mbps
Height AGL = 100 ft / Horizontal distance = 100 ft	Signal Level -72.9 dBm, Upload 55.3 Mbps, Download 47.0 Mbps	Signal Level -67.0 dBm, Upload 30.0 Mbps, Download 65.6 Mbps
Height AGL = 350 ft / Horizontal distance = 100 ft	Signal Level -73.2 dBm, Upload 58.2 Mbps, Download 39.7 Mbps	Signal Level -69.8 dBm, Upload 3.74 Mbps, Download 11.8 Mbps
Height AGL = 150 ft / Horizontal distance = 200 ft	N/A, Unable to connect	Signal Level -71.5 dBm, Upload 12.9 Mbps, Download 25.6 Mbps
Height AGL = 350 ft / Horizontal distance = 200 ft	Signal Level -81.0 dBm, Upload 1.28 Mbps, Download 2.51 Mbps	Signal Level -70.0 dBm, Upload 2.30 Mbps, Download 7.66 Mbps

Table 4.7 outlines the email latency and VOIP results from the testing.

Table 4.7: Email latency and VOIP results for APA Wi-Fi Antenna from July session

Height / Horizontal Distance	Average Email Latency	Standard Deviation	VOIP possible?
Height AGL = 100 ft / Horizontal distance = 10 ft	6.09	0.67	Y
Height AGL = 350 ft / Horizontal distance = 10 ft	8.15	2.32	Y
Height AGL = 100 ft / Horizontal distance = 100 ft	7.13	0.73	Y
Height AGL = 350 ft / Horizontal distance = 100 ft	9.87	3.42	Y
Height AGL = 150 ft / Horizontal distance = 200 ft	Unable to connect	N/A	Y
Height AGL = 350 ft / Horizontal distance = 200 ft	33.64	27.16	Y

Table 4.8: Email latency and VOIP results for Bingfu Wi-Fi Antenna from July session

Height / Horizontal Distance	Average Email Latency	Standard Deviation	VOIP possible?
Height AGL = 100 ft / Horizontal distance = 10 ft	7.80	1.37	Y
Height AGL = 350 ft / Horizontal distance = 10 ft	12.12	2.05	Y
Height AGL = 100 ft / Horizontal distance = 100 ft	5.57	0.83	Y
Height AGL = 350 ft / Horizontal distance = 100 ft	12.72	5.07	Y
Height AGL = 150 ft / Horizontal distance = 200 ft	6.69	1.06	Y
Height AGL = 350 ft / Horizontal distance = 200 ft	10.20	1.81	Y

Tables 4.7 and 4.8 shows the average latency seen while sending emails as well as its standard deviation and whether VOIP was possible at each distance. The data suggests a large spike in latency while using the APA antennas at horizontal distance = 200 ft, height AGL = 350 ft. This spike can be treated as an outlier in the data. Table 4.8 ignores these outliers and presents the average values for both antennas.

Table 4.8: Email latency and VOIP results from July session (excluding outlier data)

Antenna	Average Email Latency (s)	Standard Deviation (s)	VOIP possible?
APA	9.44	4.45	Y
Bingfu	9.18	2.03	Y

As can be seen in tables 4.6 through 4.8, the APA antenna showed higher upload/download speeds and signal levels at closer distances, particularly when the ground logging device was positioned at a horizontal distance of 10 ft. The Bingfu antenna showed higher upload/download speed at greater distances, especially when the ground logging device was positioned at a horizontal distance of 200 ft.

In the final design, the APA antenna was chosen as the Wi-Fi antenna to be implemented. This decision was made largely due to the expected use case of the system; the AHMCT team anticipates that the system will not be used frequently at a large horizontal distance from the drone. However, operators may fly the drone to a higher height to achieve a better signal, therefore making the APA antenna the superior option.

Cellular Antenna Testing

A final decision on the cellular antennas used for the aerial repeater was required before field testing. During previous tests, the Bingfu antennas were used by default. However, further testing was needed to determine whether there was an antenna better suited towards the project objectives. The AHMCT team tested four alternative cellular antennas against the Bingfu antennas. These options are shown in Table 4.9.

Table 4.9: Cellular antenna options

Make	Model	Type	Mass (g)
Eifagur	Long range LTE antenna	Omnidirectional	330
Tredault-Tec	Cellular trail camera antenna	Omnidirectional	28
Proxicast	Wide range pole mount antenna	Omnidirectional	84 (without casing)
XDRS-RF	Wideband directional antenna	Directional	678
Bingfu	4G LTE cellular antenna	Omnidirectional	36

Figure 4.11 shows product photos of the five cellular antenna options: Eifagur, Tredault-Tec, Proxicast, XDRS-RF, and Bingfu.

Figure 4.11: Cellular antenna options (from left to right: Eifagur, Tredault-Tec, Proxicast, XDRS-RF, Bingfu.)

The AHMCT team also decided on a list of parameters that would be observed while ranking these options. The parameters are as follows:

- RSSI (Received Signal Strength Indicator)
- RSRP (Reference Signal Received Power)
- RSRQ (Reference Signal Received Quality)
- SINR (Signal-to-Interference plus Noise Ratio)
- Mass
- Packaging

These parameters were observed directly through the Sierra Wireless portal and logged manually.

October Testing

Testing occurred on October 18, 2024, in the fields behind an AHMCT facility. The testing involved connecting the antennas to the wireless modem and manually logging the parameters at ground level.

While testing the directional antenna, a caveat became evident: this antenna had a particular direction in which it optimally operated. During testing, this direction was North-Northeast (NNE), which was the direction of the nearest cell tower associated with Verizon, the wireless provider chosen for the system. During deployment, the most optimal direction can only be predicted if the location of the nearest cell tower is known. The AHMCT team took this into consideration when deciding which cellular antennas to utilize. The results of this testing session are displayed in Table 4.10, and the reference ranges for parameters of interest are shown in Table 4.11.

Table 4.10: Results from October session

Parameter	Bingfu	Cellular Trail	Eifagur	Proxicast	Directional (NNE)
RSSI (dBm, average)	-69.33	-62.75	-80.00	-62.00	-60.00
RSRP (dBm, average)	-97.00	-96.00	-109.00	-90.25	-88.00
RSRQ (dB, average)	-9.33	-13.00	-18.00	-12.00	-13.00
SINR (dB, average)	8.33	3.15	2.78	8.65	5.10
Mass per antenna (g)	36	28	330	84 (without casing)	678

Table 4.11: Reference ranges for parameters of interest

Parameter	Poor	Strong
RSSI (dBm)	-120	-50
RSRP (dBm)	-140	-80
RSRQ (dB)	-19.5	-3
SINR (dB)	-10	30

As can be seen above, the Proxicast antenna was selected to be used in the final iteration of the payload package. Although the data suggests that the other antennas outperformed the Proxicast in RSRP, RSRQ, and SINR, the AHMCT team deemed the Proxicast to be the most balanced choice. Furthermore, before installing the payload package, the AHMCT team removed the waterproof casing of the antennas, subsequently reducing their mass and making installation easier.

Chapter 5: Conclusion

The final iteration of the payload package was successful in meeting all the technical criteria outlined in the project proposal. The final iteration maximizes the potential of the design in ease of installation and performance, as suggested by data collected over the testing sessions. The specific goals outlined for Task 3 of the project and how the AHMCT team met them are explained in Table 5.1.

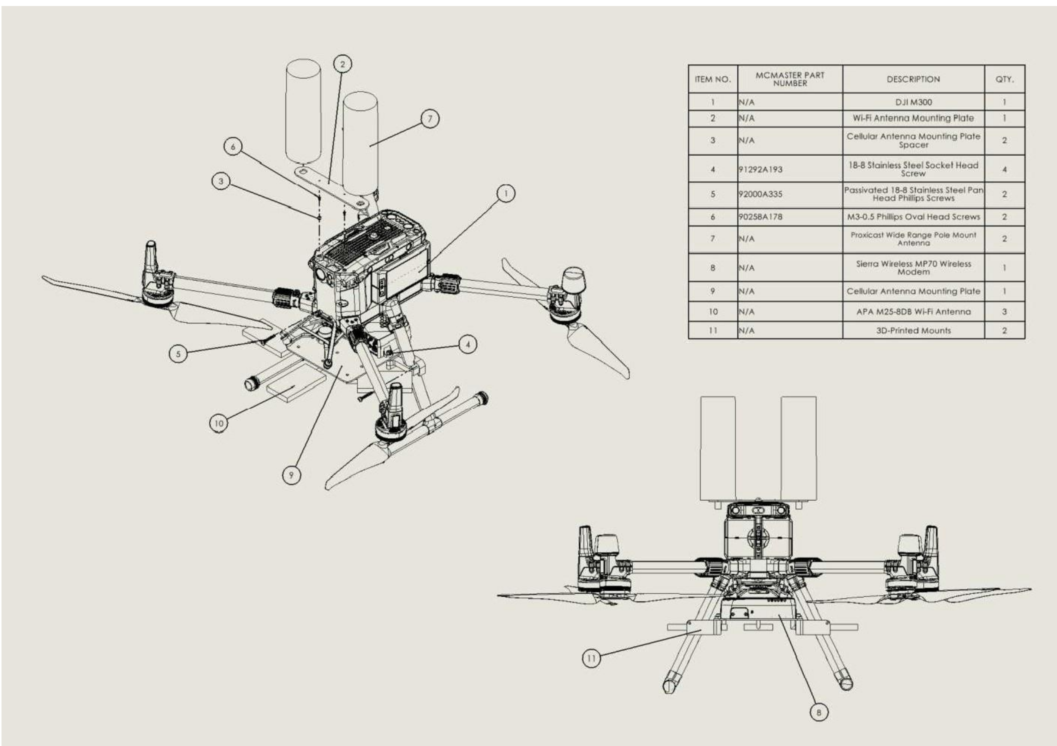
Table 5.1: Goals outlined in project proposal and how the goals were met

Goal	How the goal was met
Procurement of selected router, antennas, and other required accessories and components.	Research was carried out based on the criteria described in Task 2 of the project. Based on these requirements, components were selected and procured. (Described in greater detail in the Task 2 Interim Report.)
Design of the second generation of the payload package	Two (2) design iterations were developed for the payload package. Test sessions were held in the months of April, July, and October of 2024. Improvements in both COTS and fabricated components were made, based on results from testing. (Mass, ease of installation.)
Optimize Wi-Fi strength at ground level	Test sessions were held in April, July, and October of 2024. Choices for cellular and Wi-Fi antennas were verified or changed, based on the results of testing. (Quantitative data were collected by scripts and mobile internet test applications.)

As mentioned in the table above, the procurement of the selected router is described in the interim report for Task 2. As part of Tasks 4 and 5 of the project, the system was tested in more rigorous field trials, during which the payload package functioned without issue. (These field tests are described in the Interim Report for Task 5.)

Theoretical future considerations for the design include making existing components more robust through alternative manufacturing methods/materials. This change would be implemented to allow the payload package to withstand harsher or more frequent load conditions. Although this change may present some trade-offs in terms of the weight of the payload package, it would allow for greater durability of 3D-printed and laser cut components that may otherwise fail with excessive use.

Appendix A: Payload Package Drawing and Bill of Materials



ITEM NO.	MCMASTER PART NUMBER	DESCRIPTION	QTY.
1	N/A	DJI M300	1
2	N/A	Wi-Fi Antenna Mounting Plate	1
3	N/A	Cellular Antenna Mounting Plate Spacer	2
4	91292A193	18-8 Stainless Steel Socket Head Screw	4
5	92000A335	Passivated 18-8 Stainless Steel Pan Head Phillips Screws	2
6	90258A178	M3-0.5 Phillips Oval Head Screws	2
7	N/A	Proxicast Wide Range Pole Mount Antenna	2
8	N/A	Sierra Wireless MP70 Wireless Modem	1
9	N/A	Cellular Antenna Mounting Plate	1
10	N/A	APA M25-8DB Wi-Fi Antenna	3
11	N/A	3D-Printed Mounts	2

Figure A.1: SOLIDWORKS drawing of payload package and bill of materials

Appendix B:
April Testing Raw Data

	APA-M25 8DB	Yagi	Bingfu	APA-M25 8DB	Yagi	Bingfu	APA-M25 8DB	Yagi	Bingfu	APA-M25 8DB	Yagi	Bingfu	APA-M25 8DB	Yagi	Bingfu	APA-M25 8DB	Yagi	Bingfu	APA-M25 8DB	Yagi	Bingfu
Height AGL (ft)	Signal Strength (dBm)	Signal Strength (dBm) 2	Signal Strength (dBm) 3	connection download speed (Mb/s	connection download speed	connection download speed	connection upload speed (Mb/s	connection upload speed	connection upload speed	Latency (ms	Latency (ms)2	Latency (ms)3	Retransmiss ion (%)	Retransmiss ion (%)2	Retransmiss ion (%)3	Email Possible?	Email Possible?2	Email Possible?3	Email latency (s)	Email latency (s)2	Email latency (s)3
50	B-64, W-70	B-75, W-79	B-75, W-79	26.62	27.63	30.57	19.54	11.41	34.45	34	34	34	0	0	0	Y	Y	Y	5.24	8.2	8.07
100	B-64, W-67	B-70, W-79	B-75, W-82	13.44	18.62	17.74	12.67	13.88	19.11	31	34	36	0	0	0	Y	Y	Y	7.94	8.38	8.28
150	B-67, W-75	B-79, W-82	B-79, W-82	24.44	5.51	11.49	16.71	22.37	23.23	31	38	33	0	0.06	0	Y	Y	Y	7.78	10	6.74
200	B-64, W-79	B-82, W-85	B-79, W-85	5.16	4.97	10.28	19.6	25.16	17.4	39	37	39	0	0.39	0	Y	Y	Y	5.36	9.57	7.42
250	B-67, W-79	B-75, W-79	B-82, W-85	8.62	6.82	18.15	15.93	19.67	12.21	34	37	33	0	0	0.09	Y	Y	Y	8.09	6.87	6.74
300	B-64, W-82	B-82, W-88	B-82, W-85	8.76	8.14	13.45	17.89	23.81	11.84	34	33	33	0	0	0.1	Y	Y	Y	6.62	6.62	6.22
350	B-70, W-82	B-82, W-94	B-85, W-88	9.43	9.23	7.19	19.21	21.04	15.05	34	33	35	0	0	0.32	Y	Y	Y	9.11	11.48	7.07
50																					
100																					
50	B-64, W-79	B-70, W-82	B-70, W-82	30.19	37.34	45.75	17.94	18.09	24.31	31	33	34	0	0	0.07	Y	Y	Y	8.09	8.52	5.81
100	B-70, W-82	B-79, W-88	B-79, W-82	13.93	16.27	22.27	24.47	18.32	16.99	32	34	31	0	0	0	Y	Y	Y	15.22	6.69	6.67
150	B-67, W-70	B-82, W-91	B-75, W-82	28.13	16.8	17.68	18.36	12.7	12.79	35	33	31	0	0	3.05	Y	Y	Y	7.67	8.13	9.14
200	B-70, W-98	B-82, W-91	B-79, W-82	10.46	6.85	6.84	14.55	24.66	14.18	32	31	33	0	0.05	0.22	Y	Y	Y	8.76	7.6	7.3
250	B-67, W-82	B-82, W-88	B-85, W-85	12.87	0.81	15.74	16.33	1.11	24.77	34	49	36	0	0	0.07	Y	Y	Y	8.2	6.88	6.88
300	B-67, W-82	B-85, W-88	B-82, W-88	12.42	1.26	12.54	15.22	2.33	11.25	32	38	40	0	0	0.16	Y	Y	Y	10.41	37.1	10.1
350	B-70, W-85	B-85, W-98	B-85, W-88	9.97	1.02	7.11	15.68	5.47	18.81	33	42	34	0	0.55	0.02	Y	Y	Y	7.59	30	7.31
100																					
150																					
100	B-75, W-79	B-75, W-79	B-70, W-79	9.95	17.12	10.69	14.09	25.5	12.6	35	34	32	0.59	0	0.03	Y	Y	Y	8.29	9.38	6.54
150	B-75, W-82	B-79, W-85	B-79, W-85	16.76	18.47	21.54	23.97	24.76	16.91	32	35	37	0	0.05	0	Y	Y	Y	7.18	8.29	5.62
200	B-75, W-85	B-82, W-98	B-82, W-94	2.34	9.93	8.53	1.05	16.92	11.28	35	32	35	4.28	0	0.27	Y	Y	Y	10.3	7.75	11.37
250	B-70, W-79	B-85, W-94	B-85, W-91	9.18	11.33	15.19	21.38	9.21	22.25	31	33	39	0	0	0.08	Y	Y	Y	6.57	6.67	6.84
300	B-75, W-82	B-85, W-91	B-91, W-94	8.27	12.68	14.47	15.27	18.12	15.48	33	34	36	0	0.02	0.02	Y	Y	Y	9.53	7.21	7.66
347 (345) (350)	B-75, W-79	B-88, W-98	B-85, W-91	8.59	8.92	8.09	15.52	3.56	15.39	32	31	38	0.63	0.56	0.98	Y	Y	Y	8.43	8.3	7.44
150																					
200																					
250																					
300																					
350																					
150	B-70, W-82	B-79, W-85	B-75, W-82	18.27	18.52	37.23	23.16	16.71	14.03	34	37	34	0	1.73	0	Y	Y	Y	6.67	6.88	7.71
200	B-79, W-82	B-79, W-91	B-79, W-85	7.53	13.26	9.81	14.82	20.33	15.7	33	33	34	1.11	0	0	Y	Y	Y	9.91	7.03	8.02
250	B-79, W-82	B-85, W-94	B-85, W-94	8.48	8.92	9.52	16.42	16.17	10.51	35	37	39	0.01	0	0.12	Y	Y	Y	8.95	13.89	9.47
300	B-79, W-94	B-85, W-94	B-85, W-94	12.76	2.42	3.78	12.32	7.22	10.38	32	45	42	0	0.1	0.43	Y	Y	Y	8.82	8.89	7.82
347 (350) (350)	B-79, W-82	B-94, W-98	B-85, W-88	6.46	7.78	4.77	13.49	1.62	13.64	33	34	34	1.7	0.04	0.47	Y	Y	Y	9.09	14.05	8.94
200																					
250																					
300																					
350																					
200	B-70, W-82	B-85, W-88	B-79, W-82	3.86	4.11	12.73	23.49	24.66	14.01	38	39	33	0	0	0.03	Y	Y	Y	10.08	7.54	8.4
250	B-79, W-88	B-85, W-91	B-82, W-85	7.99	0.19	18.74	6.02	2.66	24.4	33	63	34	0.01	14.31	0.09	Y	Y	Y	10.6	9.15	8.28
300	B-79, W-82	B-82, W-91	B-85, W-91	18.54	0.07	4.83	21.12	2.84	6.59	34	78	35	0	20.22	0.01	Y	Y	Y	6.76	7.99	6.69
346 (345) (350)	B-79, W-85	B-82, W-94	B-85, W-94	1.12	1.43	6.49	20.77	5.66	3.88	32	45	36	0.02	0.45	0.4	Y	Y	Y	10.17	6.8	5.86

Figure B.1: Raw data table from April testing session

Appendix C:
July Testing Raw Data and Plots

Raw Data

		APA-M25 8DB	Bingfu	APA-M25 8DB	Bingfu	APA-M25 8DB	Bingfu	APA-M25 8DB	Bingfu	APA-M25 8DB	Bingfu	APA-M25 8DB	Bingfu	APA-M25 8DB	Bingfu	APA-M25 8DB	Bingfu
X Location (ft)	Height AGL (ft)	Signal Strength (dBm) best	Signal Strength (dBm) best	Signal Strength (dBM) worst	Signal Strength (dBm) worst2	Internet connection download speed (Mb/s	Internet connection download speed (Mb/s)3	Internet connection upload speed (Mb/s	Internet connection upload speed (Mb/s)3	Latency (ms	Latency (ms)3	Retransmission (%)	Retransmission (%)3	Email latency (s)	Email latency (s)3	VOIP possible ?	VOIP possible ?2
10	100	-64	-88	-70	-91	18.81	20.38	17.75	1.03	39	47	0	0	5.6	7.63	Y	Y
10	100	-64	-91	-67	-91	20.79	21.04	44.96	9.81	40	39	1.38	0	6.85	9.25		
10	100	-70	-88	-70	-91	21.63	22.03	13.55	9.71	38	38	0.39	0	5.81	6.53		
10	350	-67	-94	-70	-98	1.15	6.75	3.09	0.19	43	42	1.34	0	10.63	13.23	Y	Y
10	350	-64	-94	-67	-98	1.81	2.39	3.45	1.21	44	37	0	0.23	7.78	13.38		
10	350	-64	-94	-70	-98	1.51	9.92	4.95	0.32	44	43	0.38	0.02	6.04	9.76		
100	100	-79	-91	-85	-94	23.16	13.2	5.94	9.75	38	41	0	0.02	7.78	6.53	Y	Y
100	100	-82	-94	-88	-98	20.3	13.77	7.73	11.2	38	40	1	0.12	6.34	5.18		
100	100	-82	-88	-85	-98	20.12	13.98	5.23	9.97	39	42	0.98	0	7.26	5.01		
100	350	-79	-98	-82	-98	6.02	2.94	8.3	9.5	42	44	0.67	0.05	9.98	9.08	Y	Y
100	350	-79	-98	-82	-98	6.25	2.63	6.98	8.93	42	60	0	0.06	6.4	18.51		
100	350	-82	-98	-85	-98	2.75	5.65	8.32	6.24	47	43	0	0	13.23	10.57		
200	150		-94		-98		6.11		1.24		41		0.56		7.55	Y	Y
200	150		-94		-98		17.09		19.68		39		0		5.5		
200	150		-94		-98		16.06		9.67		42		1.35		7.01		
200	350	-82	-98	-85	-98	7.42	2.12	11.44	1.43	42	50	0	0	29.89	12.28	Y	Y
200	350	-82	N/A	-85	N/A	6.87	0.84	8.96	0.07	44	74	0	2.46	62.48	9.01		
200	350	-88	N/A	-94	N/A	6.61	1.97	6.22	0.53	43	58	0	0.19	8.54	9.3		

Figure C.1: Raw data table from July testing session

Processed Data

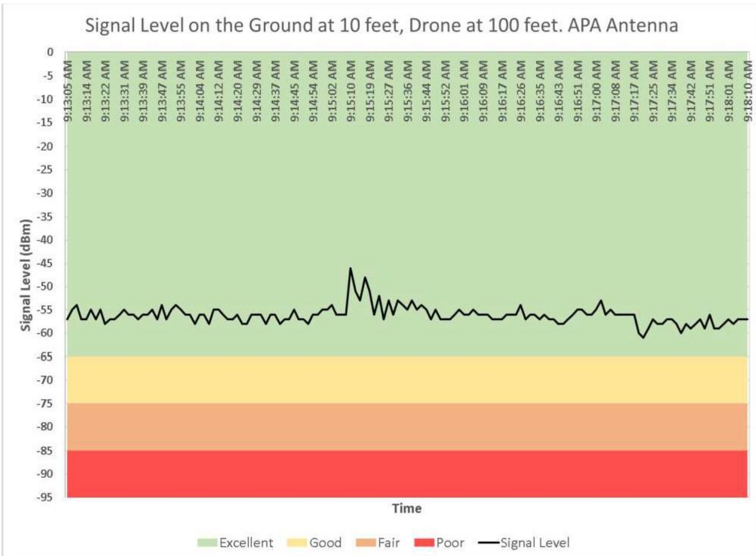


Figure C.2: Signal level for horizontal distance = 10 ft, height AGL = 100 ft for APA antenna

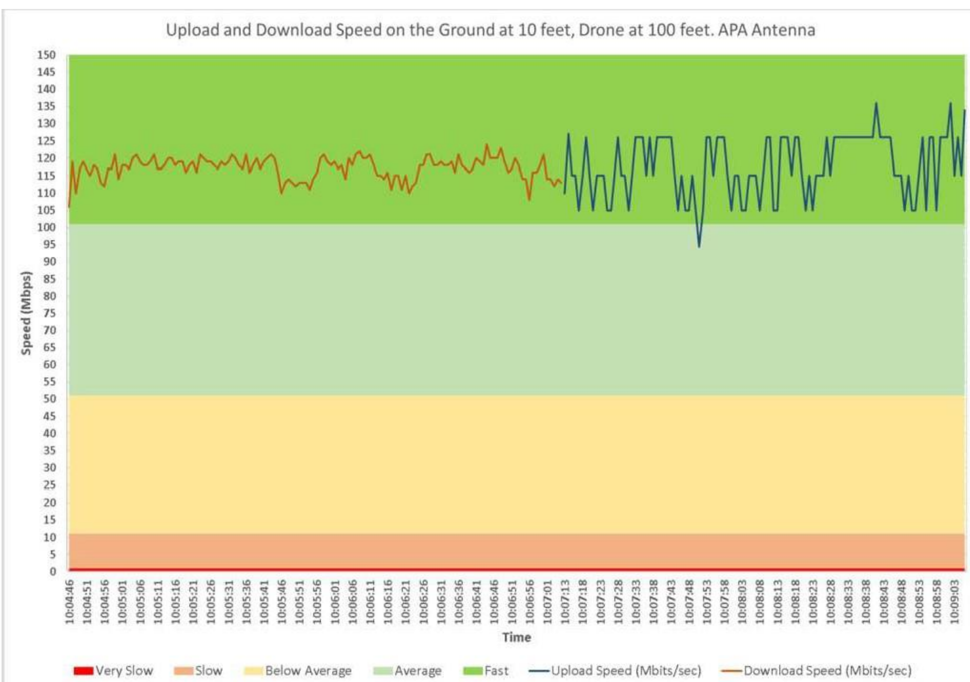


Figure C.3: Upload/download speed for horizontal distance = 10 ft, height AGL = 100 ft for APA antenna

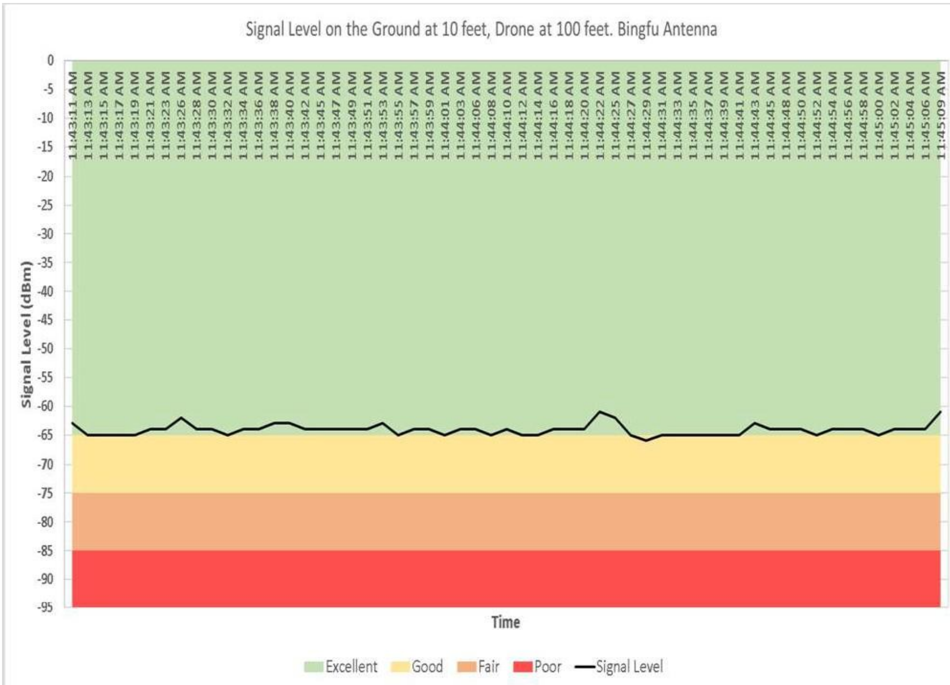


Figure C.4: Signal level for horizontal distance = 10 ft, height AGL = 100 ft for Bingfu antenna

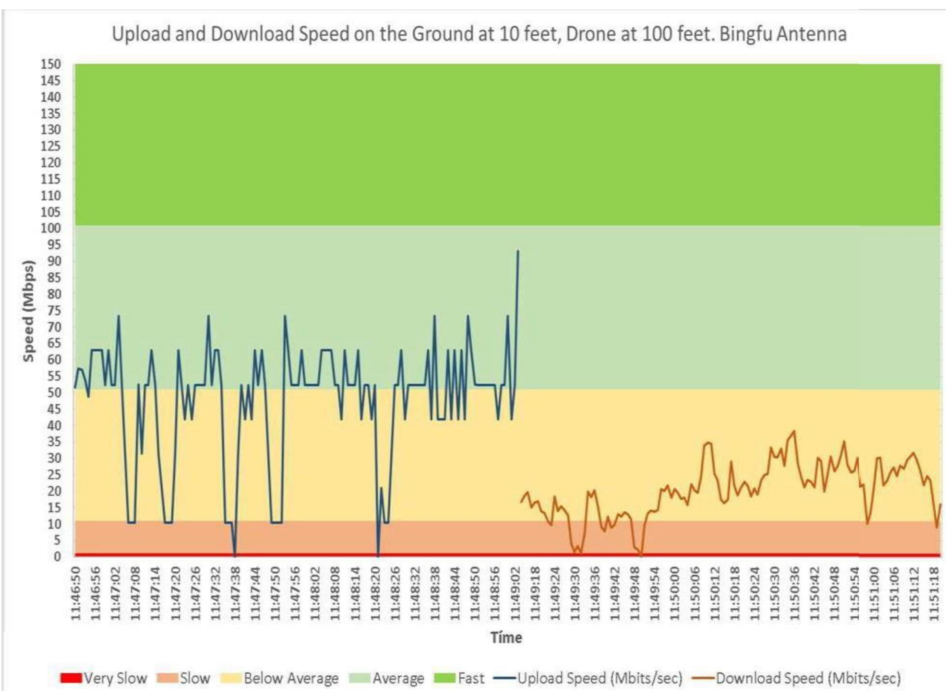


Figure C.5: Upload/download speed for horizontal distance = 10 ft, height AGL = 100 ft for Bingfu antenna

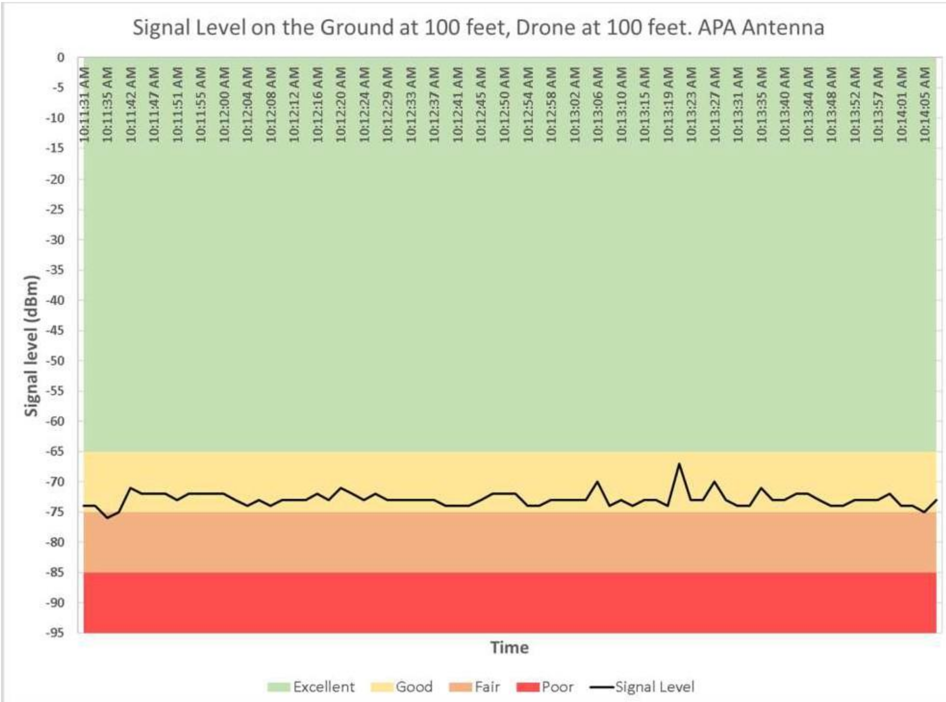


Figure C.6: Signal level for horizontal distance = 100 ft, height AGL = 100 ft for APA antenna

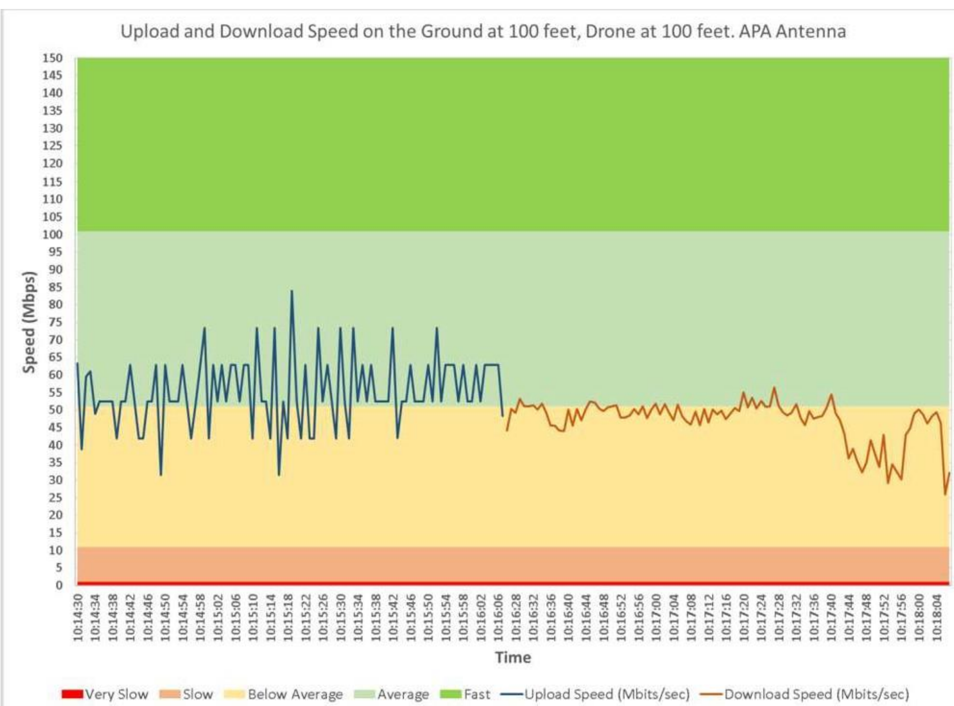


Figure C.7: Upload/download speed for horizontal distance = 100 ft, height AGL = 100 ft for APA antenna

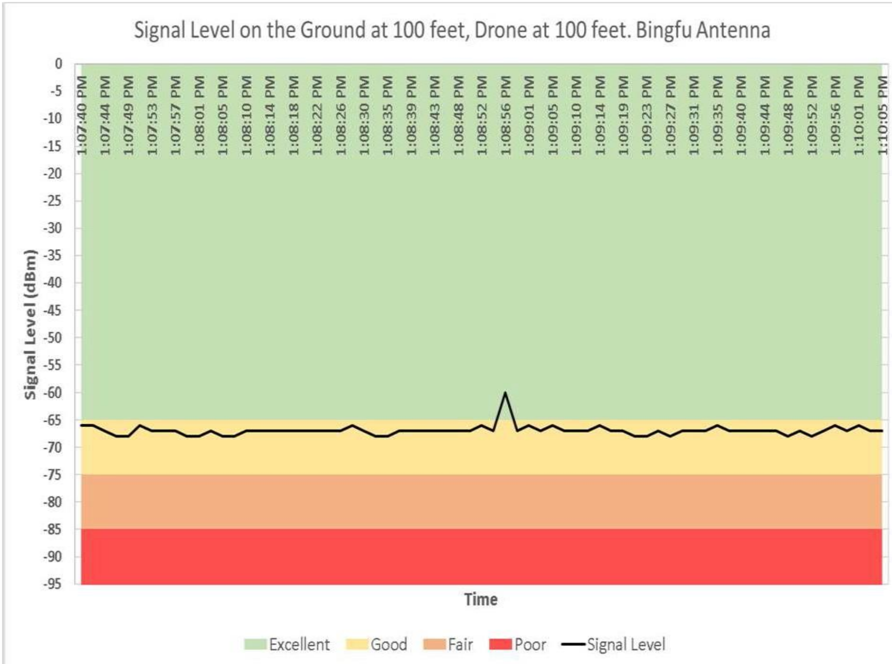


Figure C.8: Signal level for horizontal distance = 100 ft, height AGL = 100 ft for Bingfu antenna

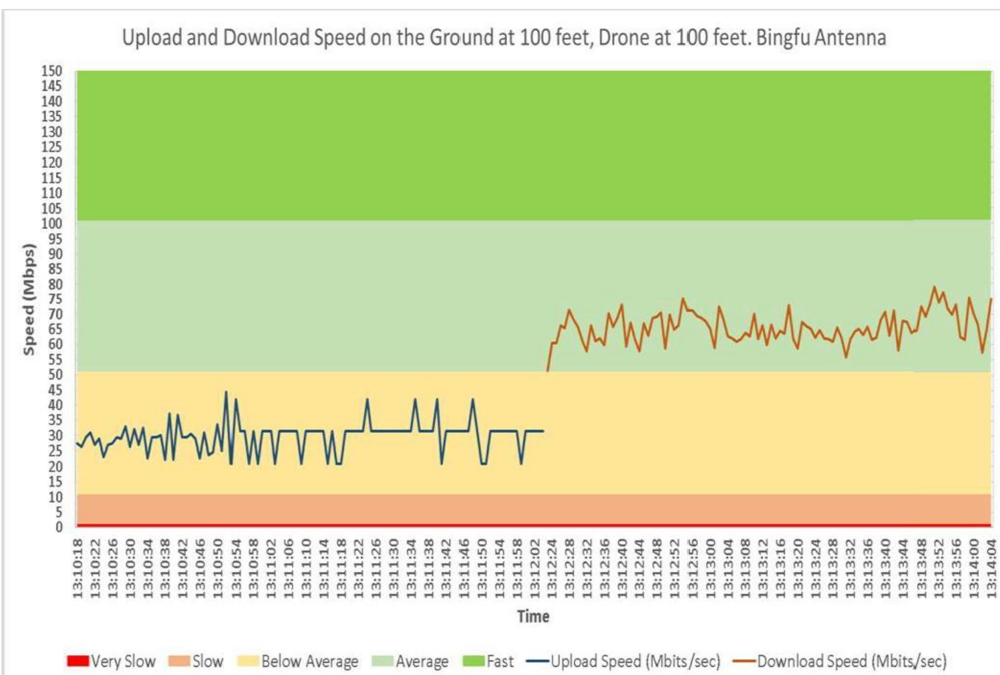


Figure C.9: Upload/download speed for horizontal distance = 100 ft, height AGL = 100 ft for Bingfu antenna

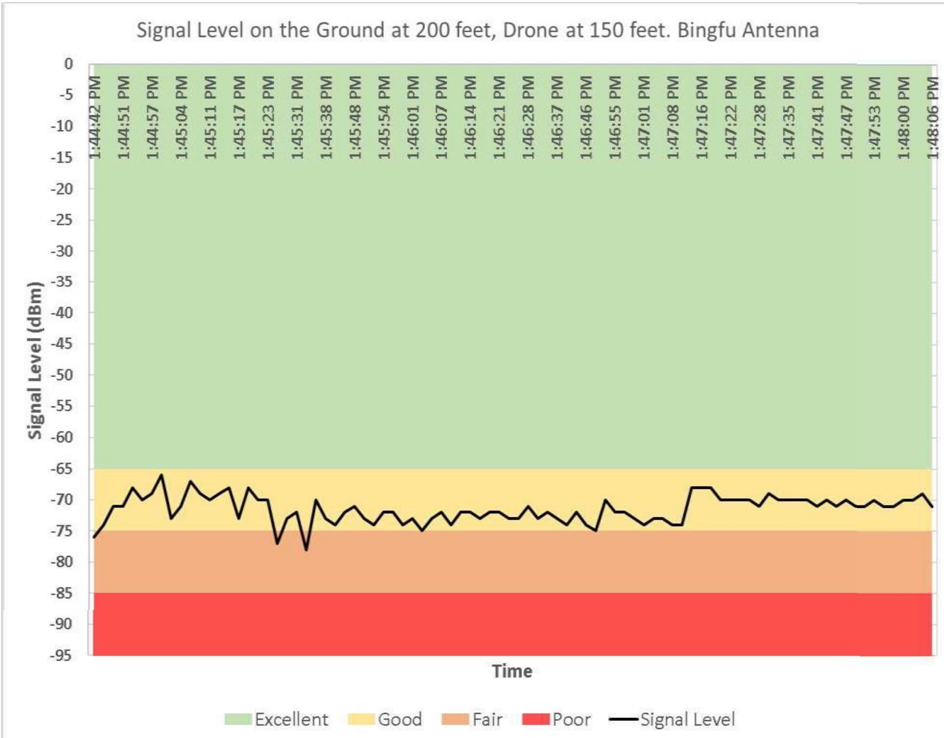


Figure C.10: Signal level for horizontal distance = 200 ft, height AGL = 150 ft for Bingfu antenna

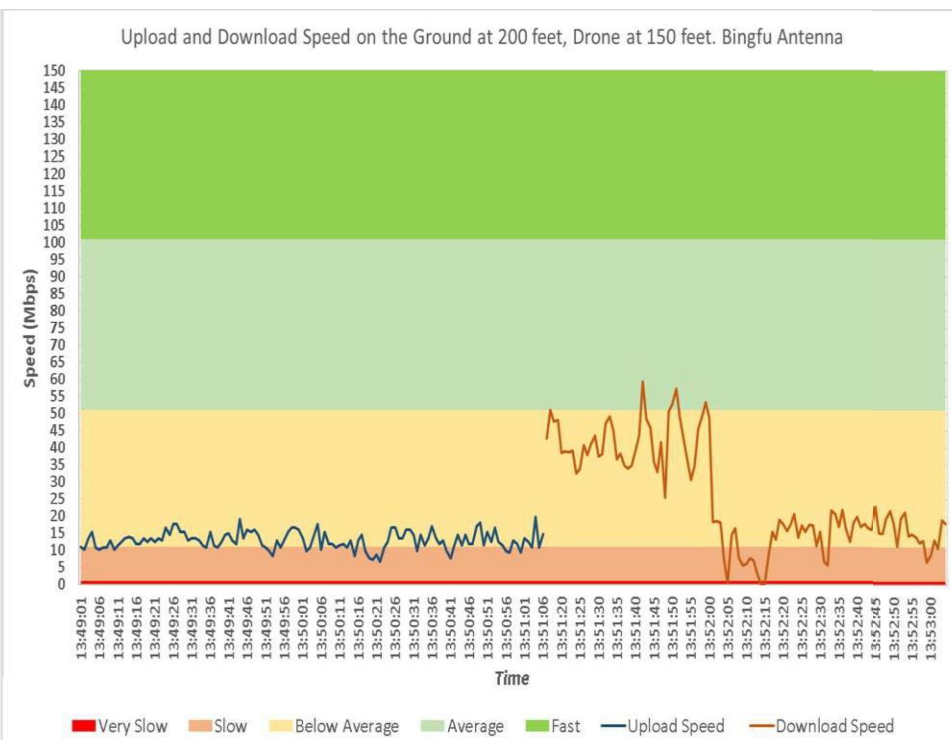


Figure C.11: Upload/download speed for horizontal distance = 200 ft, height AGL = 150 ft for APA antenna

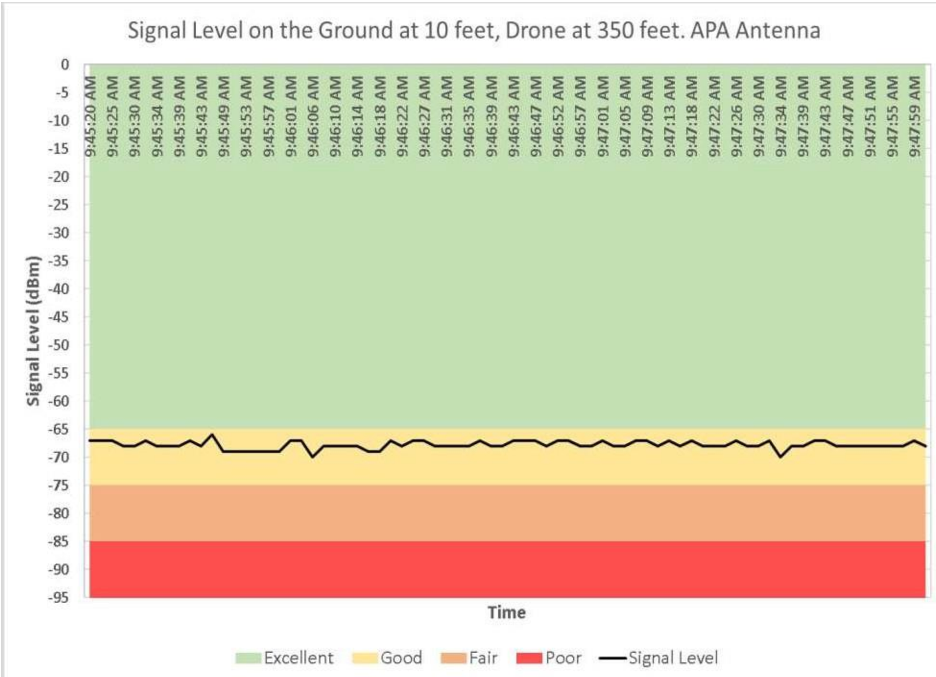


Figure C.12: Signal level for horizontal distance = 10 ft, height AGL = 350 ft for APA antenna

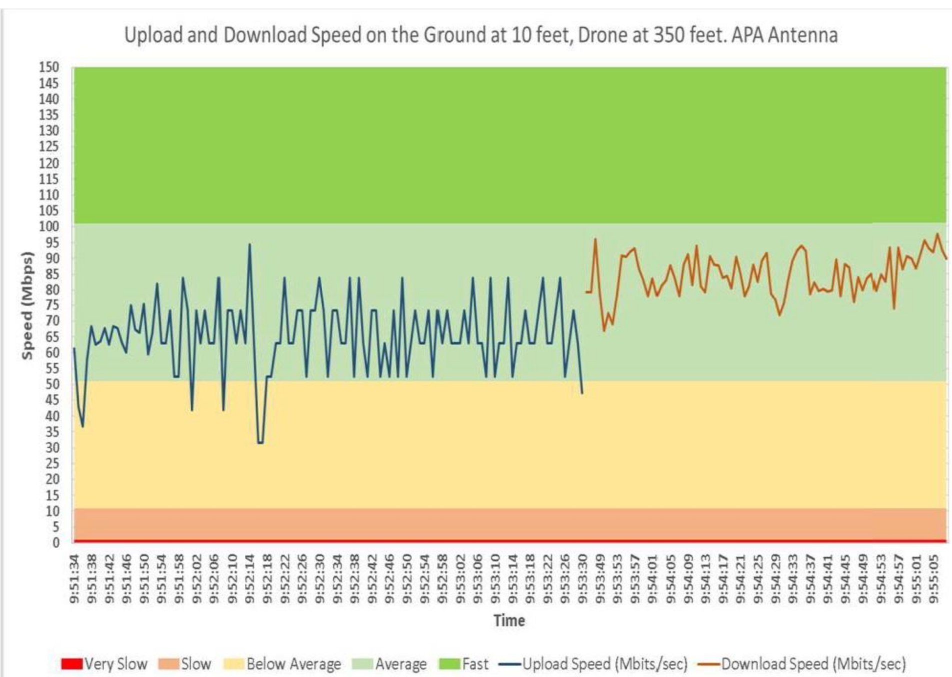


Figure C.13: Upload/download speed for horizontal distance = 10 ft, height AGL = 350 ft for APA antenna

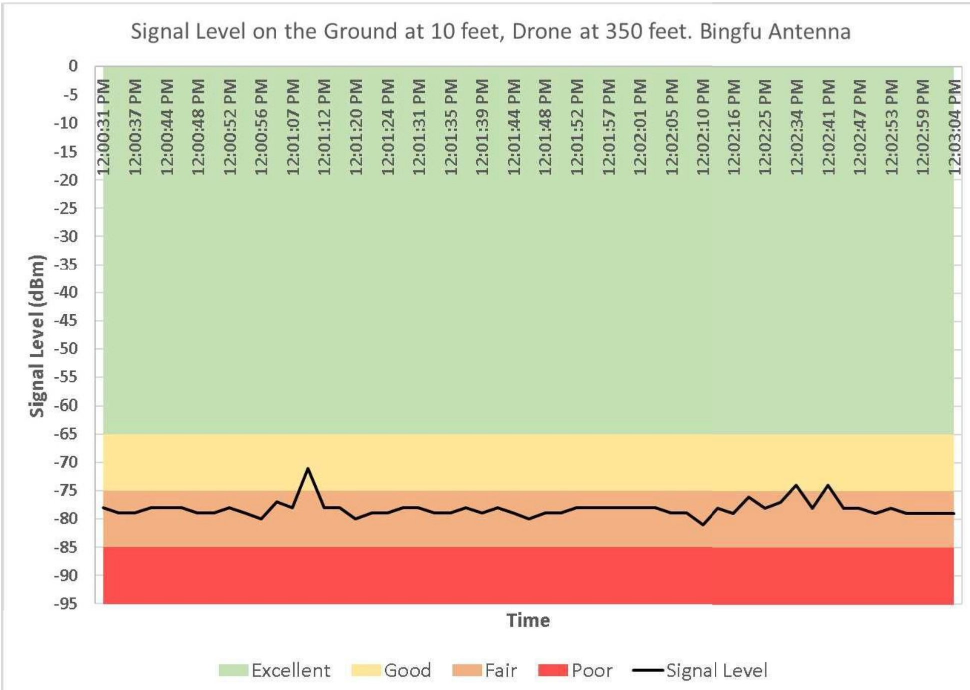


Figure C.14: Signal level for horizontal distance = 10 ft, height AGL = 350 ft for Bingfu antenna

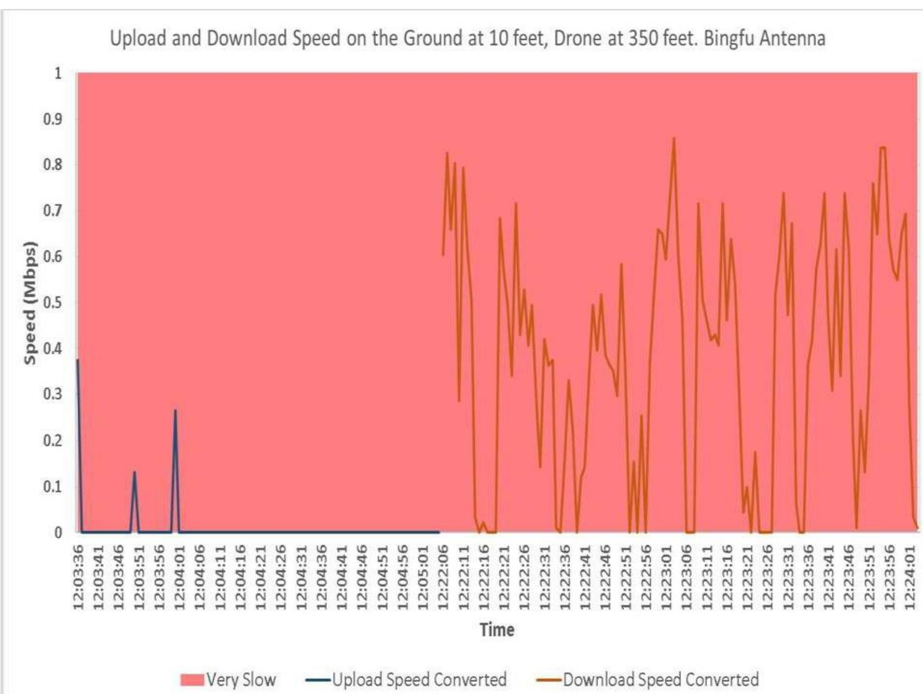


Figure C.15: Upload/download speed for horizontal distance = 10 ft, height AGL = 350 ft for Bingfu antenna

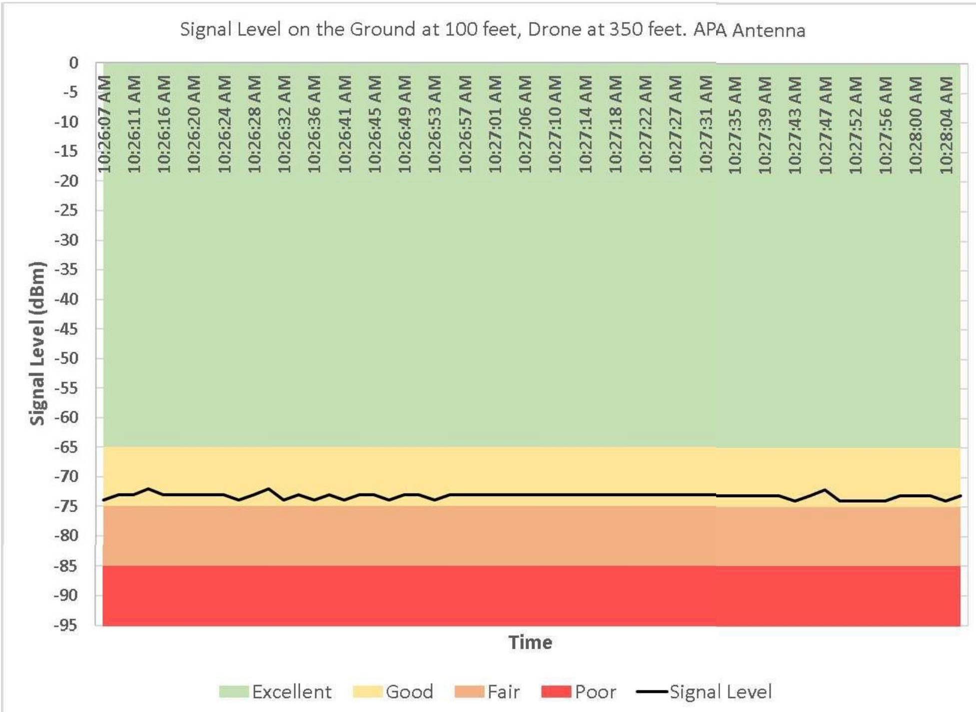


Figure C.16: Signal level for horizontal distance = 100 ft, height AGL = 350 ft for APA antenna

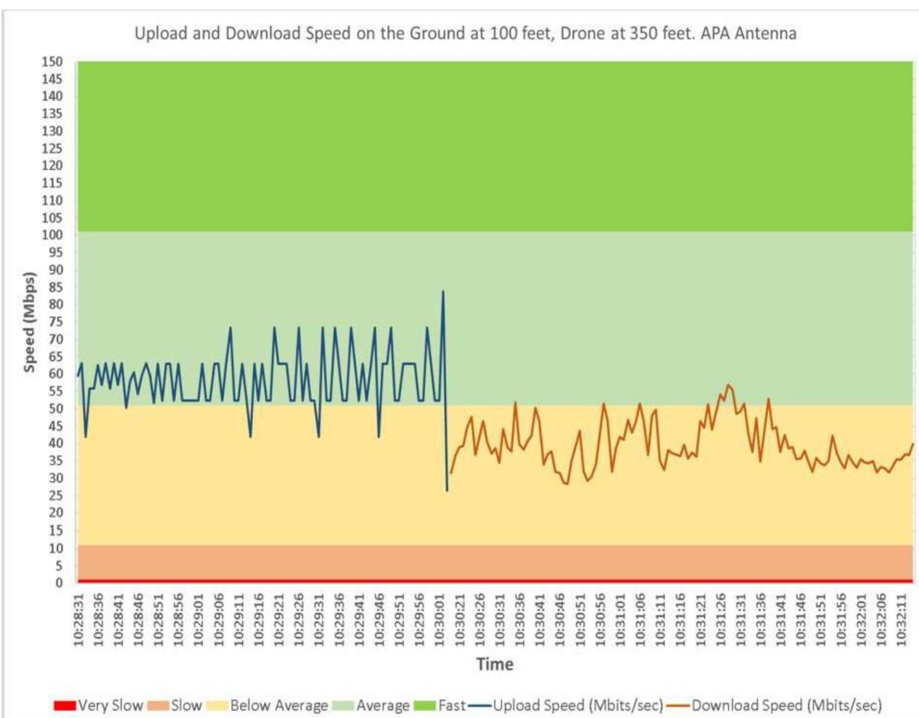


Figure C.17: Upload/download speed for horizontal distance = 100 ft, height AGL = 350 ft for APA antenna

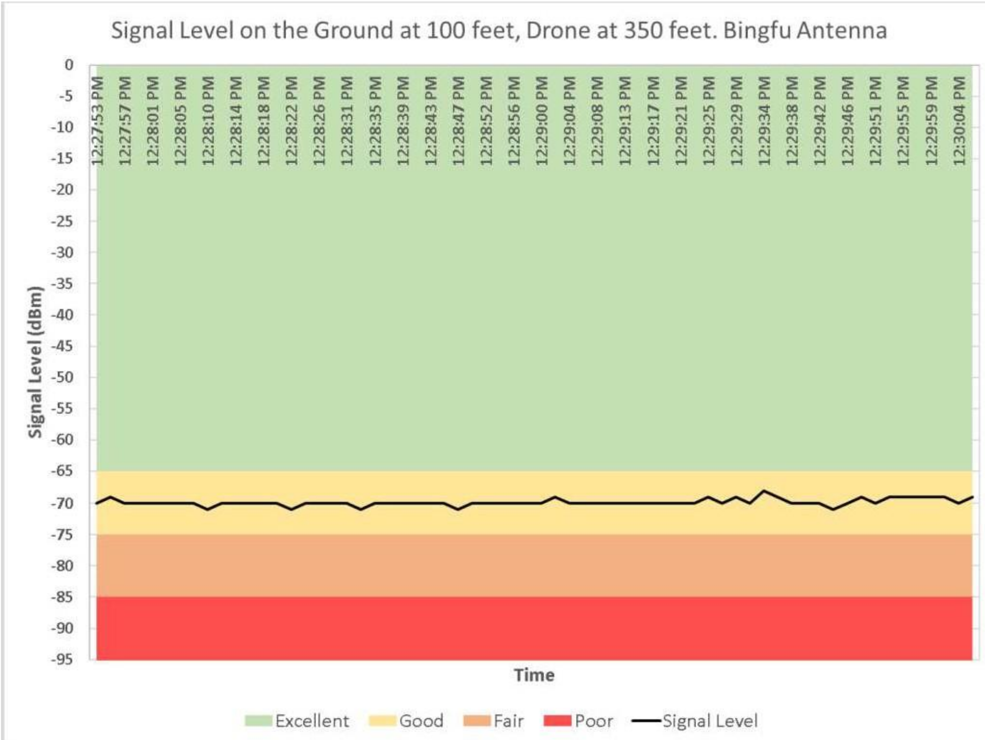


Figure C.18: Signal level for horizontal distance = 100 ft, height AGL = 350 ft for Bingfu antenna

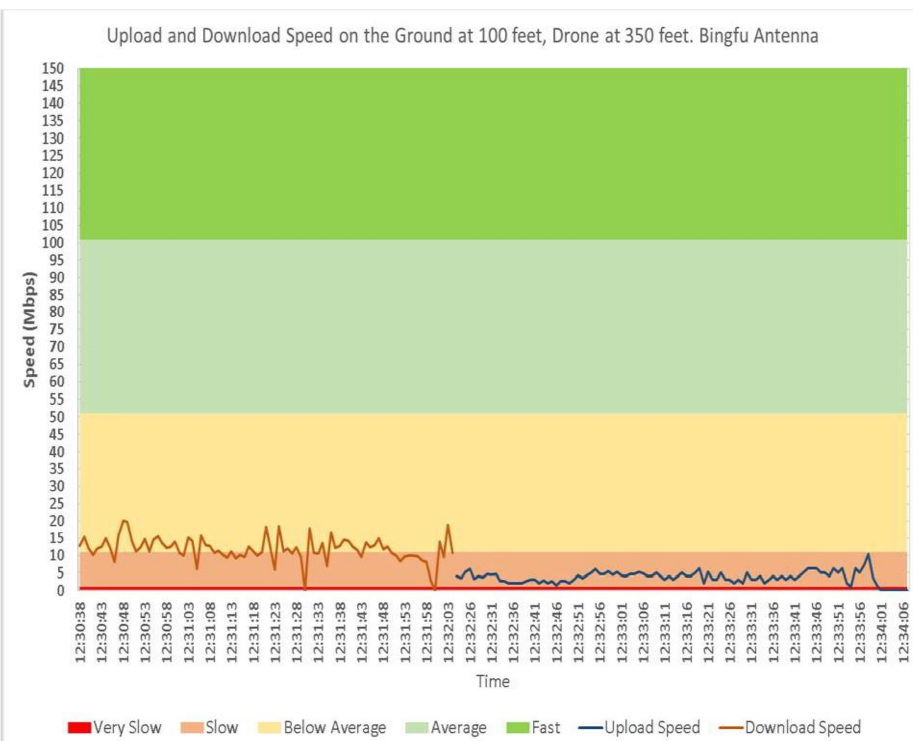


Figure C.19: Upload/download speed for horizontal distance = 100 ft, height AGL = 350 ft for Bingfu antenna

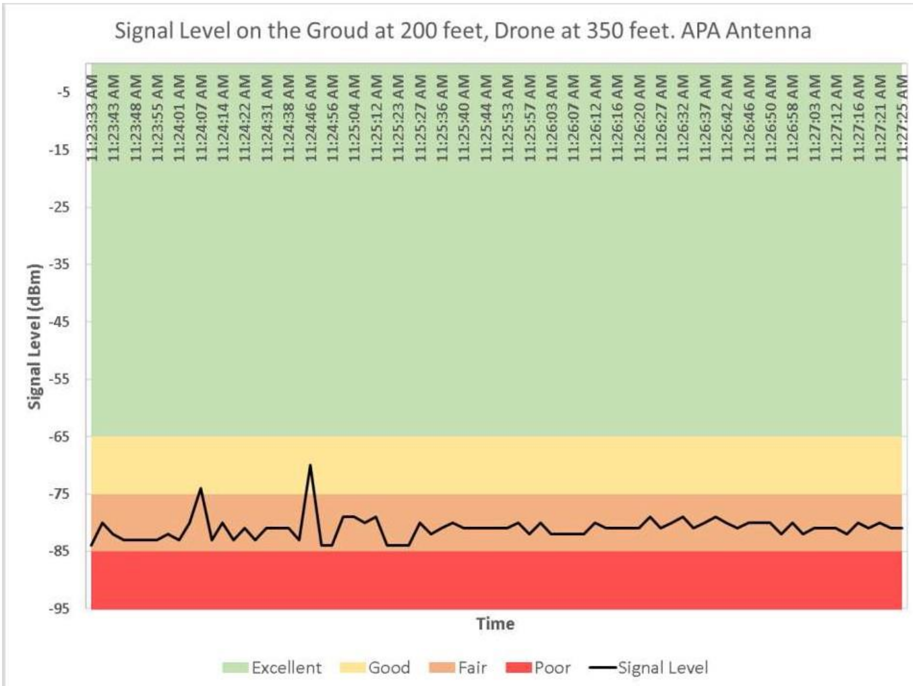


Figure C.20: Signal level for horizontal distance = 200 ft, height AGL = 350 ft for APA antenna

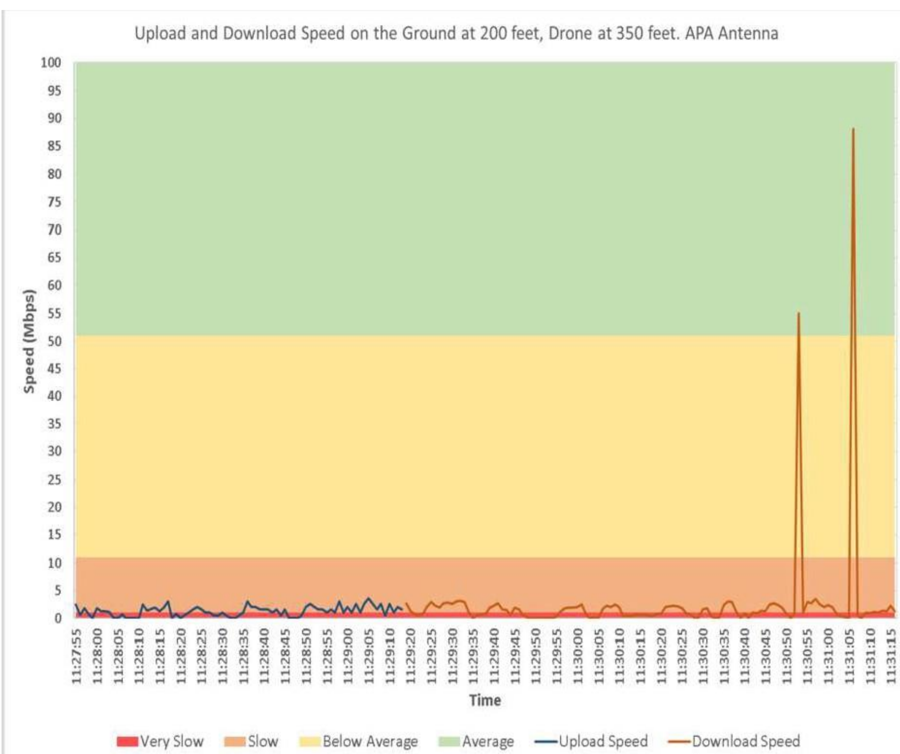


Figure C.21: Upload/download speed for horizontal distance = 200 ft, height AGL = 350 ft for APA antenna

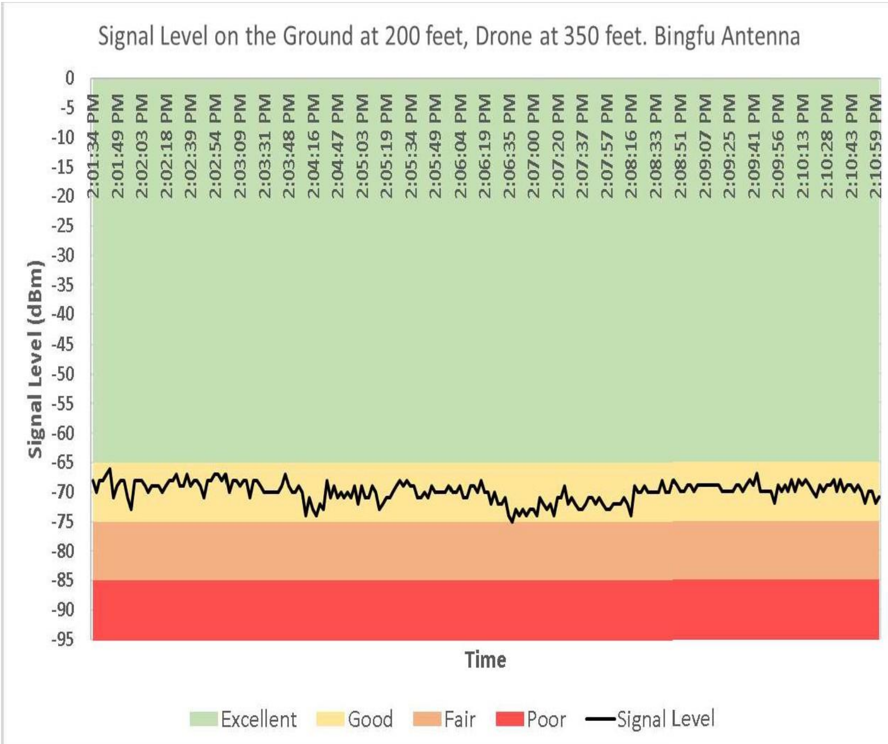


Figure C.22: Signal level for horizontal distance = 200 ft, height AGL = 350 ft for Bingfu antenna

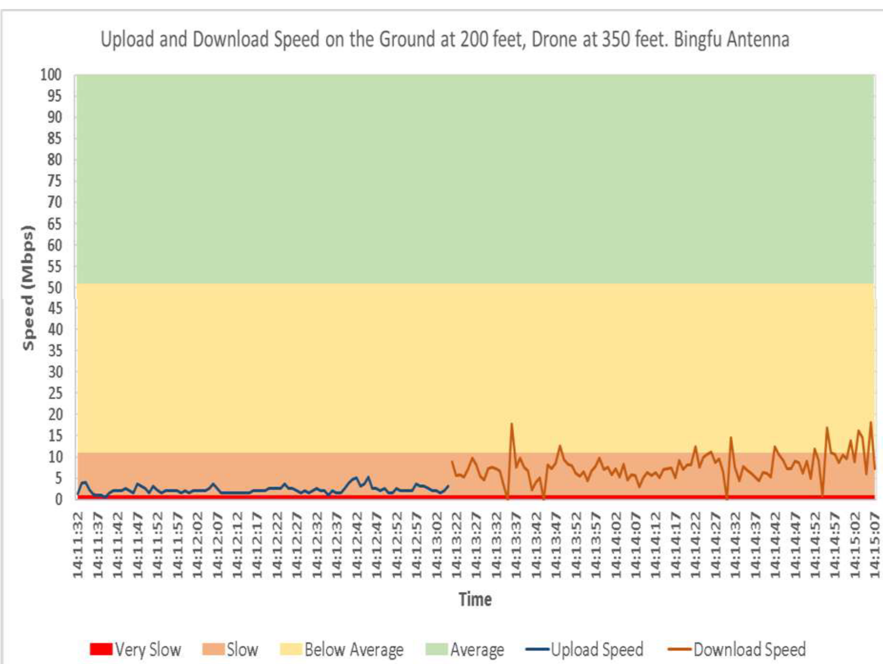


Figure C.23: Upload/download speed for horizontal distance = 200 ft, height AGL = 350 ft for APA antenna

Appendix C: Interim Report for Task 4

STATE OF CALIFORNIA • DEPARTMENT OF TRANSPORTATION

TECHNICAL REPORT DOCUMENTATION PAGE

TR-0003 (REV 04/2024)

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7. AUTHOR Evan Sim, Anh Duong, Kin Yen, Dave Torick, Shima Nazari	8. PERFORMING ORGANIZATION REPORT NO. UCD-ARR-25-03-31-05
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16. ABSTRACT

This report is part of AHMCT's research project "Development and Testing of an Unmanned Aerial System (UAS) Cellular & Wi-Fi Repeater: Phase 2." The goal of this research is to expand upon the successful UAS aerial repeater that was created in Task 3280. The researchers evaluated several commercial off-the-shelf (COTS) vehicle routers and antennas to improve the ground Wi-Fi network. After the components were selected, an easy-to-assemble payload package was designed to mount to the UAS to create a useable communication network. The goal of the research is to evaluate the benefits and drawbacks of the aerial repeater concept through field testing. This report provides the cellular mapping results.

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Unmanned Aerial System, Drone, Communications Repeater, Cellular mapping, ArcGIS Mapping, Highway Testing, Highway 299, Highway 70	No restrictions. This document is available to the public through the National Technical Information Service, Springfield, Virginia 22161.	
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DISCLAIMER

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Advanced Highway Maintenance and Construction Technology Research Center

Department of Mechanical and Aerospace Engineering
University of California at Davis

Development and Testing of an Unmanned Aerial System (UAS) Cellular & Wi-Fi Repeater: Phase 2 – Cellular Mapping and Selection of Field Trial Locations

Evan Sim, Anh Duong, Dave Torick, Kin Yen, and Shima Nazari

Report Number: CA25-4297
AHMCT Research Report: UCD-ARR-25-03-31-05
Interim Report of Contract: 65A0749 Task 4297

April 28th, 2025

California Department of Transportation

Division of Research, Innovation and System Information

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List of Acronyms and Abbreviations

Acronym	Definition
AHMCT	Advanced Highway Maintenance and Construction Technology Research Center
Caltrans	California Department of Transportation
COTS	Commercial Off–The-Shelf
DOT	Department of Transportation
DRISI	Caltrans Division of Research, Innovation and System Information
FCC	Federal Communications Commission
ICCID	Integrated Circuit Card Identification
ID	Identification
IMSI	International Mobile Subscriber Identity
LAC	Location Area Code
RSCP	Received Signal Code Power
RSRP	Reference Signal Strength Power
RSRQ	Reference Signal Received Quality
RSSI	Received Signal Strength Indicator
SINR	Signal-to-Interference-plus-Noise Ratio
SR	State Route
UAS	Uncrewed Aerial System

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Chapter 1:
Introduction- Field Trials Results and Analysis

Caltrans has many rural use cases where no current network communications exist outside of satellite services. Based on prior research from the Advanced Highway Maintenance and Construction Technology (AHMCT) Research Center, the cellular range of typical sites in rural areas is significantly limited by surrounding terrain and foliage. There is a need to provide enhanced communications availability outside of current cellular offerings without the requirement of a full-fledged investment in satellite equipment. Research performed under Phase 1 of Task 3280, showed that a UAS can elevate a payload into the cellular signal that is typically blocked by terrain and create a Wi-Fi network on the ground for worker communications. Refinement of the UAS payload is necessary to minimize deployment time and reduce the number of components necessary to establish a useable network. After the payload package has been optimized It is necessary to conduct field trials to verify the success of the technology in various terrain situations with limited to no cellular network coverage. With a temporary Wi-Fi network in construction and emergency response areas, communication can now occur through emails and Wi-Fi calling, assisting in efficiency, resource management, and accurate equipment deployment for the first time in some rural districts.

The purpose of this document is to provide the results from the field trials, analyze the performance of the UAS aerial repeater system, and provide recommendations.

Results of the Cellular Mapping

The cellular mapping results indicate that Verizon outperforms AT&T on both Highways 299 and 70. These findings were derived from key performance metrics, including Received Signal Strength Indicator (RSSI), Reference Signal Received Quality (RSRQ), Reference Signal Strength Power (RSRP), and Signal-to-Interference-plus-Noise Ratio (SINR). Tables 1.1 to 1.6 provides a detailed comparison of these metrics across three trials conducted for both Verizon and AT&T on Highways 299 and 70.

Table 1.1: Trial 1 Metrics Comparison Between Verizon and AT&T (Highway 299)

Metric	Verizon Median Value per Metric ± Standard Deviation	AT&T Median Value per Metric ± Standard Deviation
RSSI	-85 ± 23	-88 ± 22
RSRQ	-15 ± 4	-18 ± 4
RSRP	-115 ± 21	-125 ± 18
SINR	2 ± 8	0 ± 9

Table 1.2: Trial 1 Metrics Comparison Between Verizon and AT&T (Highway 70)

Metric	Verizon Median Value per Metric ± Standard Deviation	AT&T Median Value per Metric ± Standard Deviation
RSSI	-73 ± 17	-78 ± 31
RSRQ	-13 ± 4	-17 ± 4
RSRP	-102 ± 19	-112 ± 25
SINR	7 ± 9	0 ± 9

Table 1.3: Trial 2 Metrics Comparison Between Verizon and AT&T (Highway 299)

Metric	Verizon Median Value per Metric ± Standard Deviation	AT&T Median Value per Metric ± Standard Deviation
RSSI	-85 ± 19	-91 ± 18
RSRQ	-20 ± 2	-16 ± 4
RSRP	-140 ± 21	-127 ± 14
SINR	0 ± 6	0 ± 10

Table 1.4: Trial 2 Metrics Comparison Between Verizon and AT&T (Highway 70)

Metric	Verizon Median Value per Metric ± Standard Deviation	AT&T Median Value per Metric ± Standard Deviation
RSSI	-77 ± 14	-125 ± 30
RSRQ	-14 ± 4	-20 ± 4
RSRP	-106 ± 16	-140 ± 22
SINR	5 ± 10	0 ± 6

Table 1.5: Trial 3 Metrics Comparison Between Verizon and AT&T (Highway 299)

Metric	Verizon Median Value per Metric ± Standard Deviation	AT&T Median Value per Metric ± Standard Deviation
RSSI	-85 ± 17	-90 ± 20
RSRQ	-15 ± 3	-16 ± 4
RSRP	-115 ± 15	-122 ± 16
SINR	3 ± 7	2 ± 8

Table 1.6: Trial 3 Metrics Comparison Between Verizon and AT&T (Highway 70)

Metric	Verizon Median Value per Metric ± Standard Deviation	AT&T Median Value per Metric ± Standard Deviation
RSSI	-79 ± 14	-125 ± 28
RSRQ	-13 ± 3	-20 ± 4
RSRP	-111 ± 14	-140 ± 20
SINR	4 ± 7	0 ± 6

As shown in Tables 1.1 to 1.6, Verizon consistently outperformed AT&T in terms of RSSI on Highway 299 across all three trials. On Highway 70, Verizon outperformed AT&T in all key metrics—RSSI, RSRQ, RSRP, and SINR—across all three trials. **Given that RSSI is the primary metric for assessing signal strength, Verizon performed better in RSSI on both Highways 299 and 70, across all trials, making it the better carrier compared to AT&T.**

Testing Locations based on the Results of Cellular Mapping

The testing locations were chosen based on the following criteria:

1. Locations with minimal to no signal (highlighted in red and orange in Figures 1.1 and 1.2),
2. Locations that can potentially access signal according to the Federal Communications Commission (FCC) projected national broadband map (represented by the hexagons in Figures 1.1 and 1.2),
3. Locations must have shoulders that are at least 25 feet from the edge of the roadway in accordance with Caltrans safety regulations,

The testing locations on Highways 299 and 70 are marked in figures below. The numbering of the locations is the order of when the test occurred (e.g. location 1 was the first testing location).

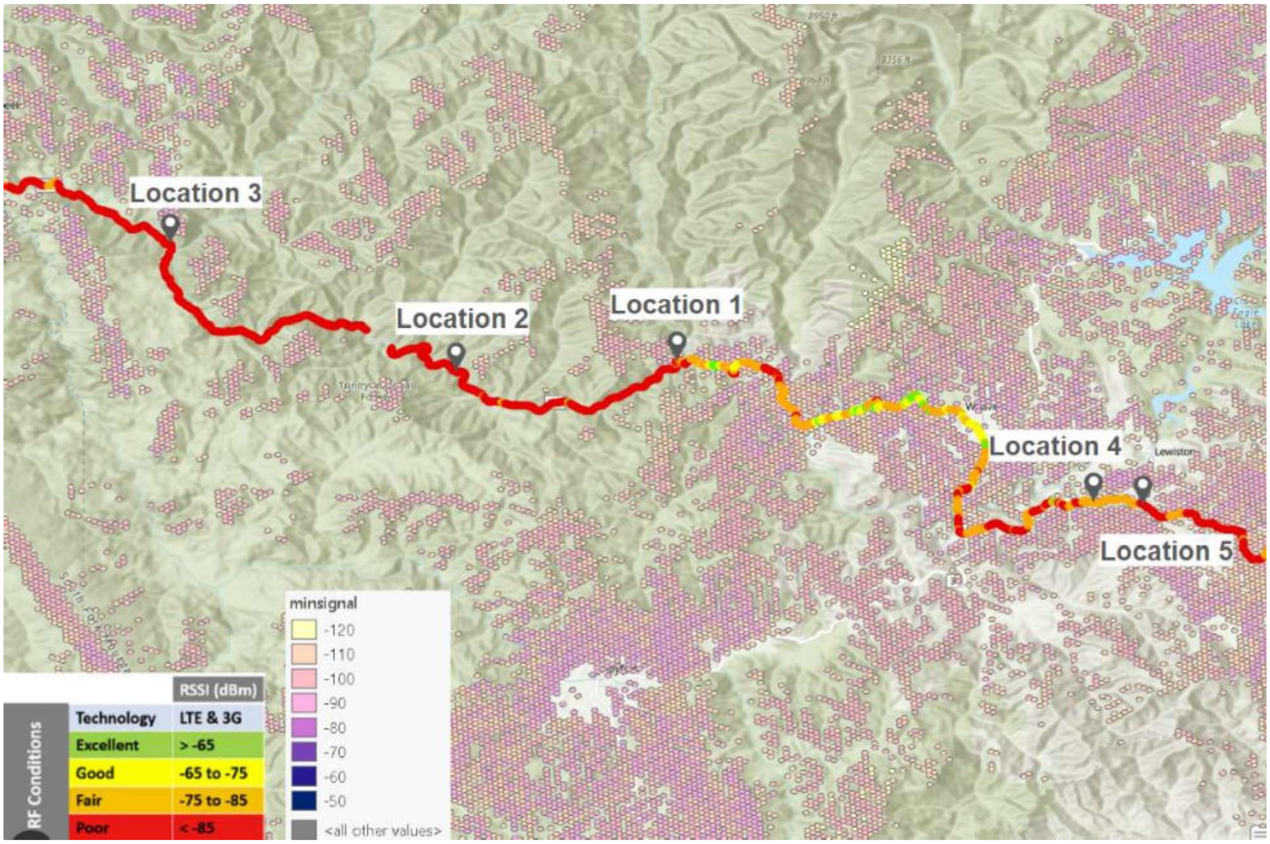

Figure 1.1: Testing locations on Highway 299. Map generated using ArcGIS software by Esri.

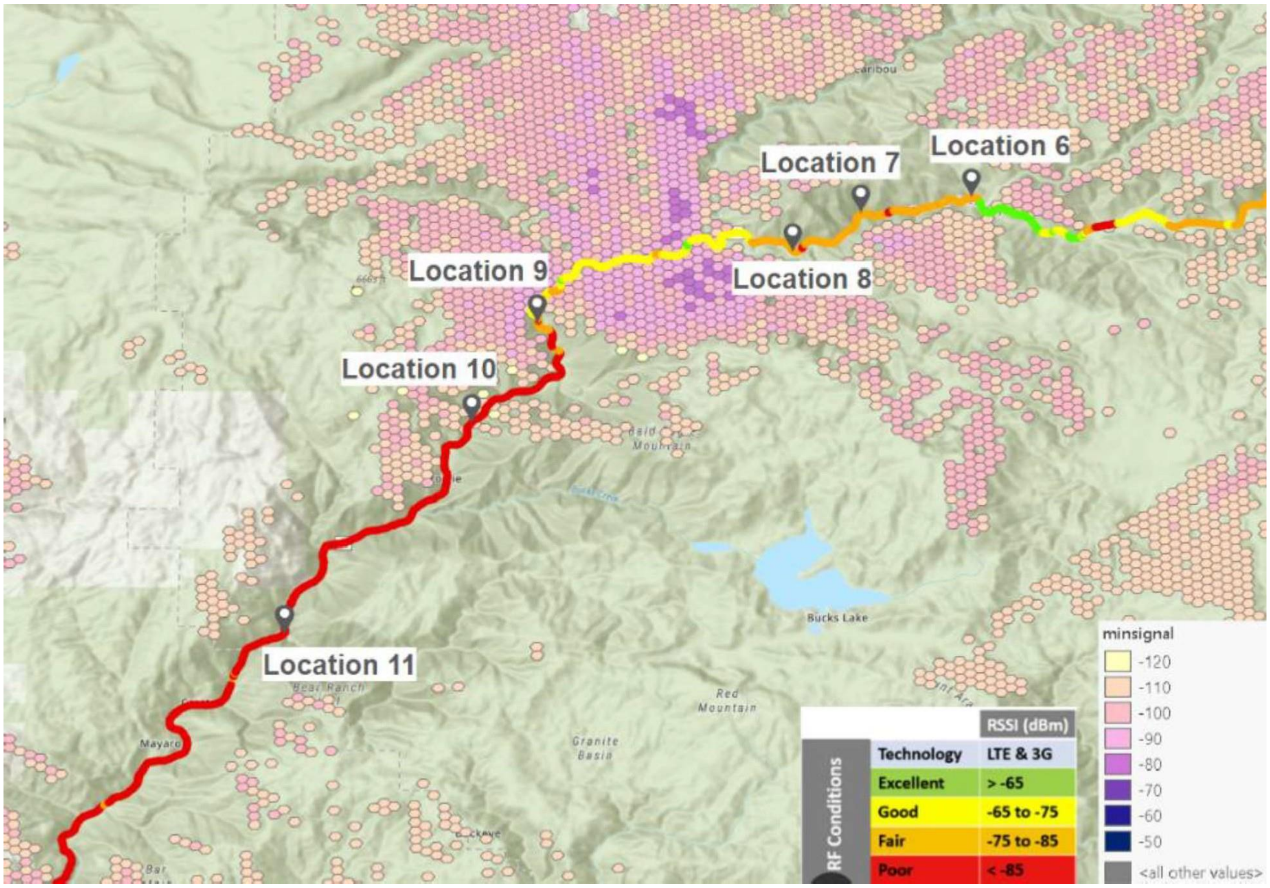

Figure 1.2: Testing locations on Highway 70. Map generated using ArcGIS software by Esri.

The testing locations were chosen because they were in the proximity of the FCC projected broadband, in regions where there is minimal to no cellular coverage, and there was at least 25 feet from the edge of the roadway to fly the UAS system.

Summary of Field Trials

During the field trials, ten out of eleven (10 out of 11) testing locations were able to connect to a signal source. The furthest distance from a signal source to a testing location was 12.5 miles (location 3 on Highway 299), while the closest distance was 0.52 miles (location 5 on Highway 299). Location 8 on Highway 70 alternated between two different signal sources, so the distances for both sources are listed. Additionally, during testing location 2 on Highway 299, the system was unable to connect to a signal source, so no distance is listed for this location. Table 1.2 summarizes the distance from each location to its signal source.

Table 1.2: Distance from each location to its signal source

Location	Distance from the location to the signal source (miles)
1	10. 7
2	Unable to connect to a signal source
3	12.5
4	1.25
5	0.52
6	2.95
7	4.33
8	5.25 and 2.6
9	2.8
10	5.5
11	11.9

The process of mapping out the signal source distance, as shown in Table 1.2, is detailed in Chapter 4.

Chapter 2:
Data Collection System Setup

The System Setup for Cellular Mapping

Building the System

The data collection system setup for cellular mapping includes a modem, a pre-programmed Raspberry Pi that connects to the modem, an antenna, connectivity cables, and a power source. The modem is linked to the antenna to receive the cellular signal and then connects to the Raspberry Pi for data collection. Both the modem and the Raspberry Pi are powered by the vehicle (in this context, the vehicle was Mazda CX-30). Figure 2.1 provides a diagram of the cellular mapping system.

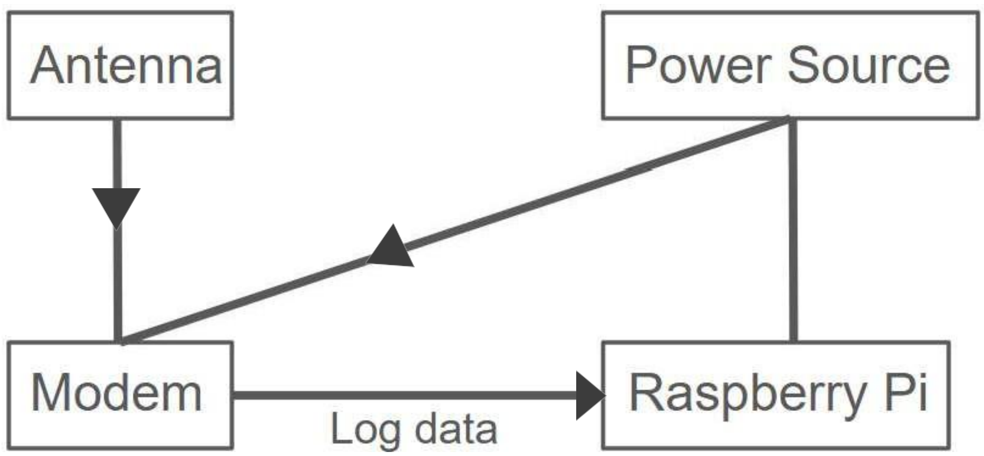

Figure 2.1: Diagram of the cellular mapping system.

To capture the cellular signals from the two carriers, AT&T and Verizon, two systems were set up. These systems operate simultaneously and can run indefinitely, as long as they remain connected to the vehicle. Figure 2.2 shows the official system setup used to collect modem data from both carriers.

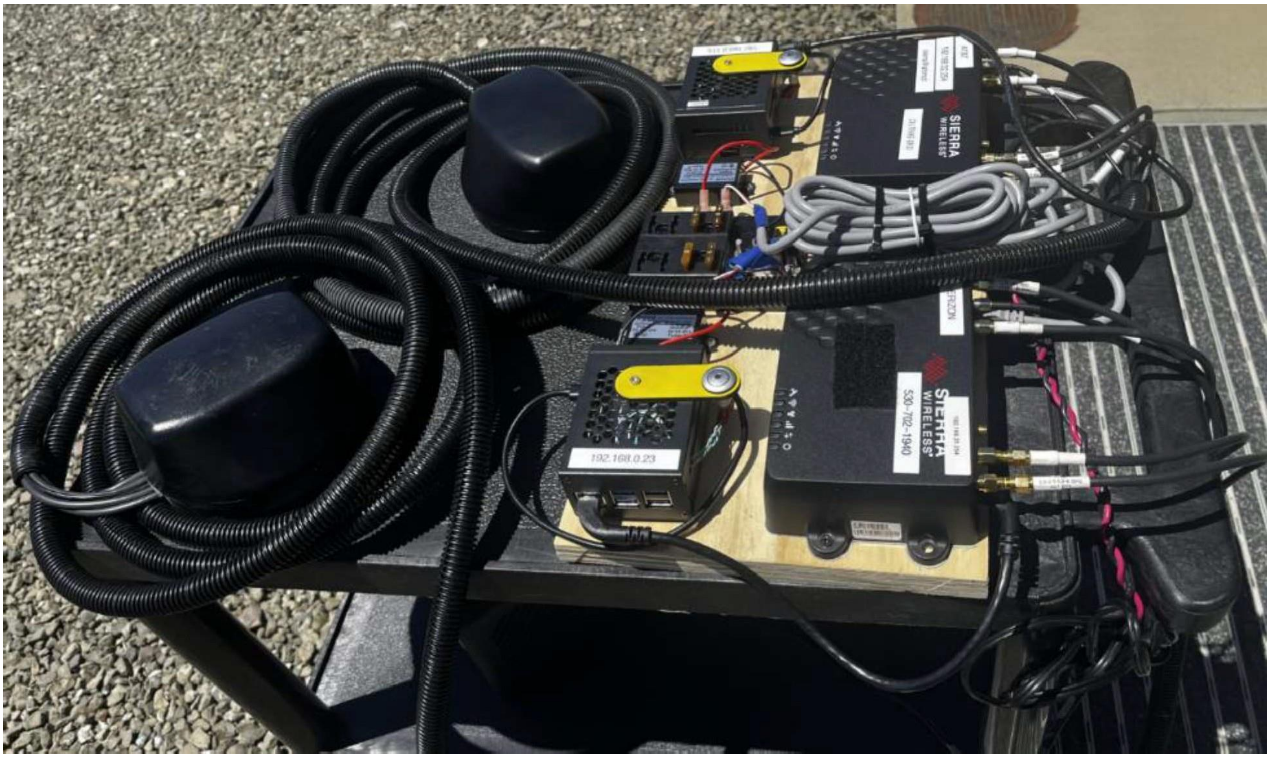

Figure 2.2: The official system setup used for cellular mapping

The official system setup was tested to verify its ability to generate and record data files. When the button (placed on the yellow strip) is pressed, the Raspberry Pi begins recording data from the modem at a rate of one data point per second, or 1 Hertz (Hz). The system was left outside for approximately ten minutes, after which the data files on the Raspberry Pi were checked to confirm that data were being recorded. Once it was confirmed that the system functioned correctly for both modems, the setup was integrated into the vehicle, as shown in Figure 2.3.

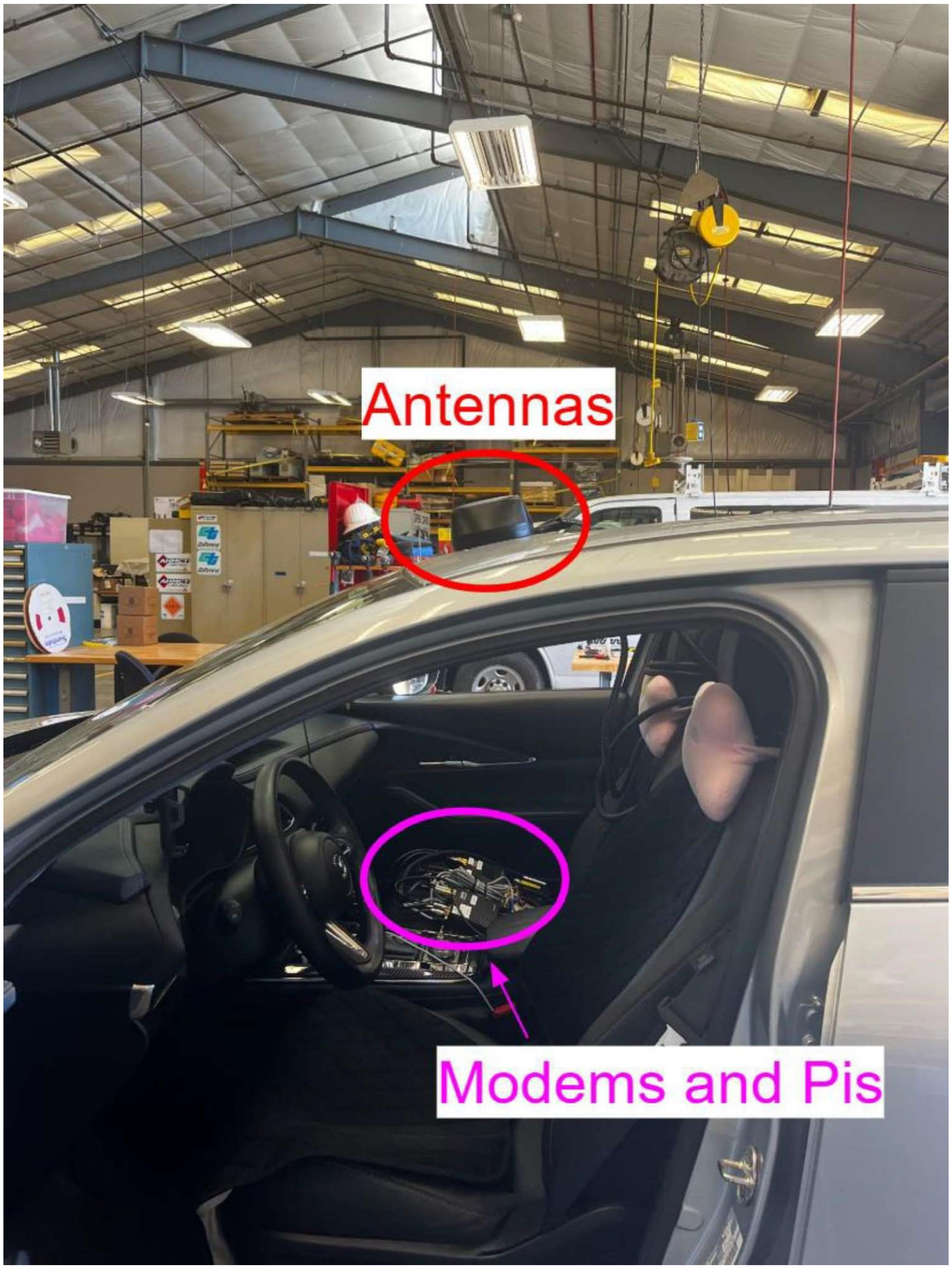

Figure 2.3: The cellular mapping system integrated into a vehicle

Data Collection

When the vehicle is moving on the road, the system traces the performance of the cellular modems along the route the vehicle takes. To extract the data from the modem, a Raspberry Pi was programmed to collect the following metrics:

- Date
- Time

- Voltage
- Board temperature
- RSSI
- RSRQ
- RSRP
- SINR
- RSCP
- Error rate
- ICCID
- Cell ID
- LAC
- IMSI
- Cell band
- Network service type
- Network operator satellite count
- Latitude
- Longitude

Figure 2.4 shows the results of a test run result to confirm that the overall system worked, and Figure 2.5 provides an example of a data table recorded by the system.

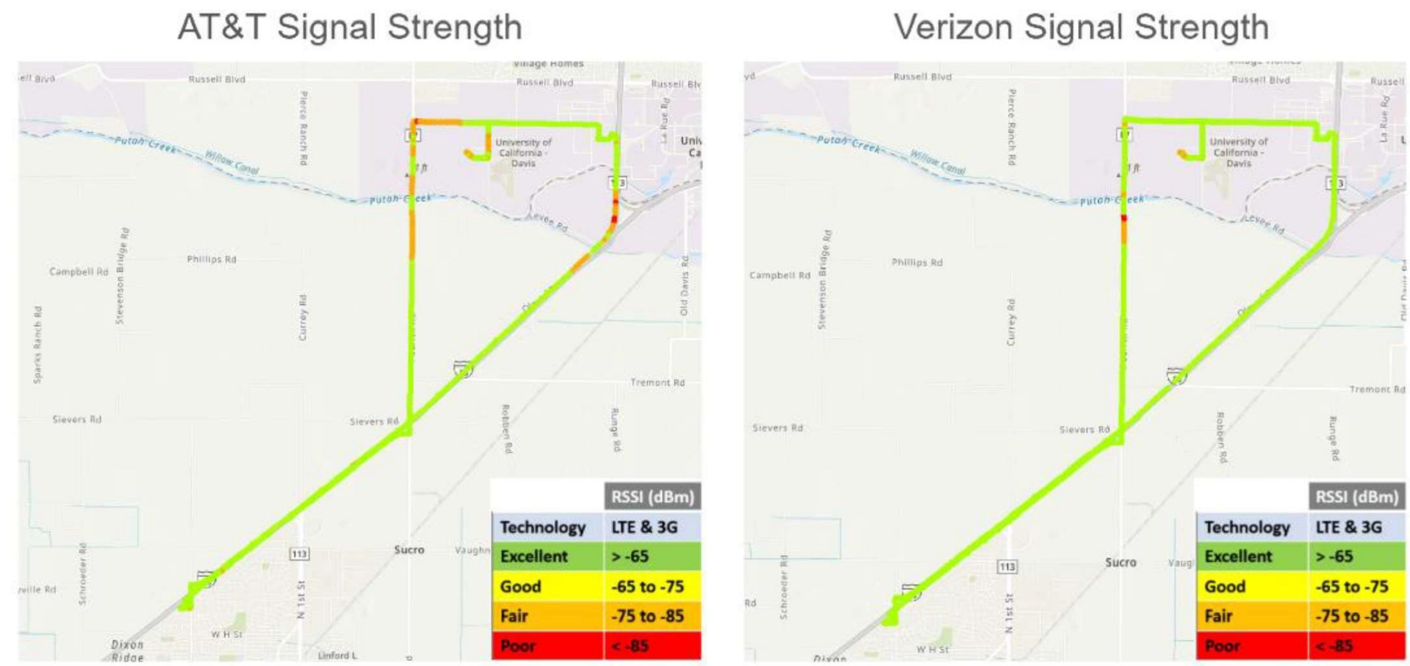

Figure 2.4: The systems were tested to ensure that they can collect cellular data simultaneously. Map generated using ArcGIS software by Esri.

date	time	voltage	boardTem	rssi	rsrq	rsrp	sinr	rscp	errorRate	SID	NID	baseClass	iccid	cellid
7/24/2024	9:05:10 AM	23.78	38	-67	-17	-98	-3.6	-67	0	0	0	121	8.91E+19	86203170
7/24/2024	9:05:12 AM	23.78	38	-67	-17	-98	-3.7	-67	0	0	0	121	8.91E+19	86203170
7/24/2024	9:05:14 AM	23.78	37	-67	-17	-98	-3.9	-67	0	0	0	121	8.91E+19	86203170
7/24/2024	9:05:17 AM	23.78	37	-67	-17	-98	-3.2	-67	0	0	0	121	8.91E+19	86203170
7/24/2024	9:05:19 AM	23.78	37	-67	-17	-98	-1.9	-67	0	0	0	121	8.91E+19	86203170
7/24/2024	9:05:21 AM	23.78	37	-67	-17	-98	-1.3	-67	0	0	0	121	8.91E+19	86203170
7/24/2024	9:05:23 AM	23.78	37	-67	-17	-98	-0.9	-67	0	0	0	121	8.91E+19	86203170
7/24/2024	9:05:25 AM	23.78	37	-67	-17	-98	-0.6	-67	0	0	0	121	8.91E+19	86203170
7/24/2024	9:05:27 AM	23.78	37	-67	-17	-98	-0.3	-67	0	0	0	121	8.91E+19	86203170
7/24/2024	9:05:29 AM	23.78	37	-67	-17	-98	0.2	-67	0	0	0	121	8.91E+19	86203170
7/24/2024	9:05:31 AM	23.78	37	-67	-17	-98	0.3	-67	0	0	0	121	8.91E+19	86203170
7/24/2024	9:05:33 AM	23.78	37	-67	-17	-98	0.7	-67	0	0	0	121	8.91E+19	86203170

Figure 2.5: Example of a data table recorded by the system. Note that not all metrics are shown.

How the System Works, and Limitations

Field Data Collection:

1. Power-on the system.
2. Press the buttons on the yellow strip of the Raspberry Pis to start data collection. The buttons will blink every 2 seconds to indicate that data is being recorded.
3. Drive along the designated route for cellular signal collection.

4. Once data collection is complete, press and hold the buttons for approximately 3 seconds to turn off the Raspberry Pis.
5. Disconnect the system from the power source.

Post-Collection Data Processing:

1. Power-on the Raspberry Pi.
2. Connect the Raspberry Pi to a computer to retrieve the data files.
3. Process the data files as needed.

While the field data collection process performed well during tests in Davis, a time-out issue occurred in the remote areas along Highway 299. The code struggled to tabulate modem data in areas with no signal, causing it to automatically exit the data collection loop. The time-out error is displayed below in Figure 2.6.

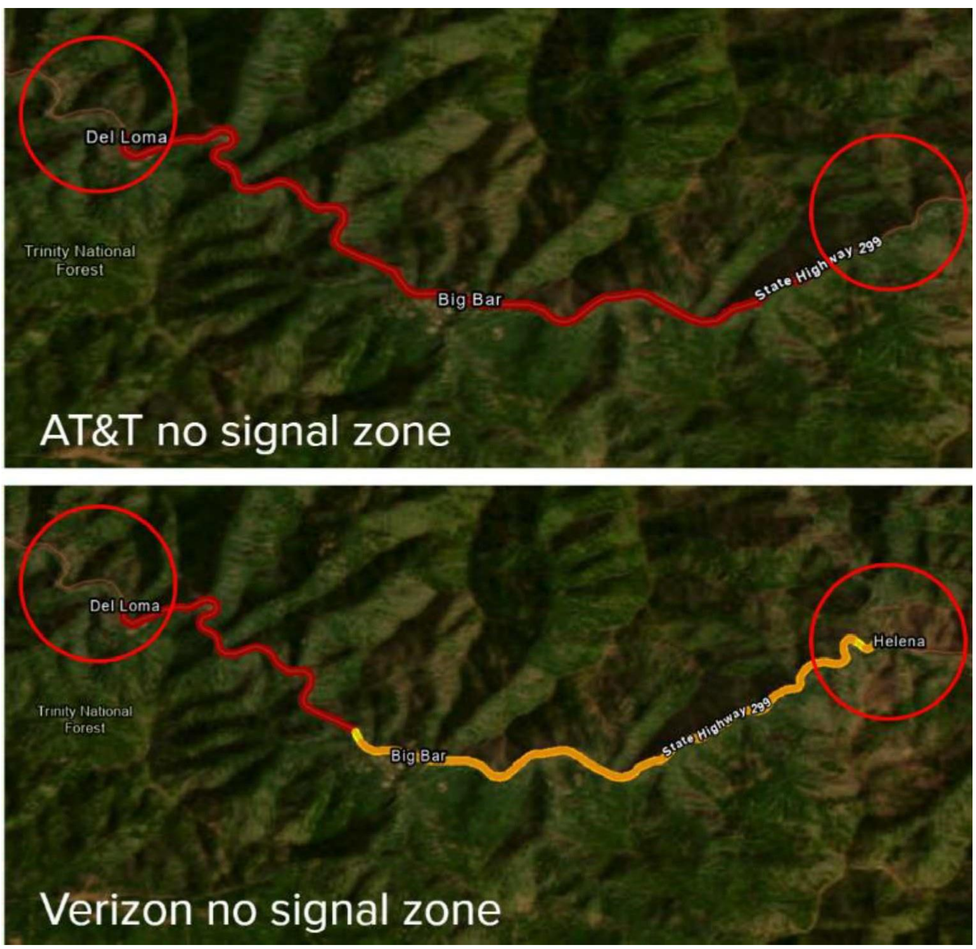

Figure 2.6: The system stopped the cellular signal tracing along Highway 299 (highlighted in red) after entering a no-signal area. Map generated using ArcGIS software by Esri.

To resolve the issue, the code was updated to record blanks when the modem could not tabulate the data. As a result, gaps appear in the no-signal zones, indicating areas where no data were collected due to lack of signal.

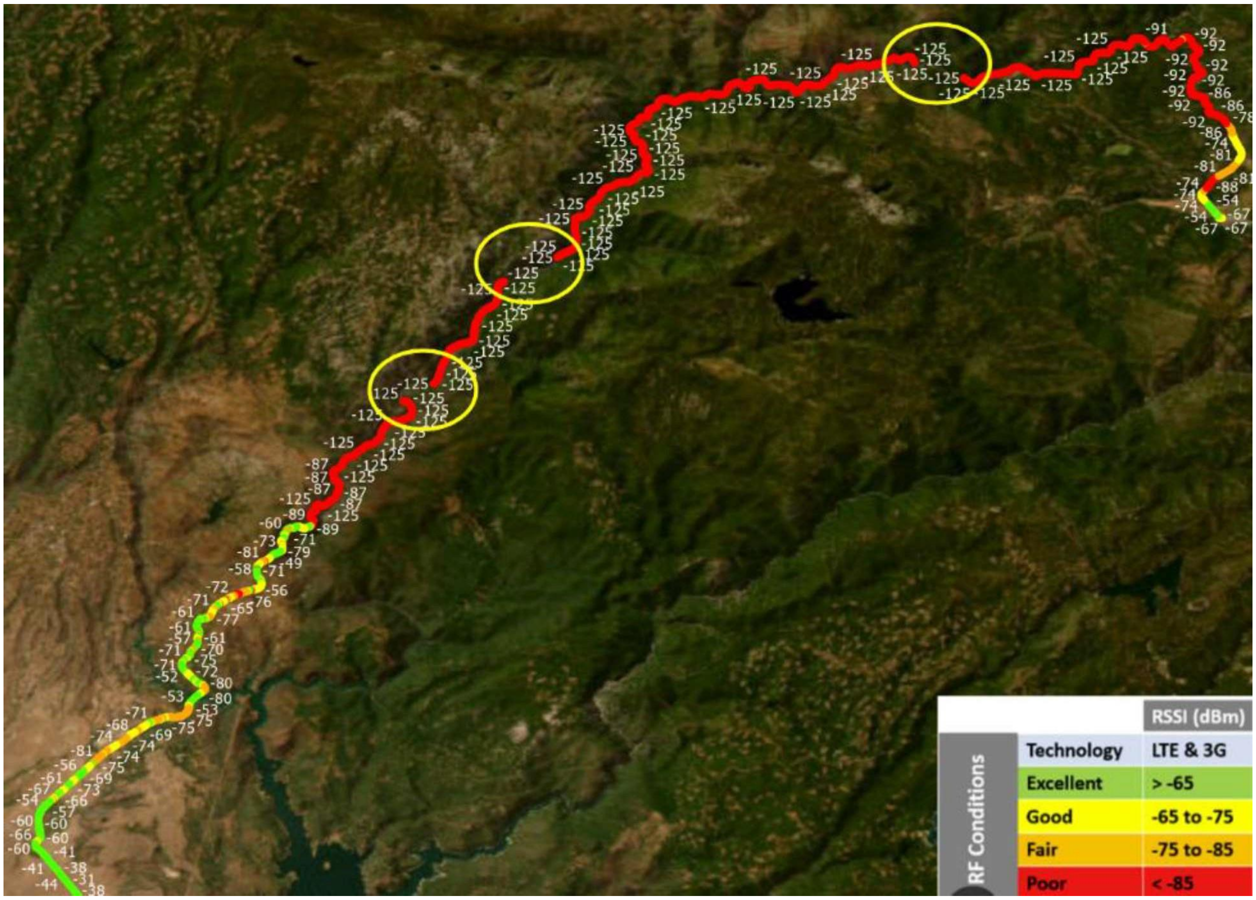

Figure 2.7: Example of the gaps in the data, where no signal output was available for the modem to tabulate. Map generated using ArcGIS software by Esri.

Chapter 3: Cellular Mapping

Test Results of the Cellular Signal Performance for AT&T and Verizon

Using the system setup from section 2, cellular signal data were collected. AT&T and Verizon were the two carriers used to test the cellular signal performance along Highways 299 and 70. According to the data collected, Verizon outperformed AT&T on these highways. Specifically, the signal strength outputs for Verizon consistently outperformed those of AT&T across all trials.

AT&T

The results of the AT&T vehicular mapping are presented across four key metrics: Received Signal Strength Indicator (RSSI), Reference Signal Received Quality (RSRQ), Reference Signal Received Power (RSRP), and Signal-to-Interference-Plus-Noise Ratio (SINR), all performed on Highways 299 and 70. Although three trials were conducted, only the results from one trial per metric are shown here. Figures 3.1 through 3.4 show the results of the third trial for AT & T on Highway 299. The complete results from all three trials can be found in Appendix A of this report.

Highway 299 Trial 3

RSSI

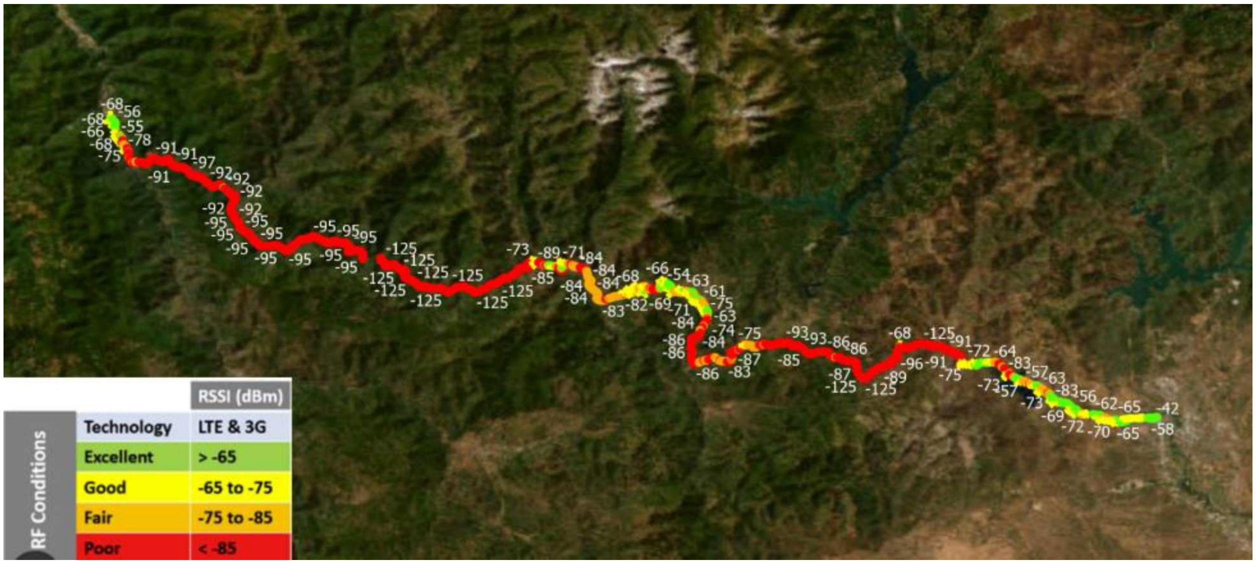

Figure 3.1: Trial 3 – AT&T RSSI mapping result along Highway 299. Map generated using ArcGIS software by Esri.

RSRQ

Figure 3.2: Trial 3 – AT&T RSRQ mapping result along Highway 299. Map generated using ArcGIS software by Esri.

RSRP

Figure 3.3: Trial 3 – AT&T RSRP mapping result along Highway 299. Map generated using ArcGIS software by Esri.

SINR

Figure 3.4: Trial 3 – AT&T SINR mapping result along Highway 299. Map generated using ArcGIS software by Esri.

Figures 3.5 through 3.8 show the results of the third trial for AT & T on Highway 70. The complete results from all three trials can be found in Appendix A of this report.

Highway 70 Trial 3

RSSI

Figure 3.5: Trial 3 – AT&T RSSI mapping result along Highway 70. Map generated using ArcGIS software by Esri.

RSRQ

Figure 3.6: Trial 3 – AT&T RSRQ mapping result along Highway 70. Map generated using ArcGIS software by Esri.

RSRP

Figure 3.7: Trial 3 – AT&T RSRP mapping result along Highway 70. Map generated using ArcGIS software by Esri.

SINR

Figure 3.8: Trial 3 – AT&T SINR mapping result along Highway 70. Map generated using ArcGIS software by Esri.

Verizon

The results of the Verizon vehicular mapping are presented across four key metrics: Received Signal Strength Indicator (RSSI), Reference Signal Received Quality (RSRQ), Reference Signal Received Power (RSRP), and Signal-to-

Interference-Plus-Noise Ratio (SINR), all performed on Highways 299 and 70. Although three trials were conducted, only the results from one trial per metric are shown here. Figures 3.9 through 3.12 show the results of the third trial for Verizon on Highway 299. The complete results from all three trials can be found in Appendix A.

Highway 299

RSSI

Figure 3.9: Trial 3 – Verizon RSSI mapping result along Highway 299. Map generated using ArcGIS software by Esri.

RSRQ

Figure 3.10: Trial 3 – Verizon RSRQ mapping result along Highway 299. Map generated using ArcGIS software by Esri.

RSRP

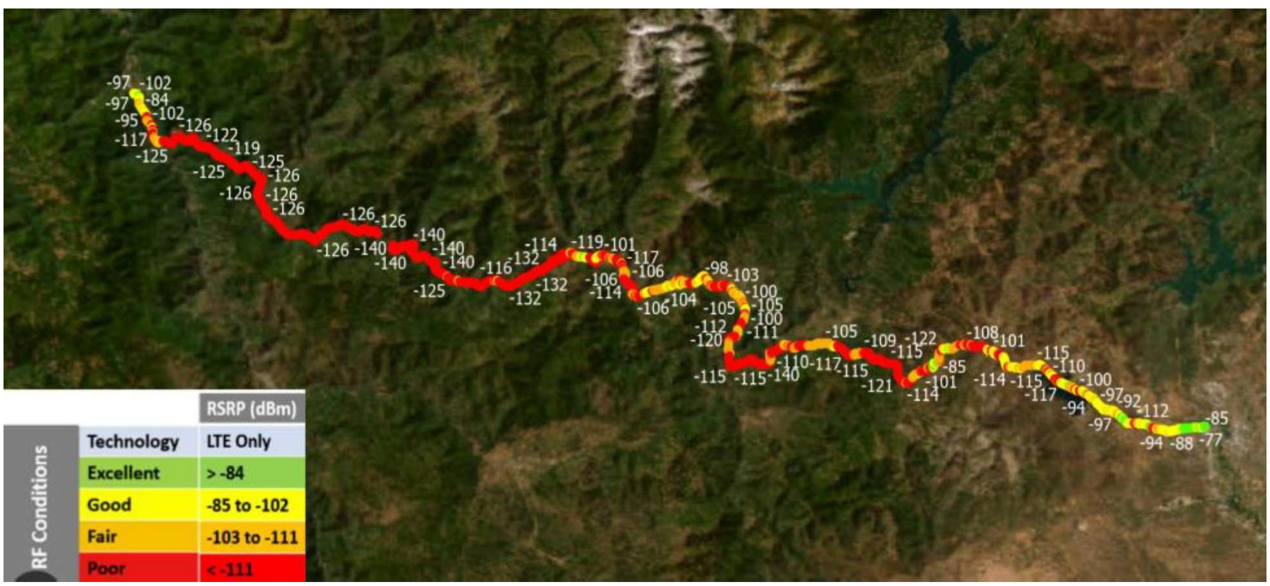

Figure 3.11: Trial 3 – Verizon RSRP mapping result along Highway 299. Map generated using ArcGIS software by Esri.

SINR

Figure 3.12: Trial 3 – Verizon SINR mapping result along Highway 299. Map generated using ArcGIS software by Esri.

Figures 3.13 through 3.16 show the results of the third trial for Verizon on Highway 70. The complete results from all three trials can be found in Appendix A.

Highway 70

RSSI

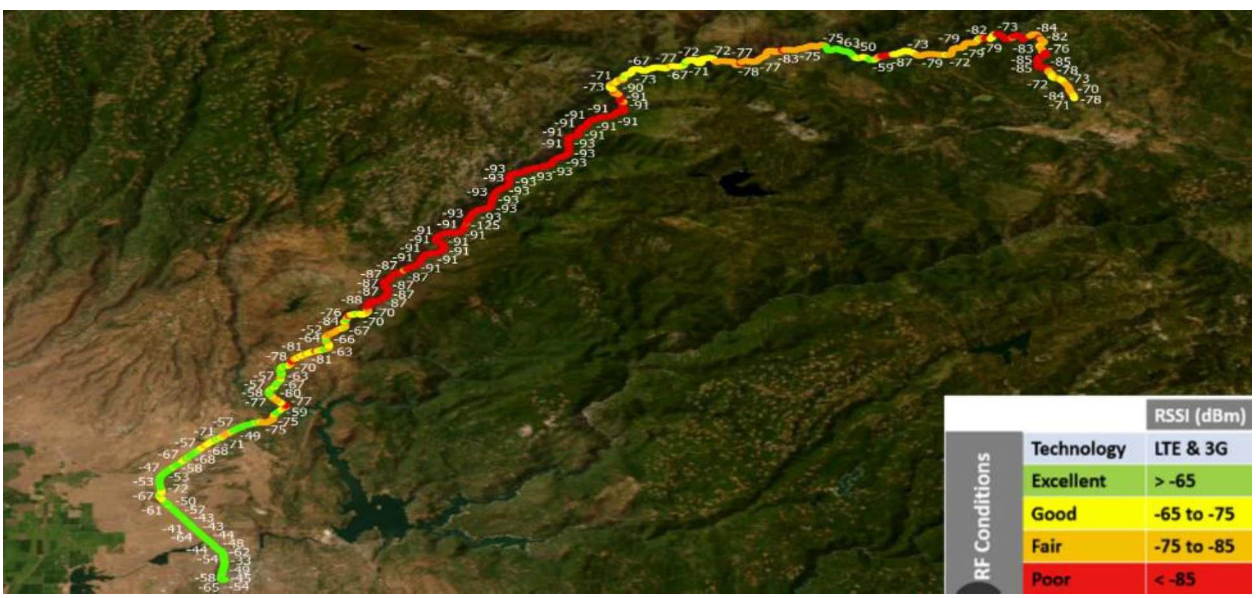

Figure 3.13: Trial 3 – Verizon RSSI mapping result along Highway 70. Map generated using ArcGIS software by Esri.

RSRQ

Figure 3.14: Trial 3 – Verizon RSRQ mapping result along Highway 70. Map generated using ArcGIS software by Esri.

RSRP

Figure 3.15: Trial 3 – Verizon RSRP mapping result along Highway 70. Map generated using ArcGIS software by Esri.

SINR

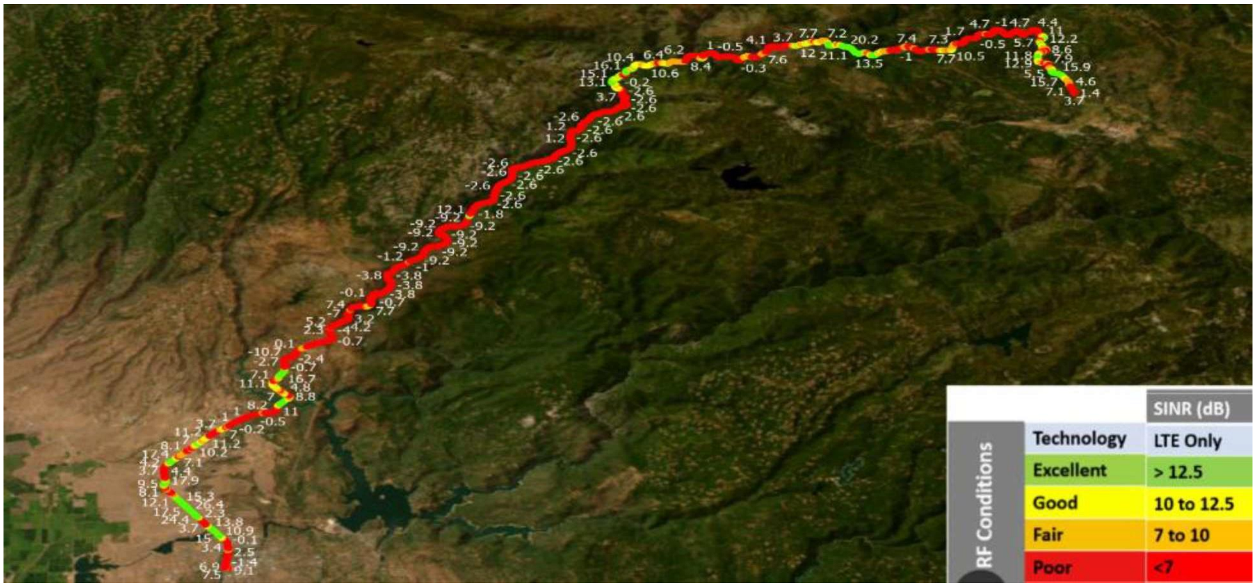

Figure 3.16: Trial 3 – Verizon SINR mapping result along Highway 70. Map generated using ArcGIS software by Esri.

FCC Data Incorporates into Cellular Mapping

The FCC provides a national broadband map that illustrates cellular coverage across the country (see Figure 3.17). The map can be accessed here: [Home | FCC National Broadband Map (https://broadbandmap.fcc.gov/home)](https://broadbandmap.fcc.gov/home). This FCC data is used in conjunction with the cellular mapping collected by the AHMCT team to identify and project testing locations.

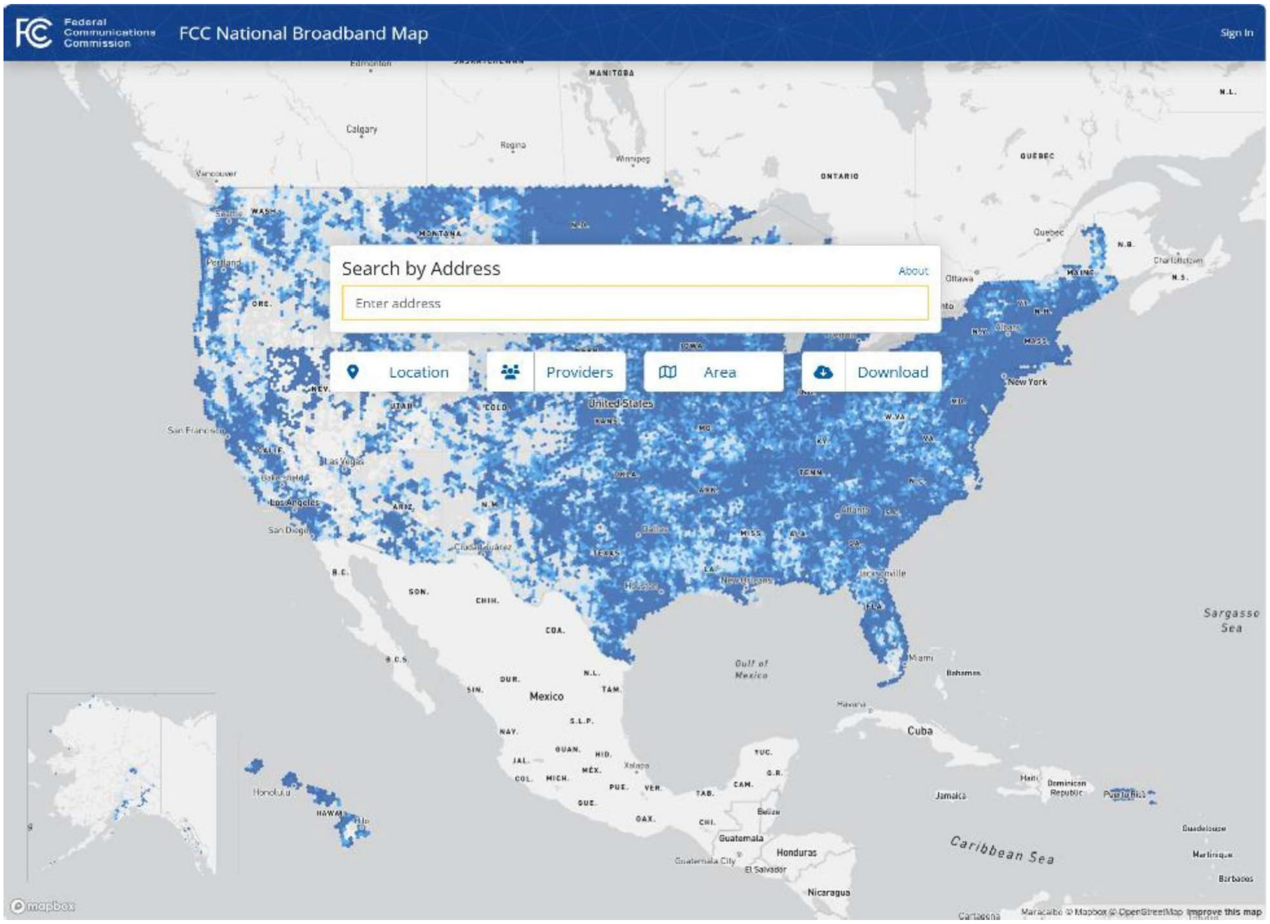

Figure 3.17: FCC website provides the broadband map of your desire providers at any area.

The layer of the broadband map for Verizon was downloaded and incorporated into the cellular mapping, as shown in Figures 3.18 and 3.19.

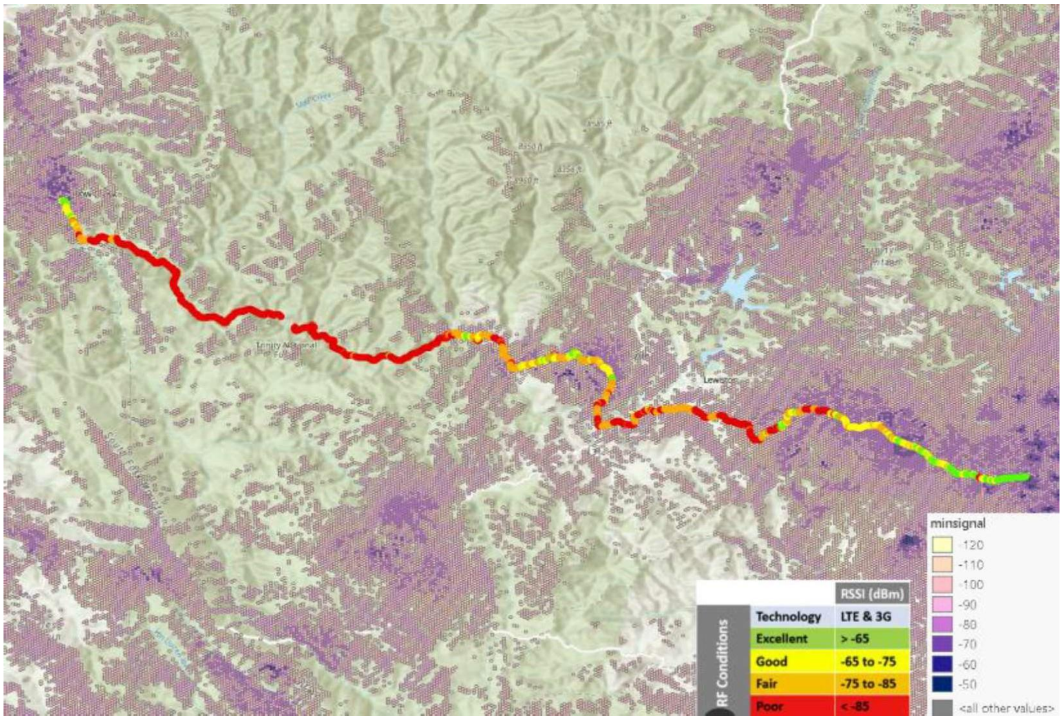

Figure 3.18: FCC broadband map is integrated with AHMCT cellular mapping on Highway 299. Map generated using ArcGIS software by Esri.

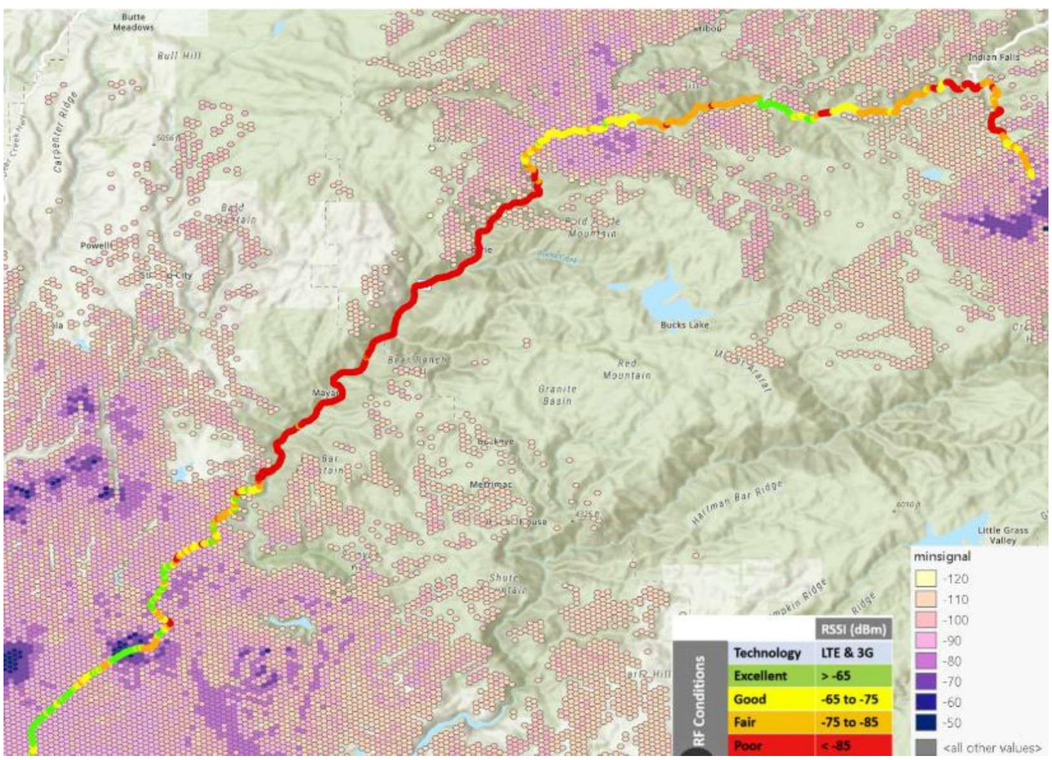

Figure 3.19: FCC broadband map is integrated with AHMCT cellular mapping on Highway 70. Map generated using ArcGIS software by Esri.

The FCC broadband map aligns with the cellular mapping, with the shade of purple indicating signal strength. Darker purple areas represent stronger cellular signals, typically found in more populated regions. Consequently, the cellular mapping tends to show green in areas close to these dark purple regions. In contrast, areas with minimal or no broadband coverage are typically represented in red on the cellular mapping routes.

Projected Signal Source Incorporates into Cellular Mapping

In addition to the FCC broadband map, projected cellular towers in the area have been incorporated into the cellular mapping. Cellular towers that are likely sources of signals for field trials are highlighted with red circles in Figures 3.20 and 3.21. The projected cellular towers are valuable for the AHMCT team, as they prefer to select testing locations near these towers to ensure optimal connectivity during trials.

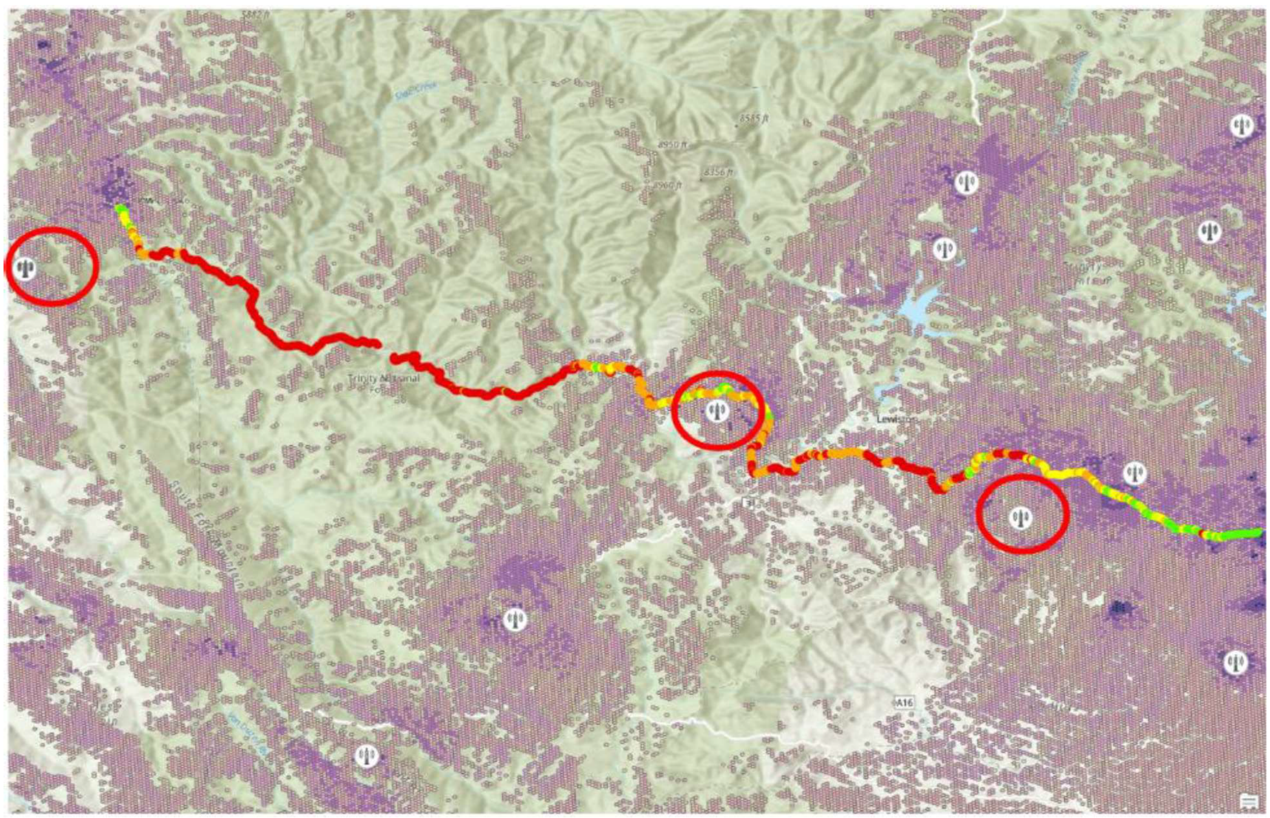

Figure 3.20: Projected cellular towers along Highway 299, which may be relevant for field trials, are circled in red. Testing locations are preferred to be situated near these cellular towers to ensure optimal connectivity during the field trials. Map generated using ArcGIS software by Esri.

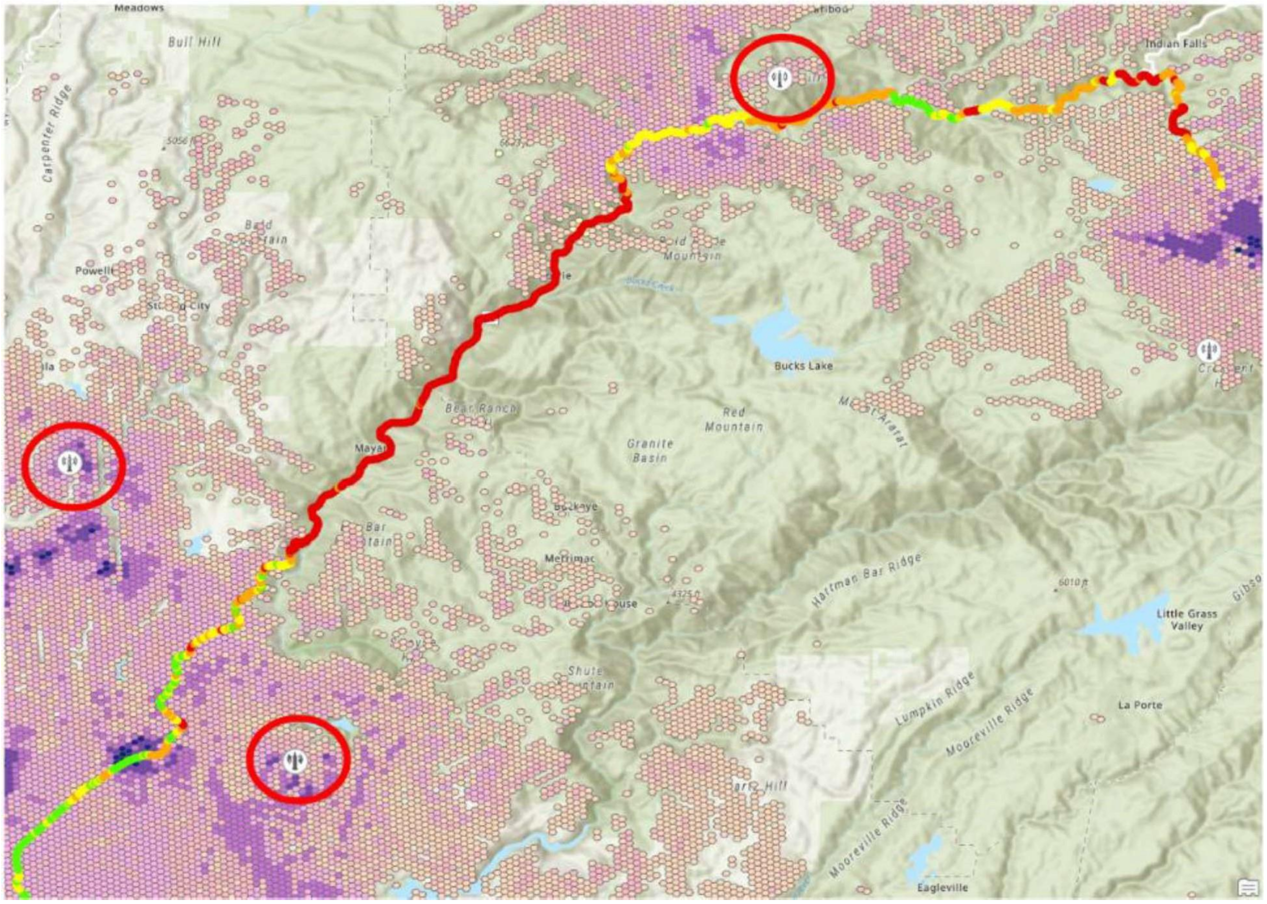

Figure 3.21: Projected cellular towers along Highway 70, which may be relevant for field trials, are circled in red. Testing locations are preferred to be situated near these cellular towers to ensure optimal connectivity during the field trials. Map generated using ArcGIS software by Esri.

Utilizing the FCC broadband map, the cellular mapping, and the projected cellular towers, the AHMCT team were able to determine the optimal locations for testing. The selection of field trial locations is detailed in the next chapter.

Chapter 4: Selection of Field Trial Locations

Predicting Testing Locations

The cellular mapping results reveal areas with limited or no signal coverage. In conjunction with the data gathered by the AHMCT team, the FCC national broadband map was used to identify regions where signal strength could be improved if terrain conditions are overcome. In the AHMCT RSSI mapping, areas with minimal or no cellular signals are highlighted in red and orange. The FCC broadband map illustrates potential signal coverage, with hexagons representing regions where cellular signals may be captured, in which darker hexagons indicate regions where signal capture is more feasible. Figures 4.1 and 4.2 mark all the potential testing locations, where improving signal reception on Highways 299 and 70 is possible, assuming terrain overcast can be overcome in normal weather conditions.

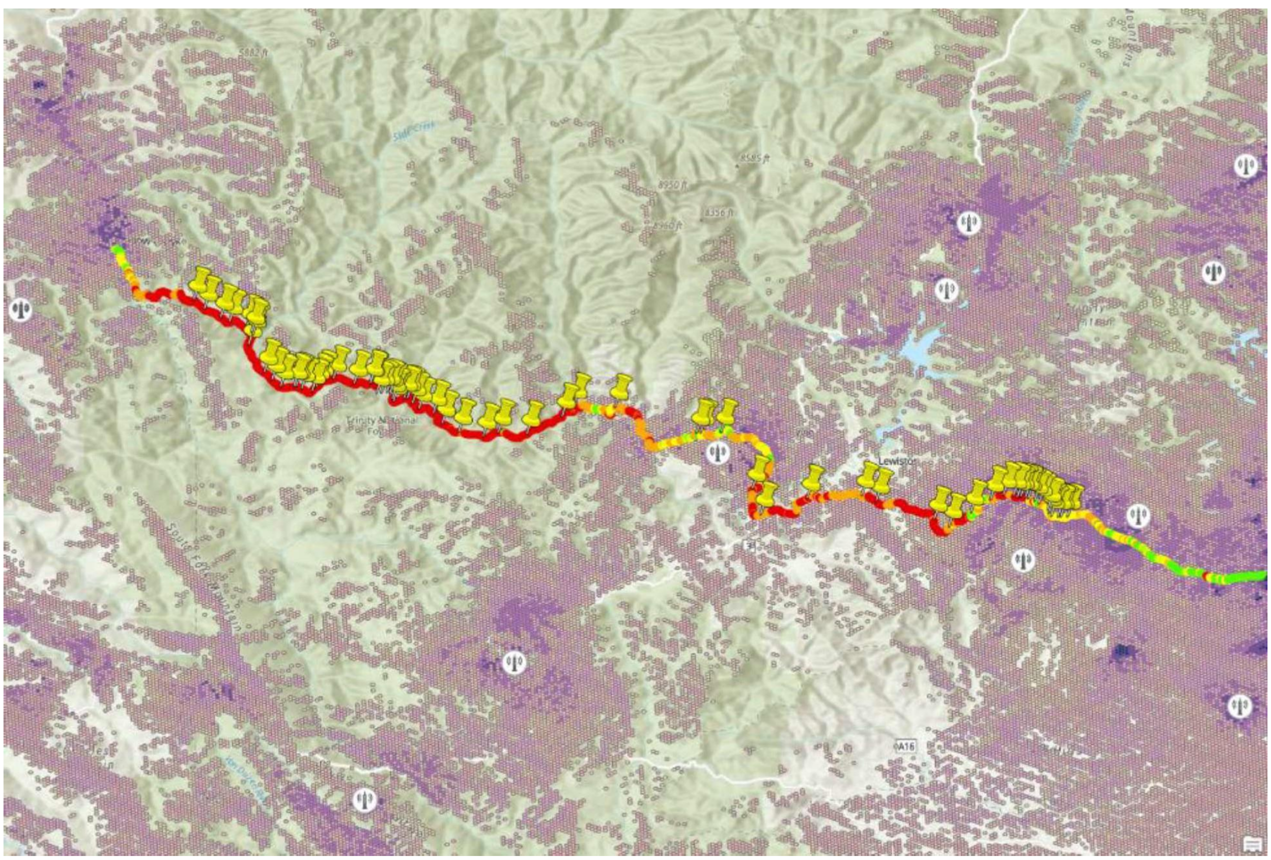

Figure 4.1: Possible locations (pinned in yellow) where cellular signals can be improved if overcoming terrain conditions on Highway 299. Map generated using ArcGIS software by Esri.

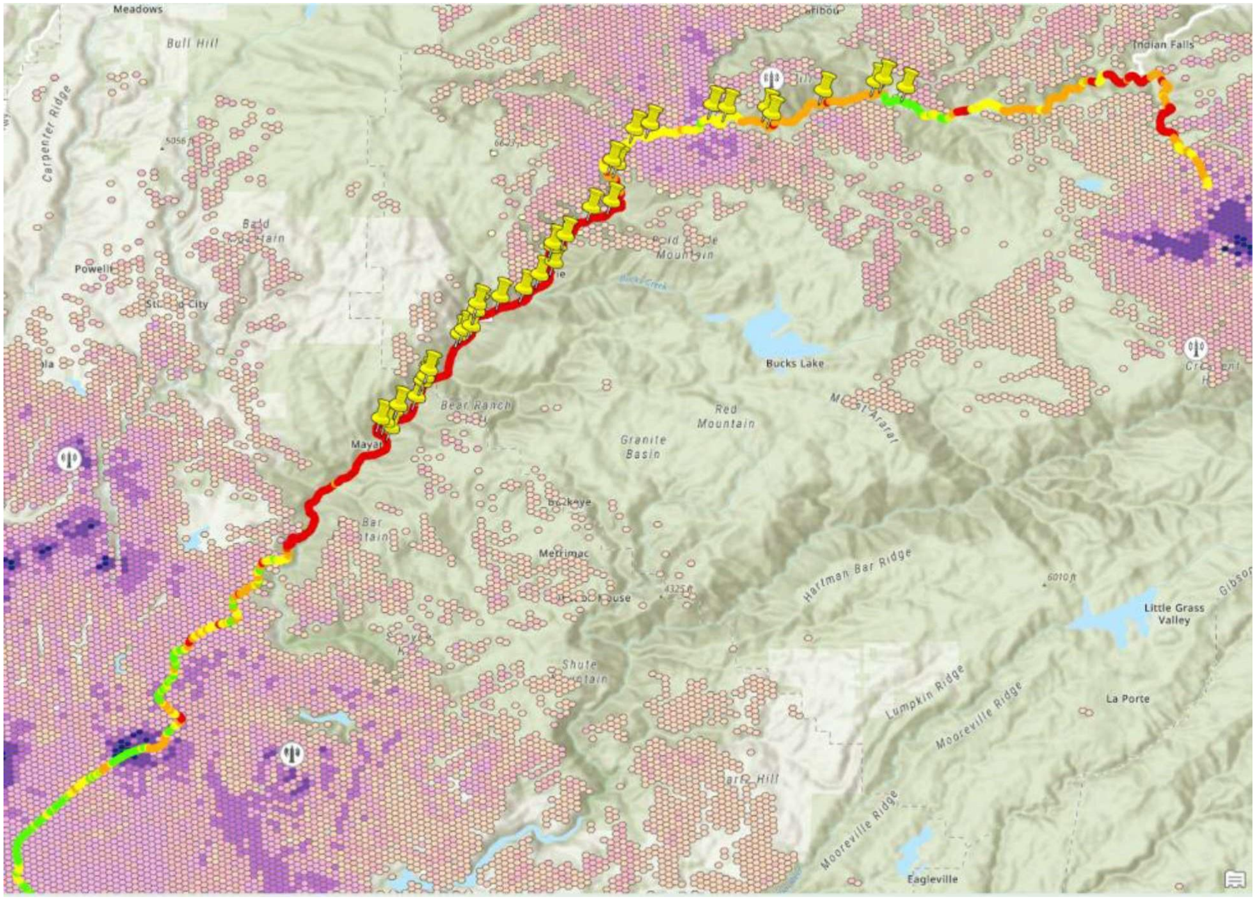

Figure 4.2: Possible locations (pinned in yellow) where cellular signals can be improved if overcoming terrain conditions on Highway 70. Map generated using ArcGIS software by Esri.

While capturing signals in areas with no signal (highlighted in red) is ideal, capturing signal in areas with minimal signal (highlighted in orange) is necessary, as these locations may provide valuable data if the no-signal segments fail to do so. Therefore, three (3) locations with no signal and three (3) locations with minimal signal were chosen for each highway. Additionally, the selected locations must fall within the coverage area of the projected FCC broadband map and, ideally, be in proximity (within 10 miles) to a projected cellular tower.

Choosing Testing Locations

The criteria for selecting testing locations for Highways 299 and 70 were as follows, arranged from most important to least important:

1. To ensure safety, the chosen locations must have space to accommodate the AHMCT team 25 feet from the edge of the roadway.

2. The chosen locations must have space for the AHMCT team to back up and observe the drone during flight, to ensure safety.
3. The chosen locations should be near the projected FCC national broadband coverage to ensure optimal coverage during field trials.
4. The chosen locations should be in minimal to no signal segments (highlighted in red and orange on the cellular mapping).
5. The chosen locations are preferably within 10 miles of the projected cellular towers.

Utilizing Google Earth functions, the testing locations were reviewed and analyzed before the AHMCT team headed to the field. The AHMCT team evaluated the areas and finalized the testing locations along Highways 299 and 70, as explained in the following sections.

Highway 299

The testing locations along Highway 299 were selected based on the established criteria. Table 4.1 provides the coordinates for the no-signal locations, along with backup options in case the main locations were unavailable in the field. Table 4.2 provides the coordinates for the minimal-signal locations, in case the main locations were unable to yield meaningful data in the field.

Table 4.1: Coordinates of the testing locations with no cellular signal coverage on Highway 299

Locations	Latitude	Longitude
Spot 7 - Main	40.761688°	-123.287782°
Spot 6 - Back-up for Spot 7	40.750617°	-123.278457°
Spot 27 - Main	40.790245°	-123.438493°
Spot 24 - Back-up for Spot 27	40.785308°	-123.418834°
Spot 33 - Main	40.849873°	-123.484190°
Spot 31 - Back-up for Spot 33	40.835491°	-123.487539°

Table 4.2: Coordinates of the testing locations with minimal cellular signal coverage on Highway 299

Locations	Latitude	Longitude
Spot 19	40.666928°	-122.809799°
Spot 22	40.652439°	-122.934545°
Spot 23	40.680513°	-122.943220°
Spot 28	40.769341°	-123.136310°

In Figure 4.3, the main testing locations for Highway 299 are shown circled on a map.

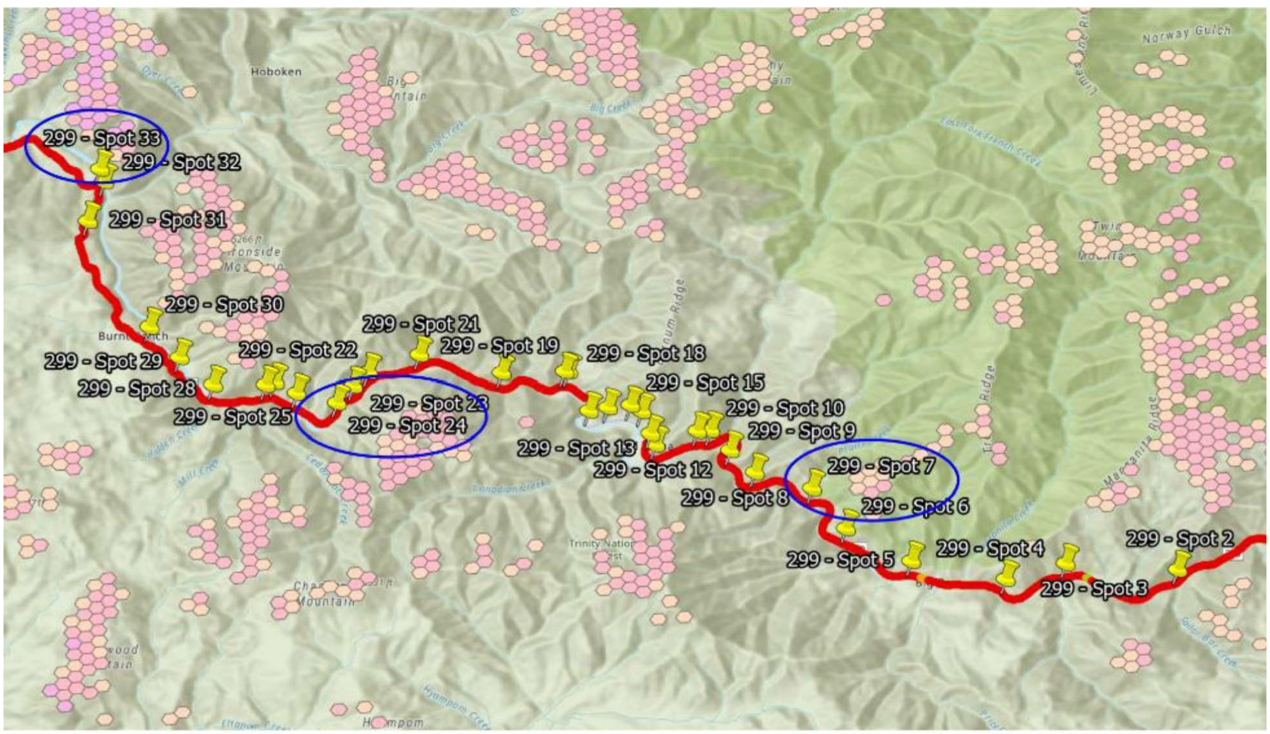

Figure 4.3: The main testing locations for Highway 299 are circled on the map. The locations with minimal cellular signal coverage are not shown in this figure. Map generated using ArcGIS software by Esri.

All the testing locations in Tables 4.1 and 4.2 were reviewed using Google Earth. Below is an example of how Google Earth was utilized to observe and analyze the testing locations selected on Highway 299.

Figure 4.4: Google Earth functions utilized to ensure the testing locations on Highway 299 meet the safety criteria. Photo courtesy of Google Earth.

Highway 70

The testing locations along Highway 70 were selected based on the established criteria. Table 4.3 provides the coordinates for the no-signal locations, along with backup options in case the main locations are unavailable in the field. Table 4.4 provides the coordinates for the minimal-signal locations in case the main locations are unable to yield meaningful data in the field. All the testing locations in Tables 4.3 and 4.4 were reviewed using Google Earth.

Table 4.3: Coordinates of the testing locations with no cellular signal coverage on Highway 70

Locations	Latitude	Longitude
Spot 8 - Main	39.863006°	-121.387253°
Spot 6 - Back-up for Spot 8	39.856369°	-121.390507°
Spot 16 - Main	39.909267°	-121.332735°
Spot 14 - Back-up for Spot 16	39.900763°	-121.359295°
Spot 21 - Main	39.939630°	-121.309093°
Spot 23 - Back-up for Spot 21	39.959319°	-121.282679°

Table 4.4: Coordinates of the testing locations with minimal cellular signal coverage on Highway 70

Locations	Latitude	Longitude
Spot 24	39.980904°	-121.279368°
Spot 30	40.012943°	-121.193707°
Spot 32	40.022569°	-121.161395°
Spot 33	40.027481°	-121.131659°

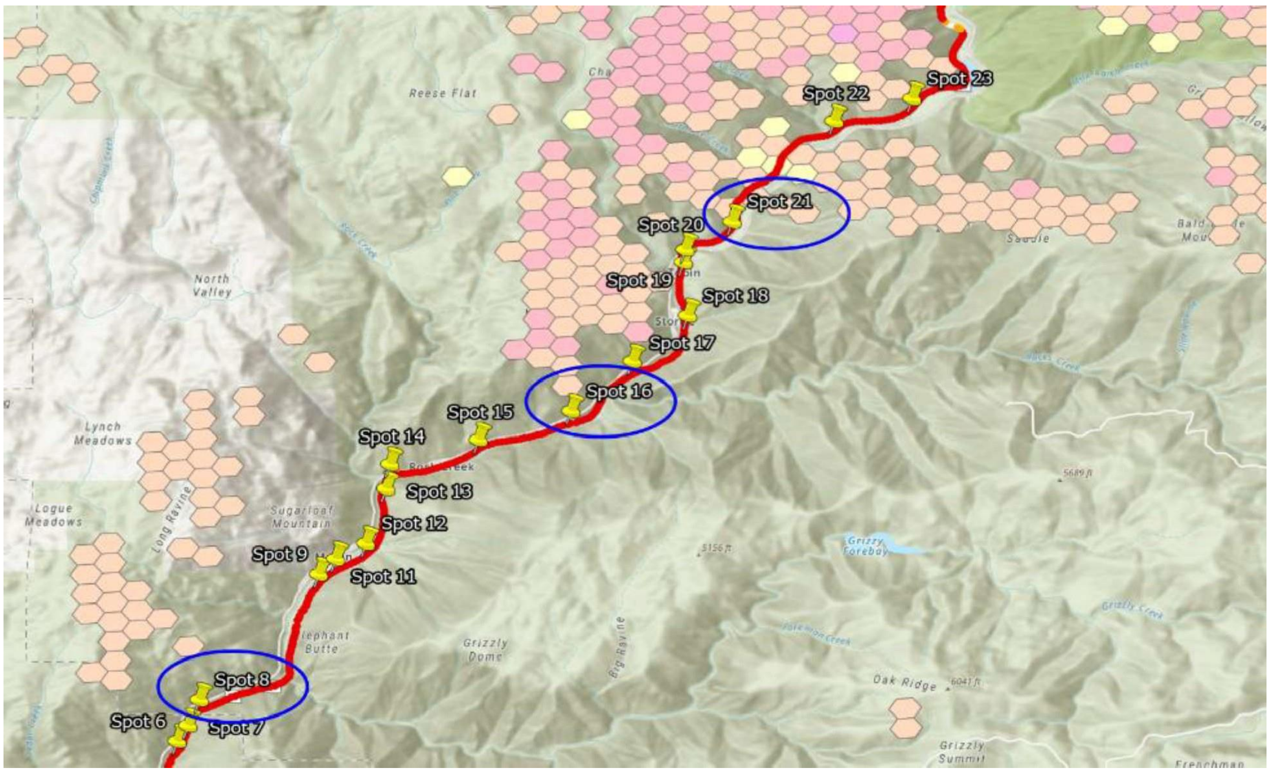

Figure 4.5: The main testing locations for Highway 70 are circled on the map. The locations with minimal cellular signal coverage are not shown in this figure. Map generated using ArcGIS software by Esri.

Figure 4.6 provides an example of how Google Earth was utilized to observe and analyze the testing locations selected on Highway 70.

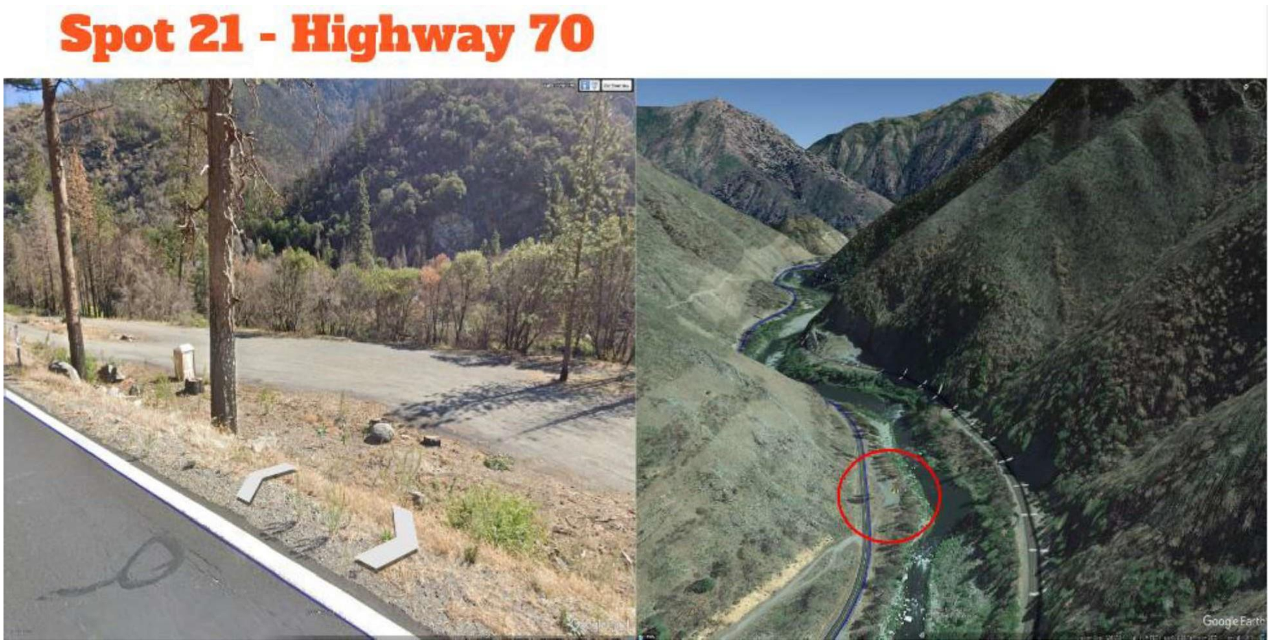

Figure 4.6: Google Earth functions utilized to ensure the testing locations on Highway 70 meet the safety criteria. Photo courtesy of Google Earth.

Test Plan for Highways 299 and 70

The testing procedures were as follows:

1. Drive to the main testing locations.

- Highway 299 main locations: Spots 7, 27, and 33
- Highway 70 main locations: Spots 8, 16, and 21

2. Set up the UAS system.

- Set up the signal logging system on the ground by connecting to the Raspberry Pi.
- Power-on the UAS should power the rest of the signal recording system.

3. Collect data.

- Once the ground logging system is activated by command, it begins logging data continuously. However, the system is unable to log data if the modem cannot establish a cellular connection. In instances where data is unavailable, the AHMCT team gathered data in areas with minimal signal to monitor improvements in connectivity as the UAS ascends.

Official Testing Locations

At some of the main locations along Highways 299 and 70, we were unable to capture a cellular signal, preventing data collection. As a result, the AHMCT team turned to the minimal-signal locations to gather meaningful data. Figures 4.7 and 4.8 show the official testing locations for Highways 299 and 70, respectively. The locations are numbered in the order in which the tests were conducted.

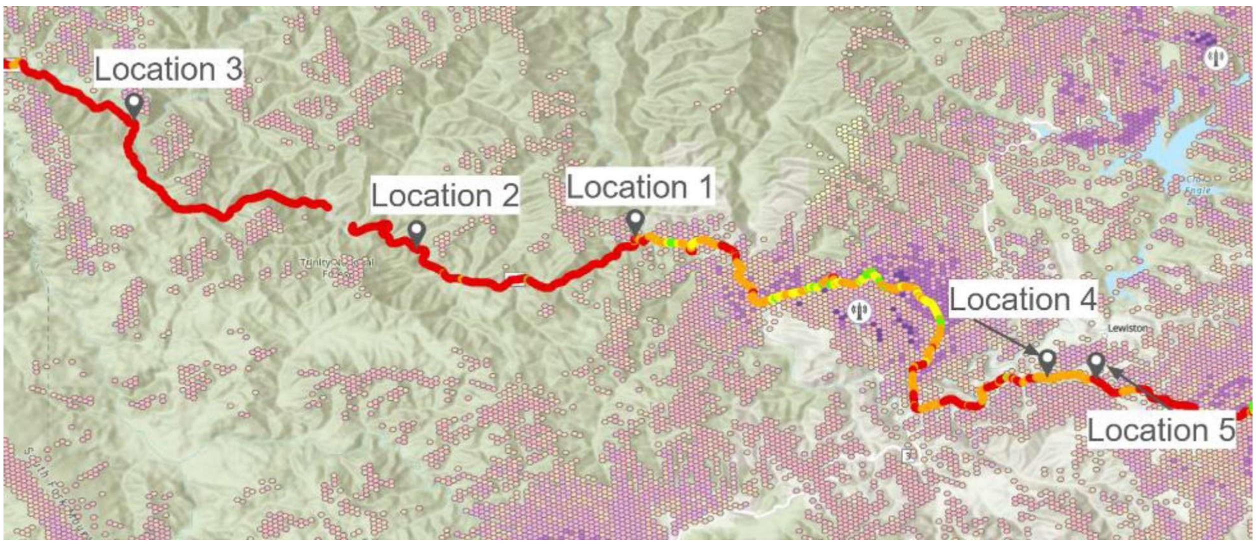

Figure 4.7: Official testing locations on Highway 299. Map generated using ArcGIS software by Esri.

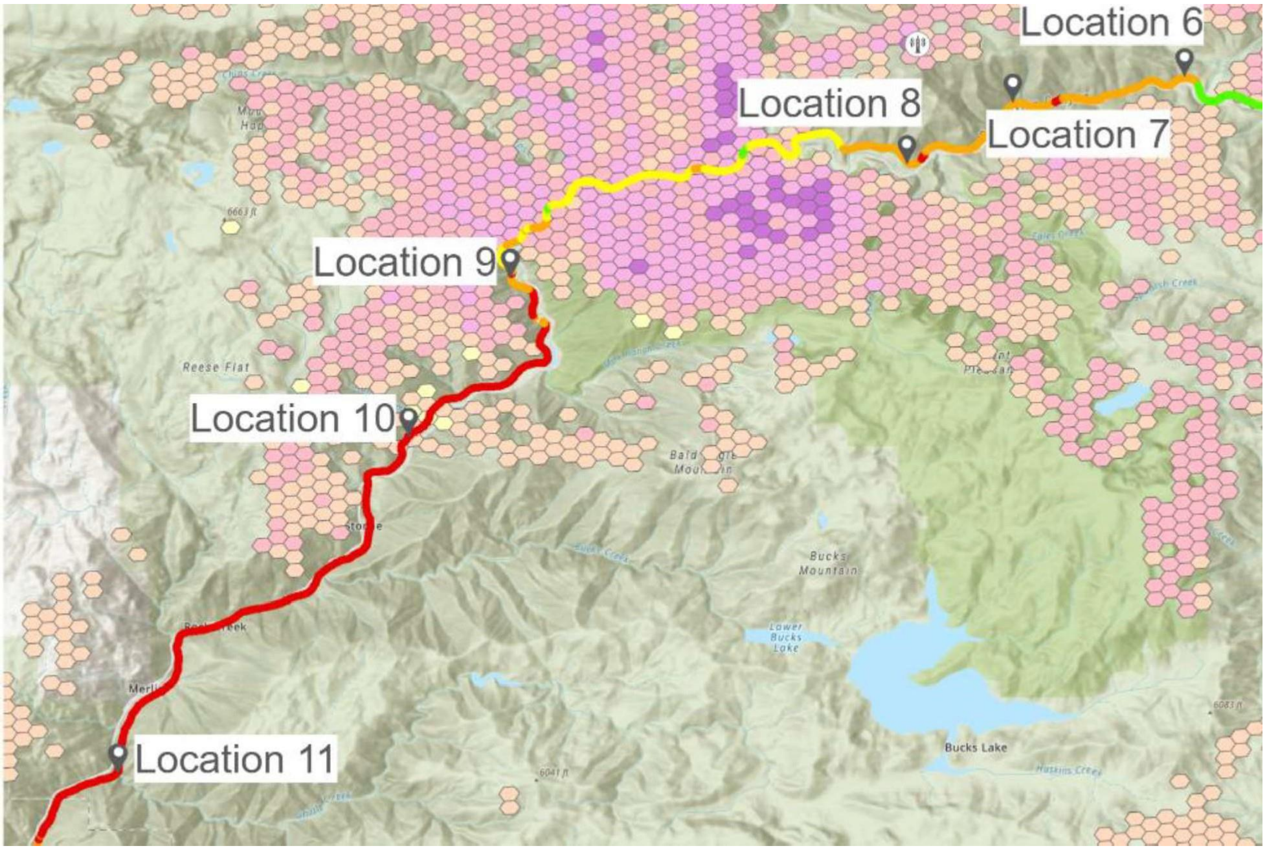

Figure 4.8: Official testing locations on Highway 70. Map generated using ArcGIS software by Esri.

The official testing locations were a combination of no-signal and minimal-signal areas. Despite the plan change, the AHMCT team was able to collect sufficient data for analysis.

Mapping Out the Actual Signal Source for Each Testing Location

From the data collected, the AHMCT team was able to map out the signal source for each location. The team used the unwired labs OpenCellID's online Open Database of Cell Towers (https://www.opencellid.org/) resource as a tool to determine the location of the signal source. By utilizing the OpenCellID (cellular identification), LAC (location area code), MCC (mobile country code), and MNC (mobile network code) extracted from the data, a cell tower was matched to each testing location. In addition to matching each location to its signal source, the distance from each location to the signal source was measured. Figures 4.9 and 4.10 provide visual representations of the distance from each location to its respective signal source.

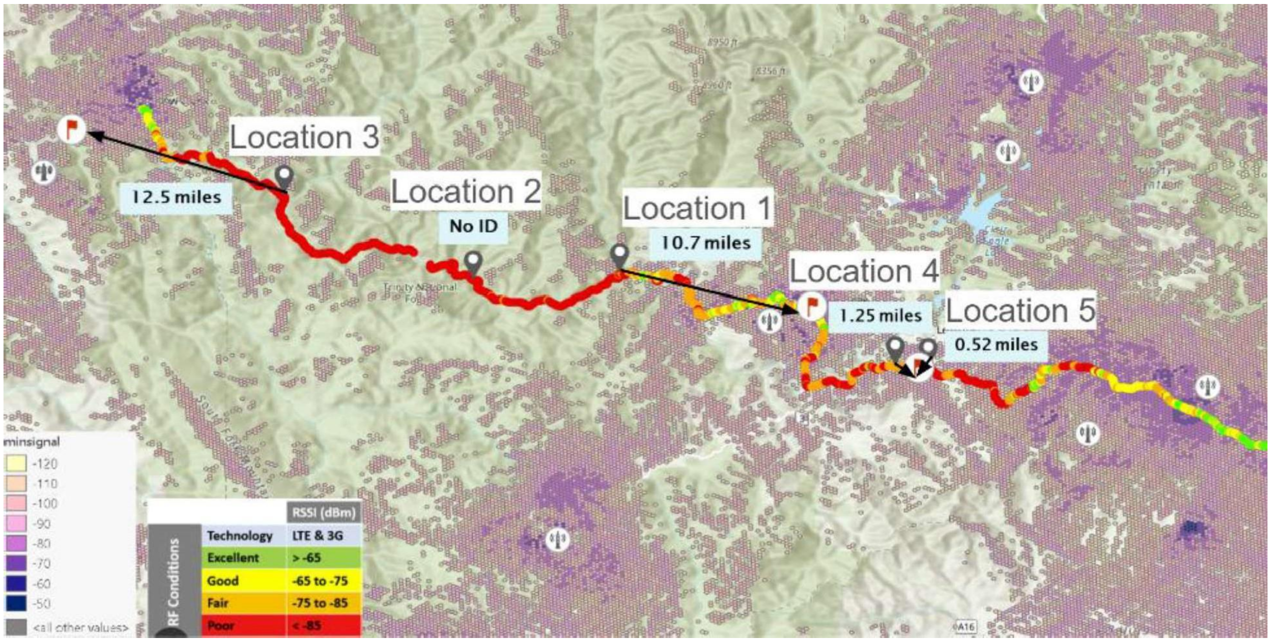

Figure 4.9: Highway 299 – Each location is mapped to its corresponding signal source, along with the distance from the location to the signal source. Map generated using ArcGIS software by Esri.

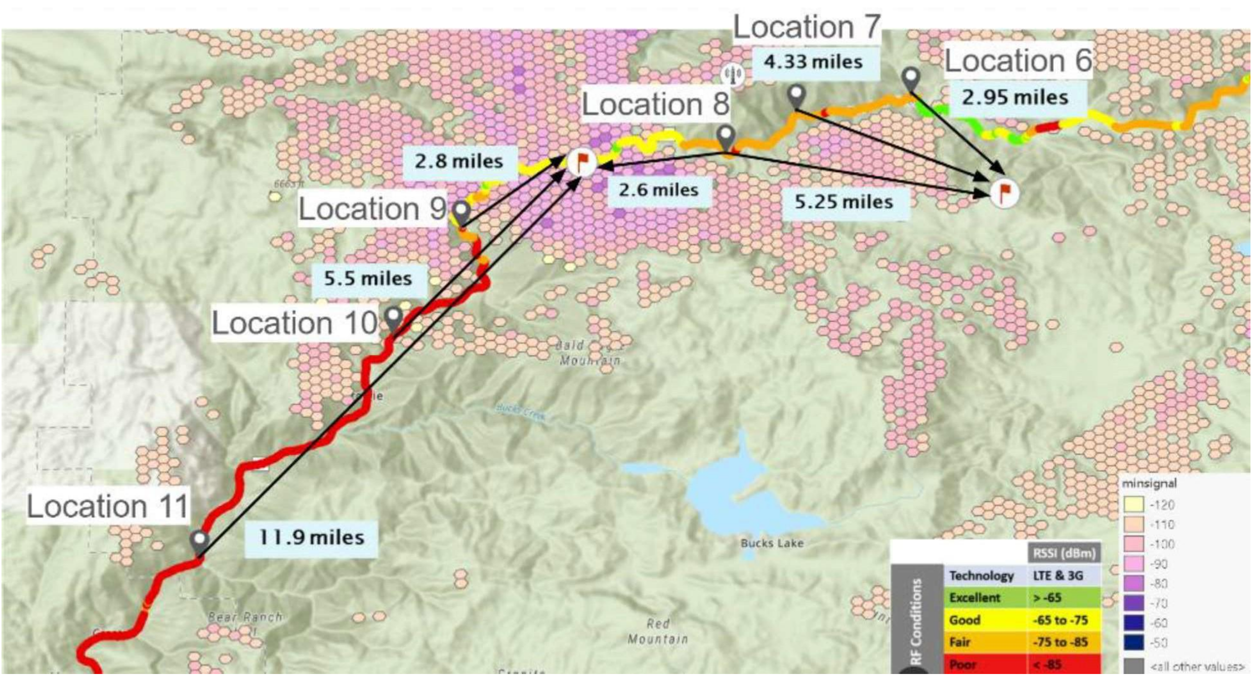

Figure 4.10: Highway 70 – Each location is mapped to its corresponding signal source, along with the distance from the location to the signal source. Map generated using ArcGIS software by Esri.

Appendix A: Results from Cellular Mapping across All Trials on Highways 299 and 70

Since the results for Trial 3 on Highways 299 and 70 are already presented in Chapter 3 of the report, only the results from Trials 1 and 2 are included in Appendix A. These results include measurements of Received Signal Strength Indicator (RSSI), Reference Signal Received Quality (RSRQ), Reference Signal Received Power (RSRP), and Signal-to-Interference-plus-Noise Ratio (SINR) from Trials 1 and 2.

Highway 299

AT&T

Trial 1

RSSI

Figure A.1: Trial 1 – AT&T RSSI mapping result along Highway 299. Map generated using ArcGIS software by Esri.

RSRQ

Figure A.2: Trial 1 – AT&T RSRQ mapping result along Highway 299. Map generated using ArcGIS software by Esri.

RSRP

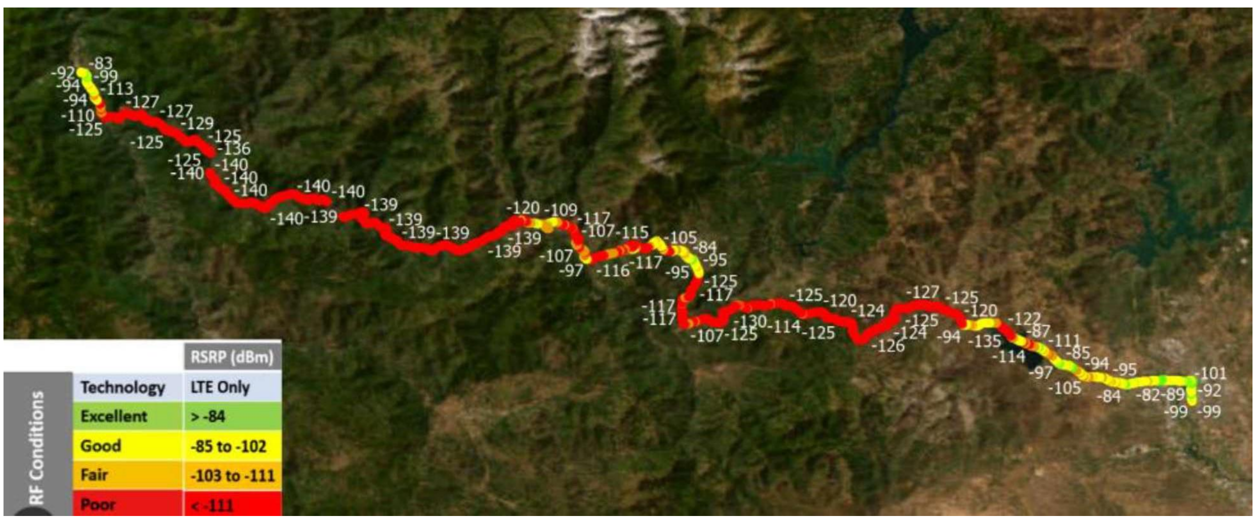

Figure A.3: Trial 1 – AT&T RSRP mapping result along Highway 299. Map generated using ArcGIS software by Esri.

SINR

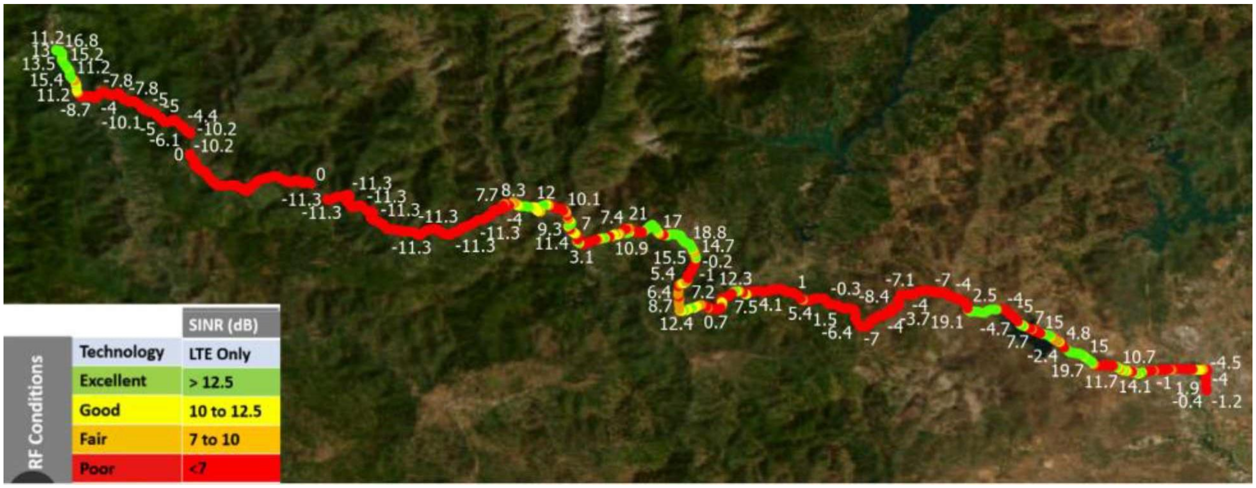

Figure A.4: Trial 1 – AT&T SINR mapping result along Highway 299. Map generated using ArcGIS software by Esri.

Trial 2

RSSI

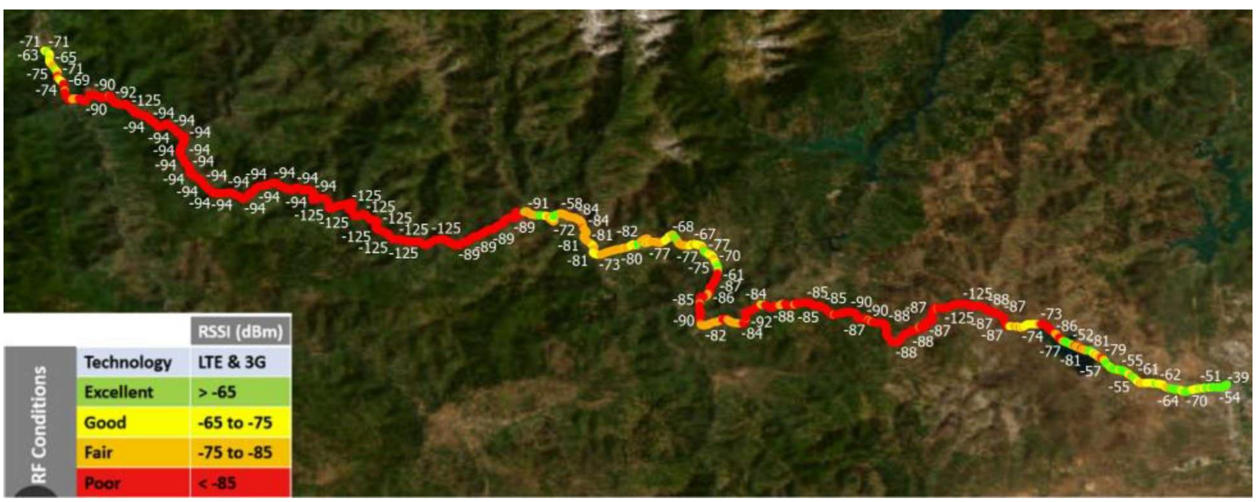

Figure A.5: Trial 2 – AT&T RSSI mapping result along Highway 299. Map generated using ArcGIS software by Esri.

RSRQ

Figure A.6: Trial 2 – AT&T RSRQ mapping result along Highway 299. Map generated using ArcGIS software by Esri.

RSRP

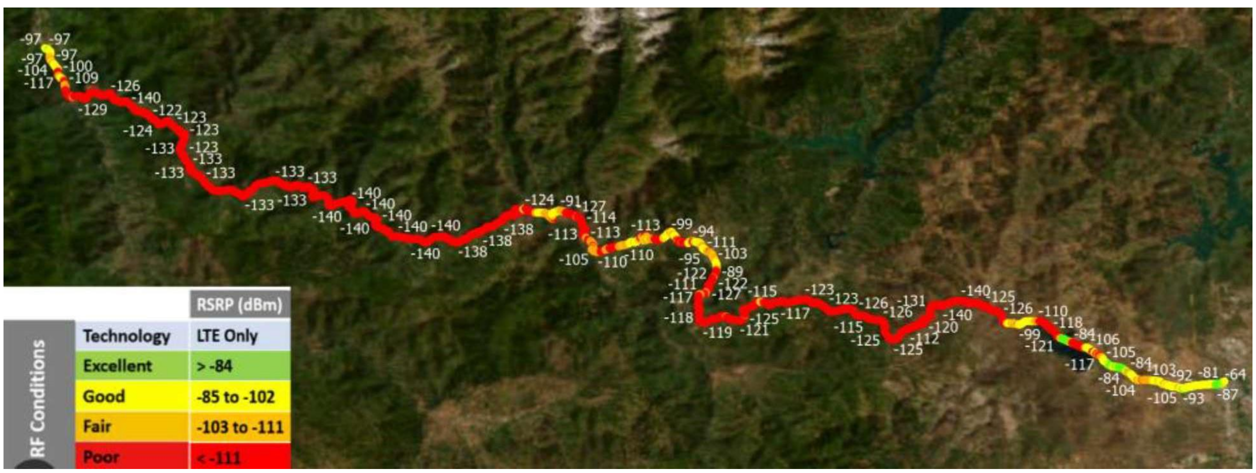

Figure A.7: Trial 2 – AT&T RSRP mapping result along Highway 299. Map generated using ArcGIS software by Esri.

SINR

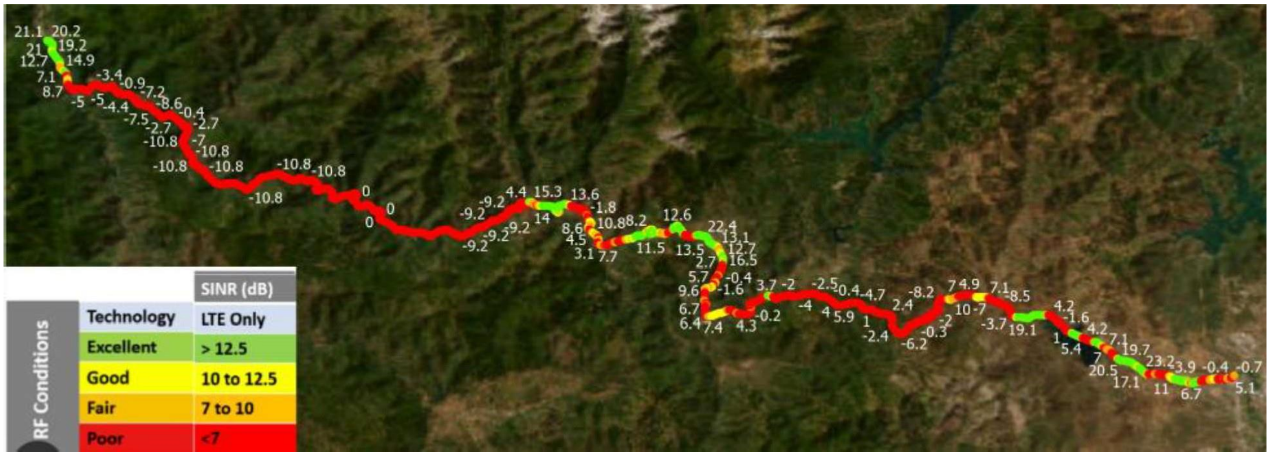

Figure A.8: Trial 2 – AT&T SINR mapping result along Highway 299. Map generated using ArcGIS software by Esri.

Verizon

Trial 1

RSSI

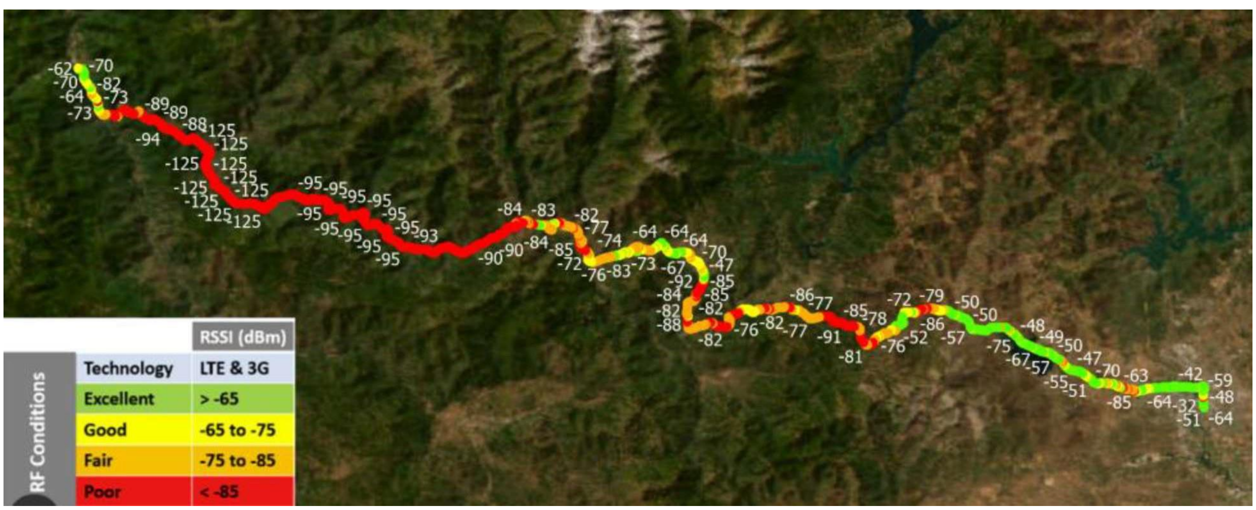

Figure A.9: Trial 1 – Verizon RSSI mapping result along Highway 299. Map generated using ArcGIS software by Esri.

RSRQ

Figure A.10: Trial 1 – Verizon RSRQ mapping result along Highway 299. Map generated using ArcGIS software by Esri.

RSRP

Figure A.11: Trial 1 – Verizon RSRP mapping result along Highway 299. Map generated using ArcGIS software by Esri.

SINR

Figure A.12: Trial 1 – Verizon SINR mapping result along Highway 299. Map generated using ArcGIS software by Esri.

Trial 2

RSSI

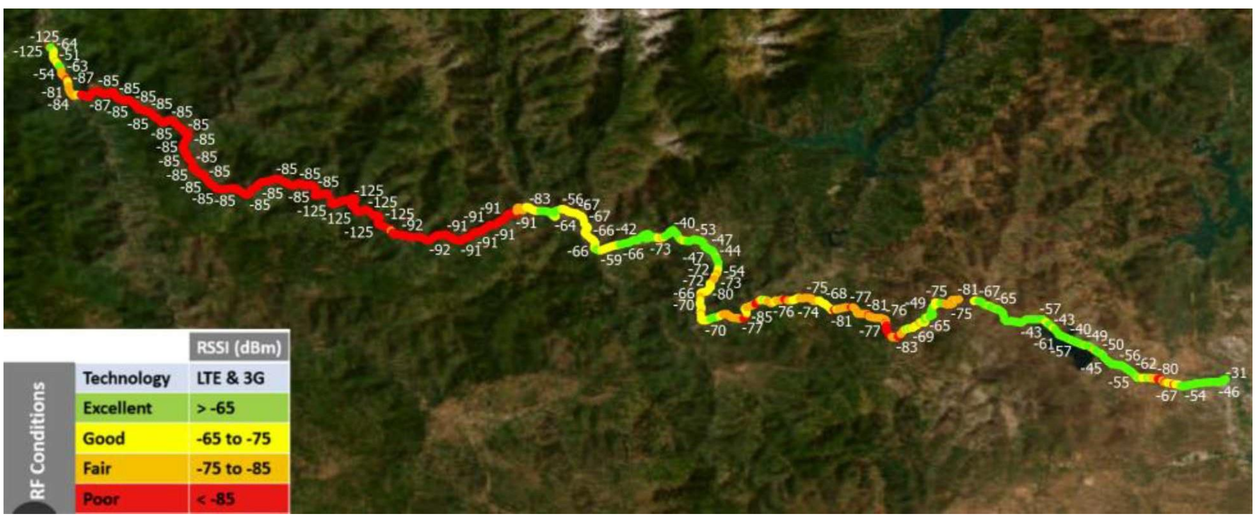

Figure A.13: Trial 2 – Verizon RSSI mapping result along Highway 299. Map generated using ArcGIS software by Esri.

RSRQ

Figure A.14: Trial 2 – Verizon RSRQ mapping result along Highway 299. Map generated using ArcGIS software by Esri.

RSRP

Figure A.15: Trial 2 – Verizon RSRP mapping result along Highway 299. Map generated using ArcGIS software by Esri.

SINR

Figure A.16: Trial 2 – Verizon SINR mapping result along Highway 299. Map generated using ArcGIS software by Esri.

Highway 70

AT&T

Trial 1

RSSI

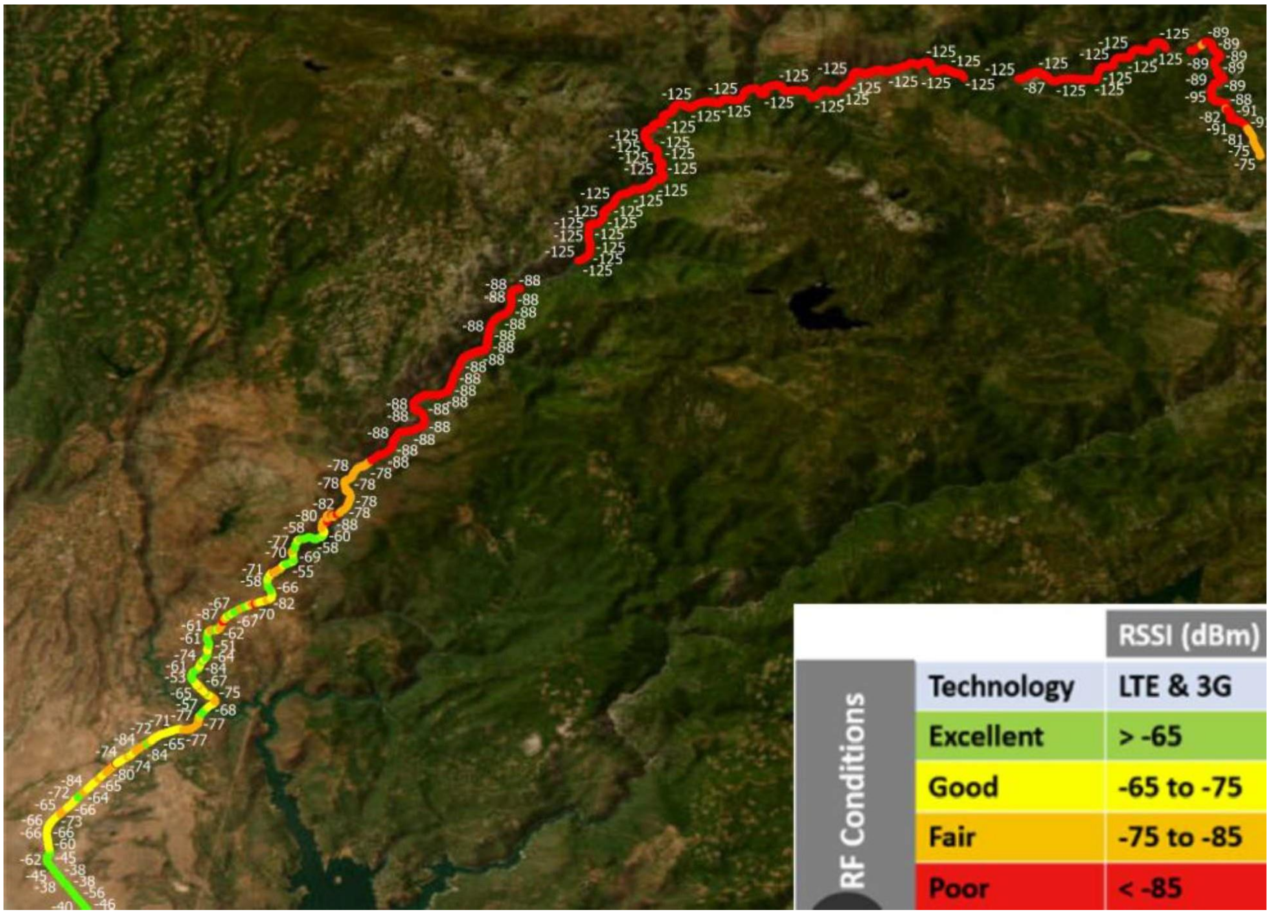

Figure A.17: Trial 1 – AT&T RSSI mapping result along Highway 70. Map generated using ArcGIS software by Esri.

RSRQ

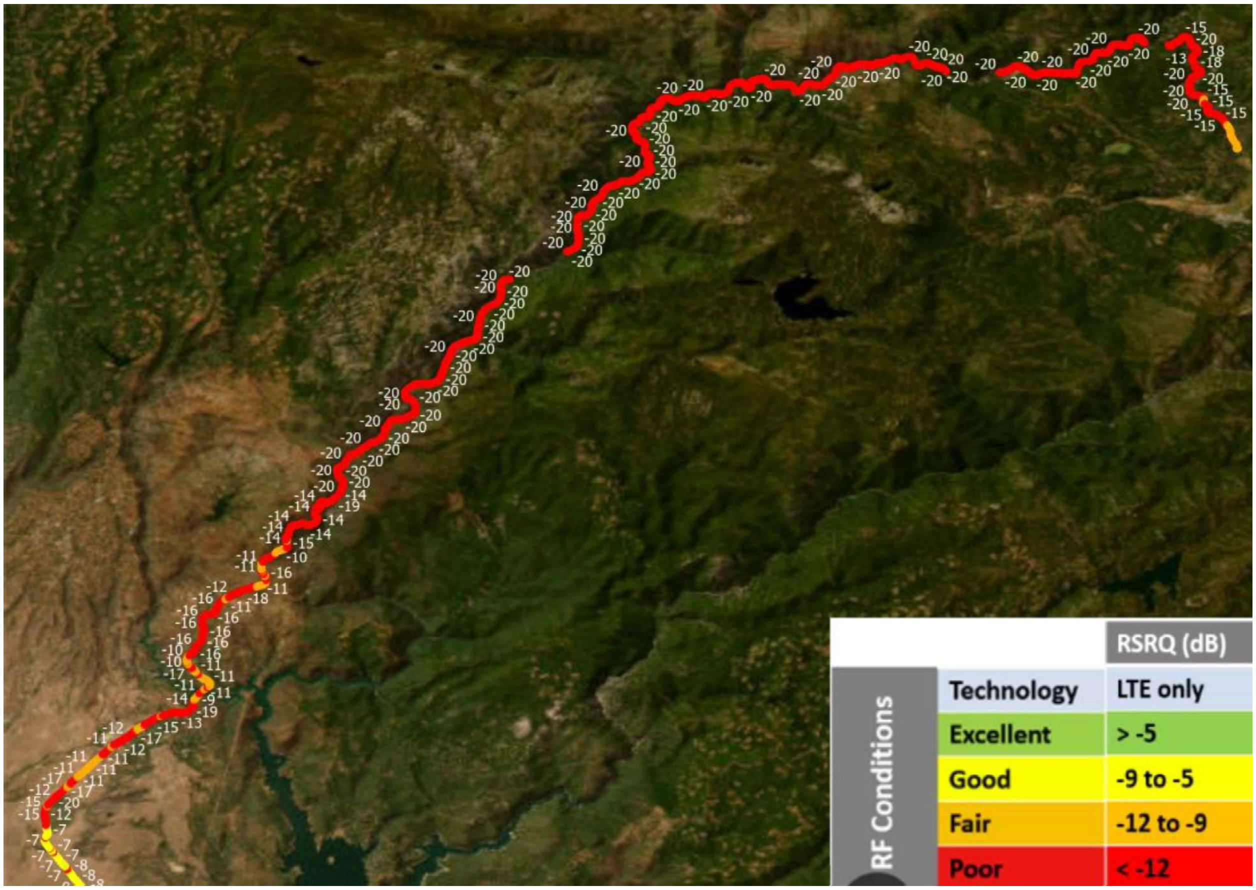

Figure A.18: Trial 1 – AT&T RSRQ mapping result along Highway 70. Map generated using ArcGIS software by Esri.

RSRP

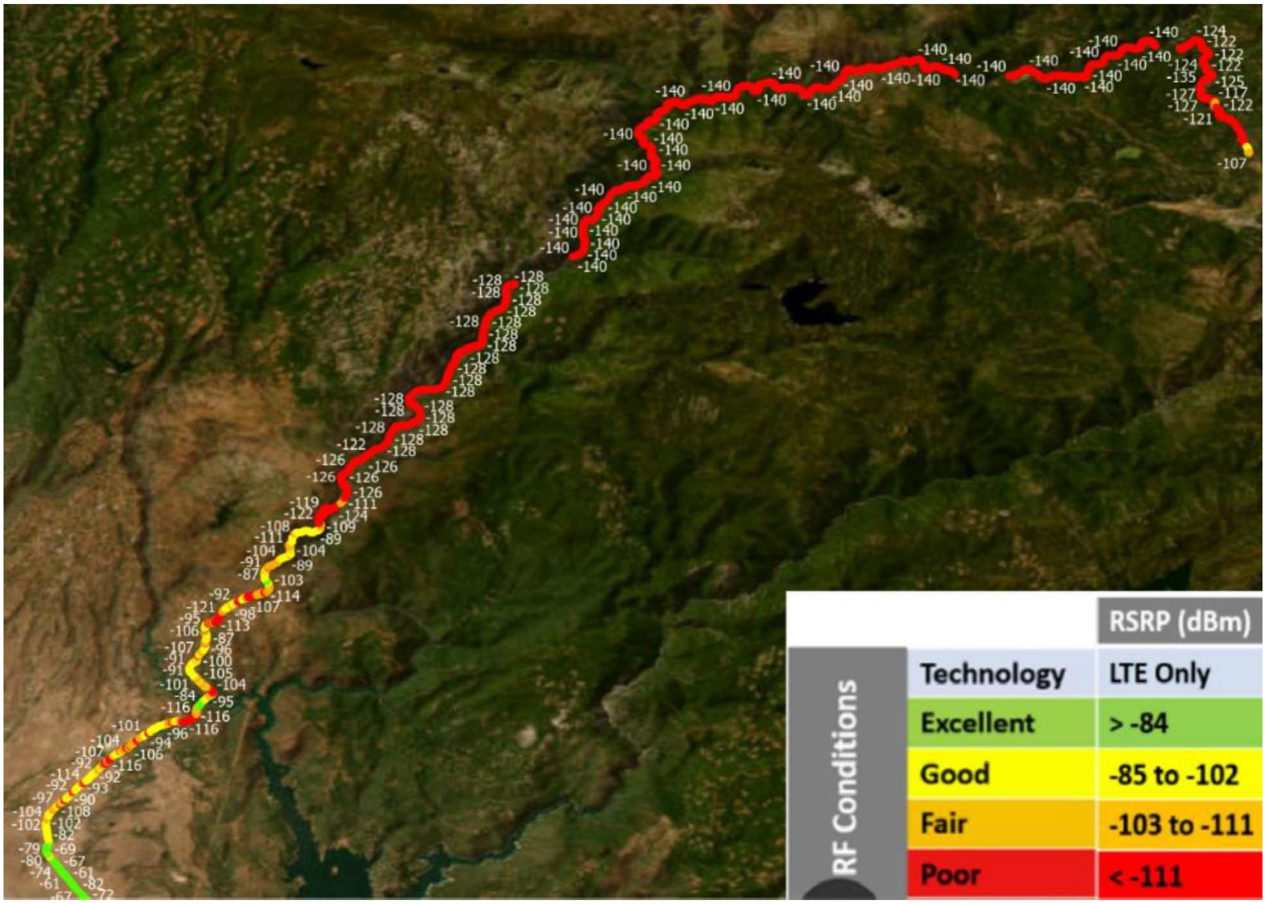

Figure A.19: Trial 1 – AT&T RSRP mapping result along Highway 70. Map generated using ArcGIS software by Esri.

SINR

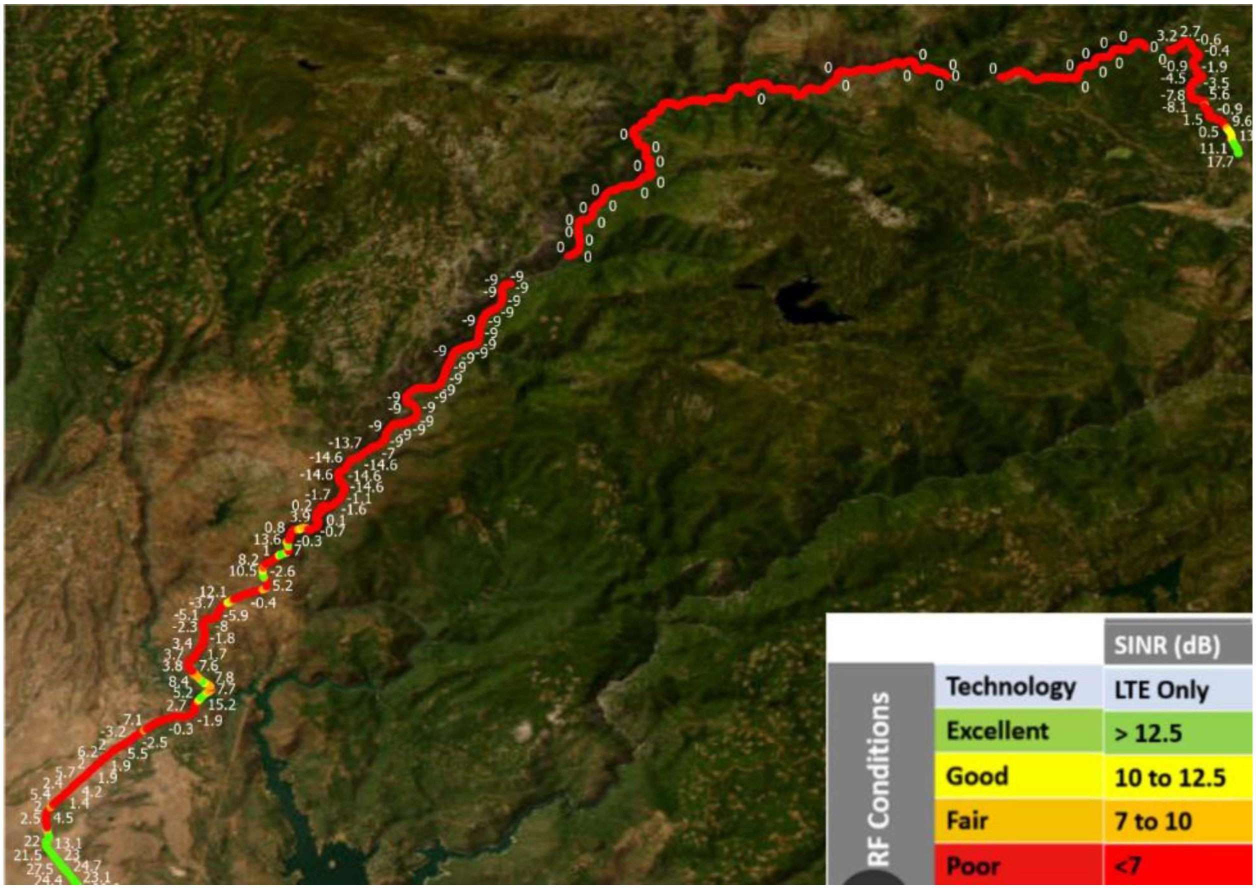

Figure A.20: Trial 1 – AT&T SINR mapping result along Highway 70. Map generated using ArcGIS software by Esri.

Trial 2

RSSI

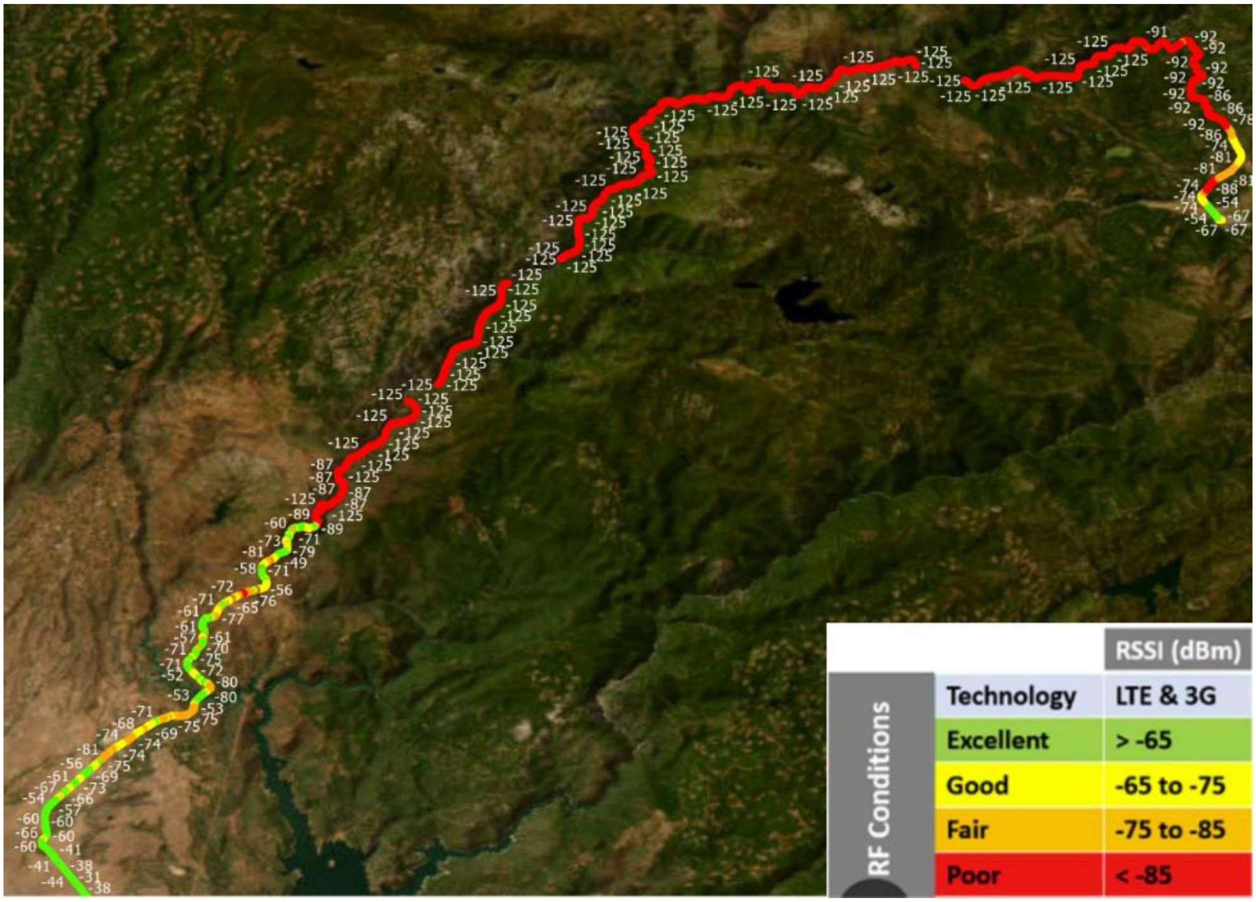

Figure A.21: Trial 2 – AT&T RSSI mapping result along Highway 70. Map generated using ArcGIS software by Esri.

RSRQ

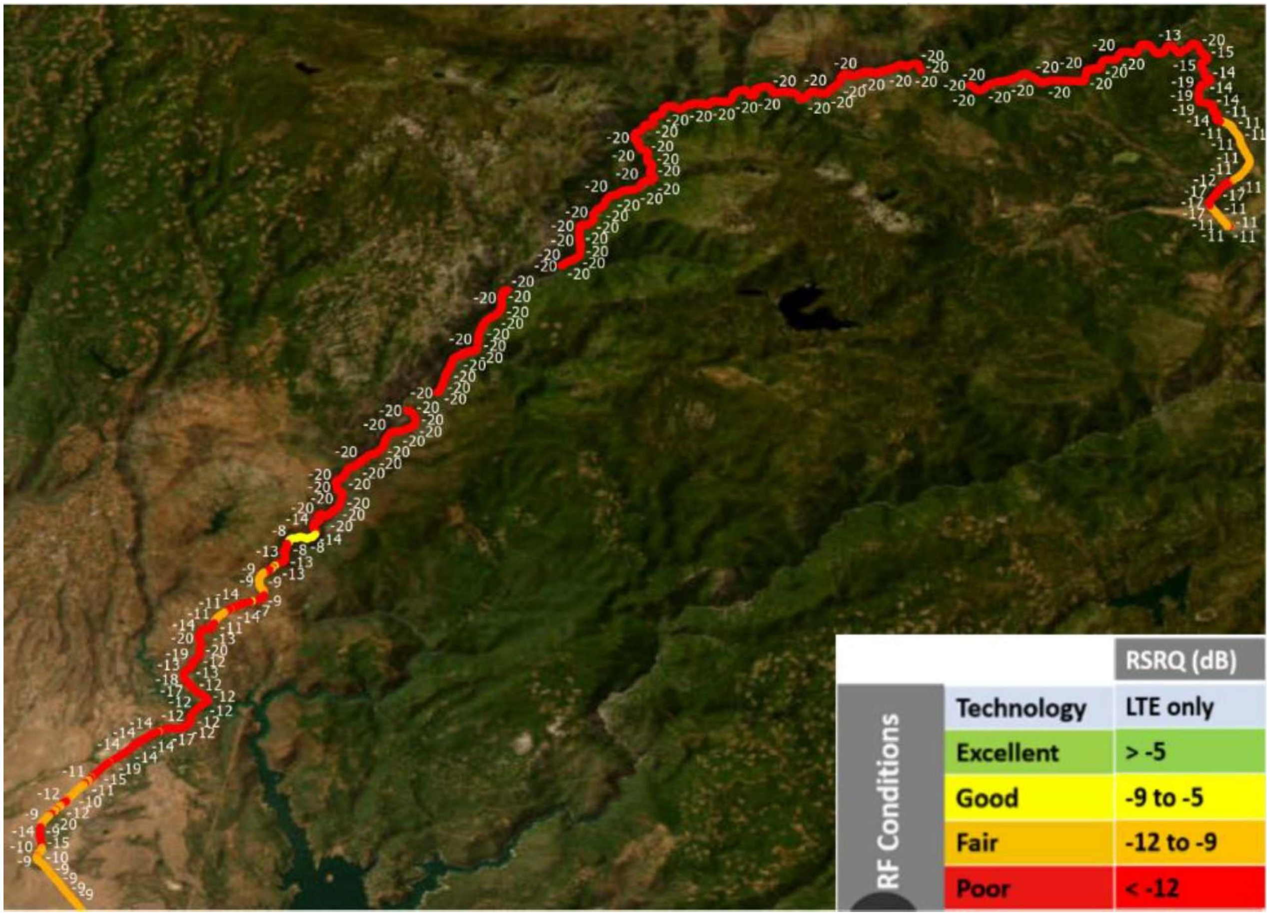

Figure A.22: Trial 2 – AT&T RSRQ mapping result along Highway 70. Map generated using ArcGIS software by Esri.

RSRP

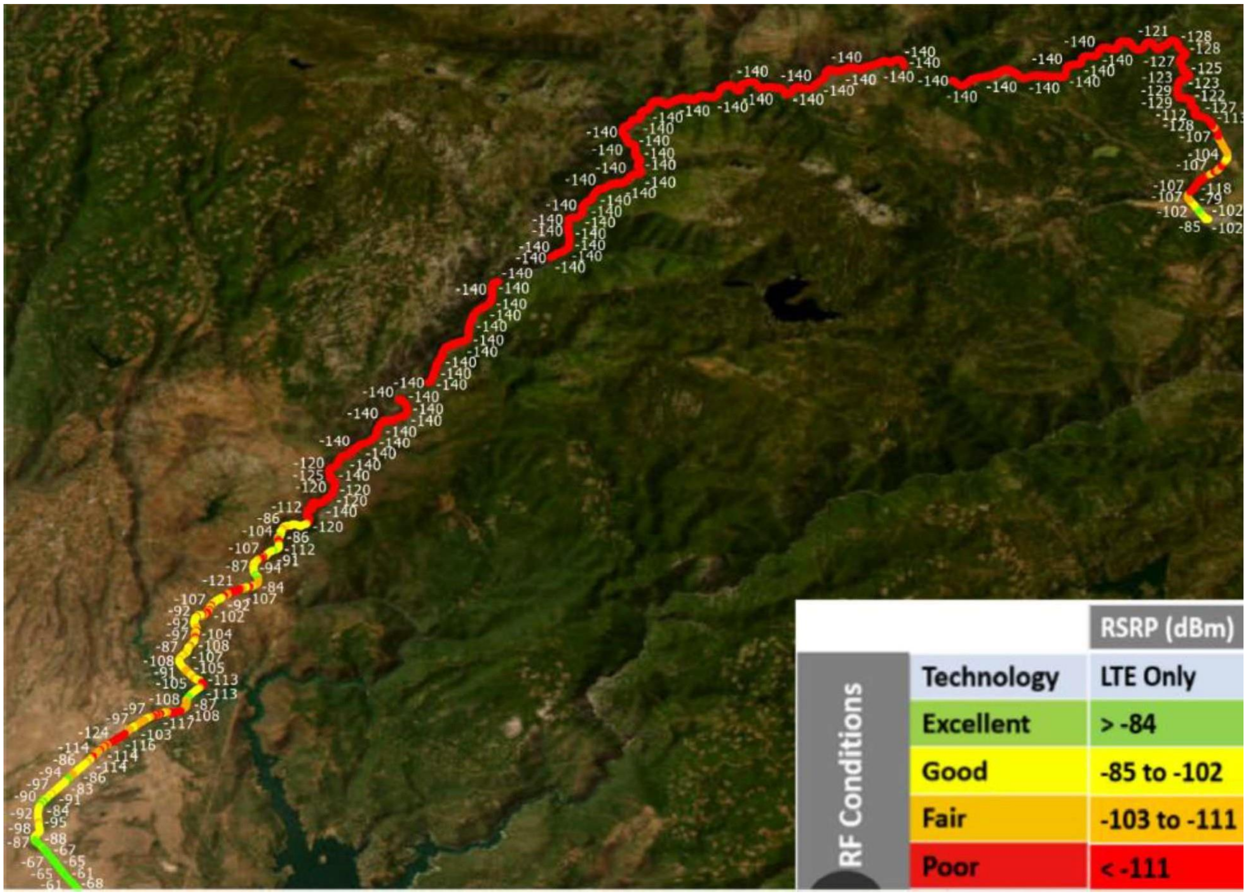

Figure A.23: Trial 2 – AT&T RSRP mapping result along Highway 70. Map generated using ArcGIS software by Esri.

SINR

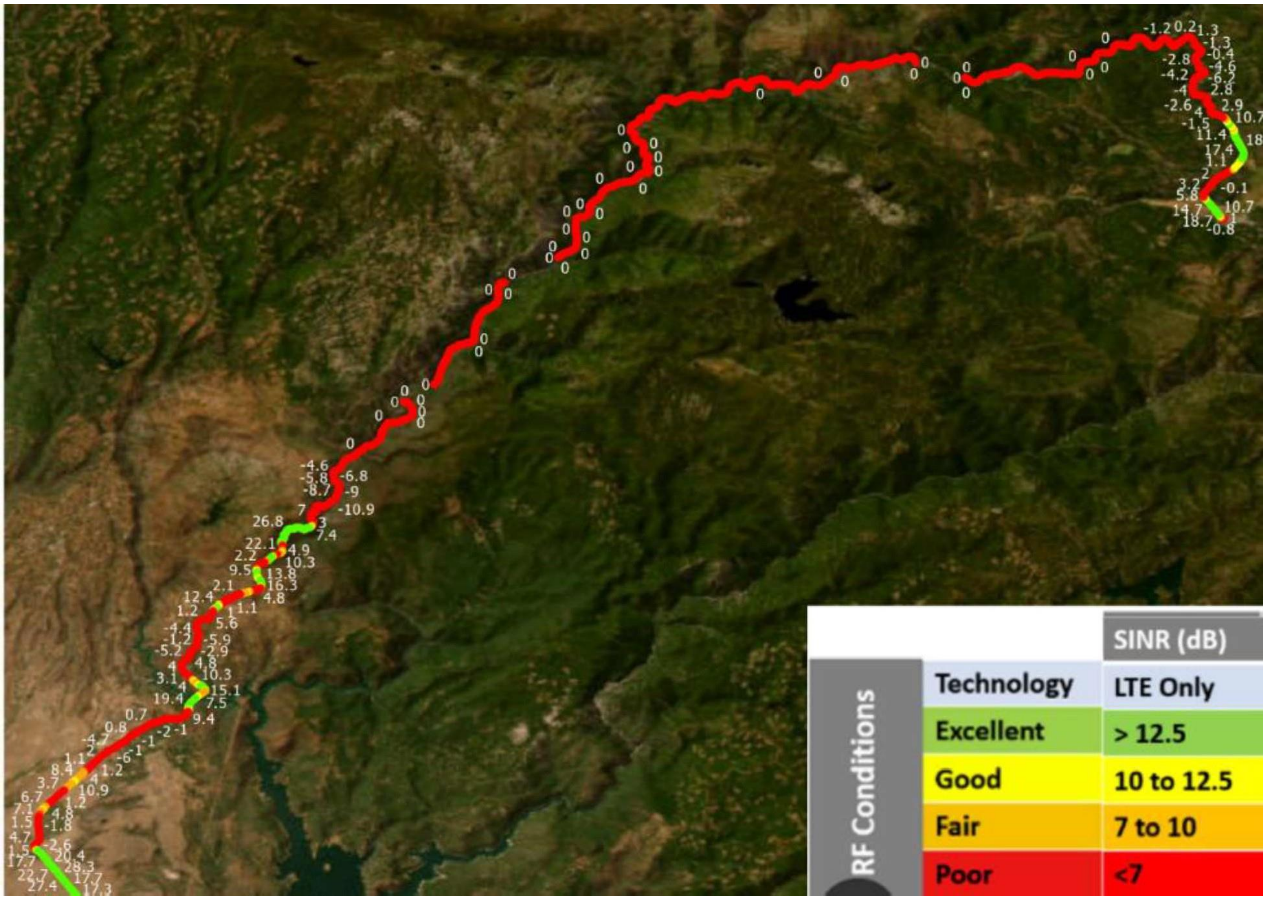

Figure A.24: Trial 2 – AT&T SINR mapping result along Highway 70. Map generated using ArcGIS software by Esri.

Verizon

Trial 1

RSSI

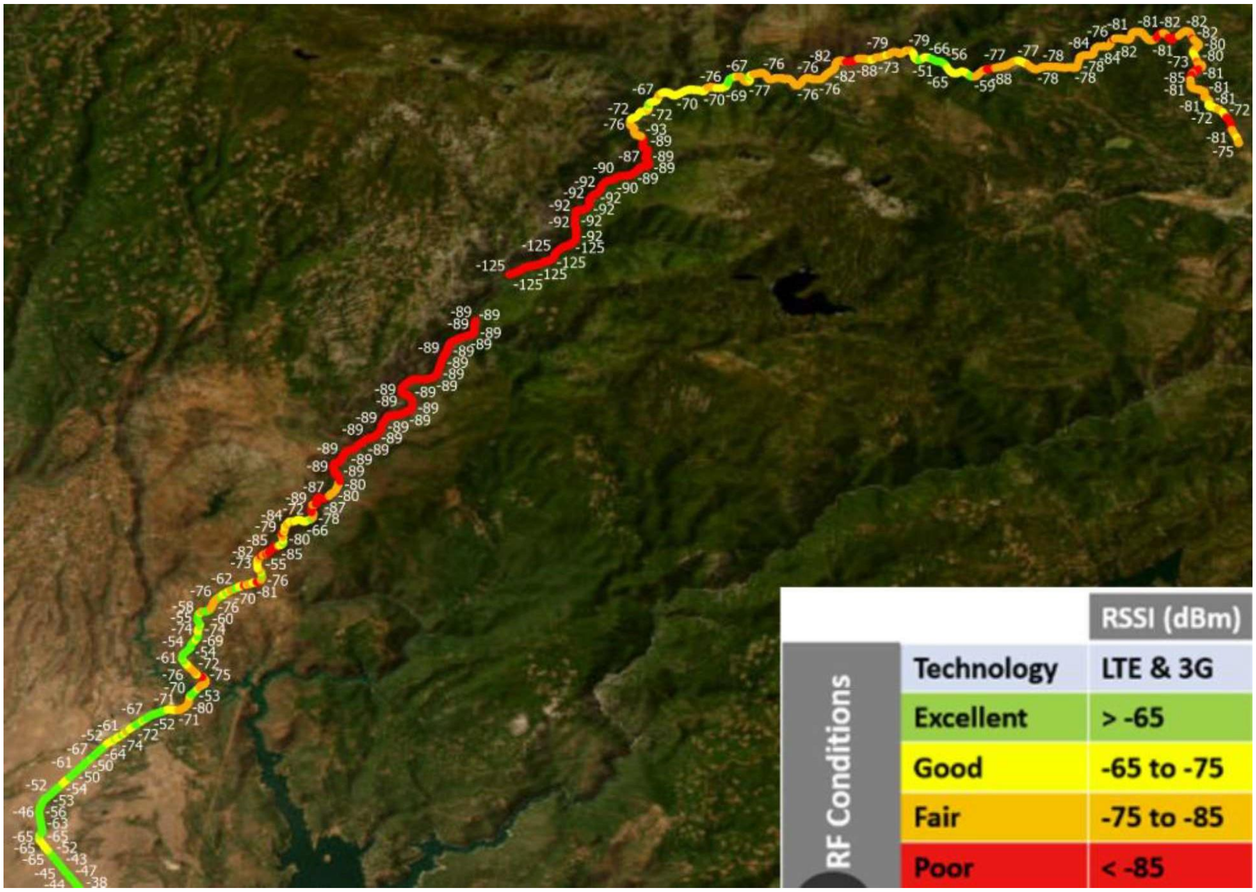

Figure A.25: Trial 1 – Verizon RSSI mapping result along Highway 70. Map generated using ArcGIS software by Esri.

RSRQ

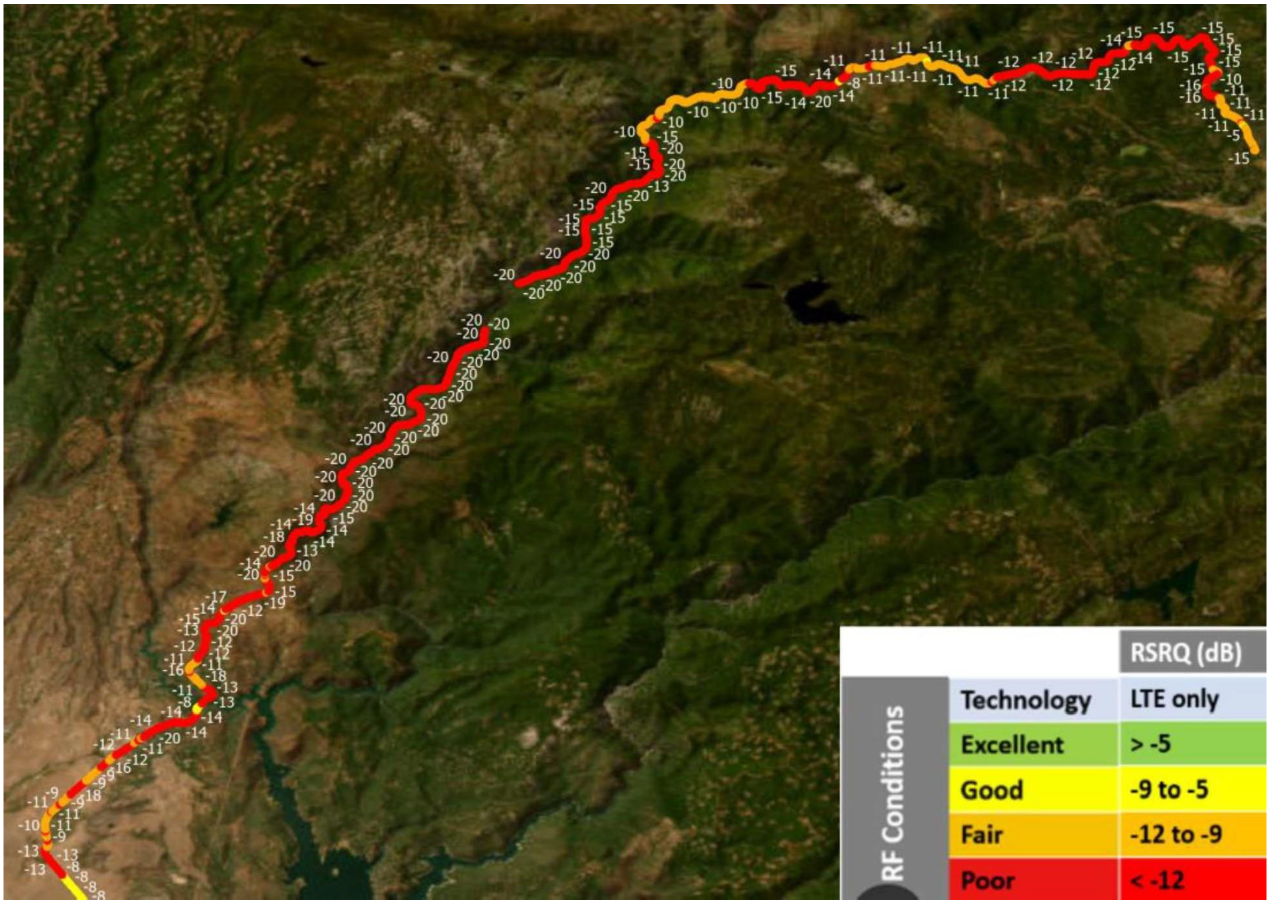

Figure A.26: Trial 1 – Verizon RSRQ mapping result along Highway 70. Map generated using ArcGIS software by Esri.

RSRP

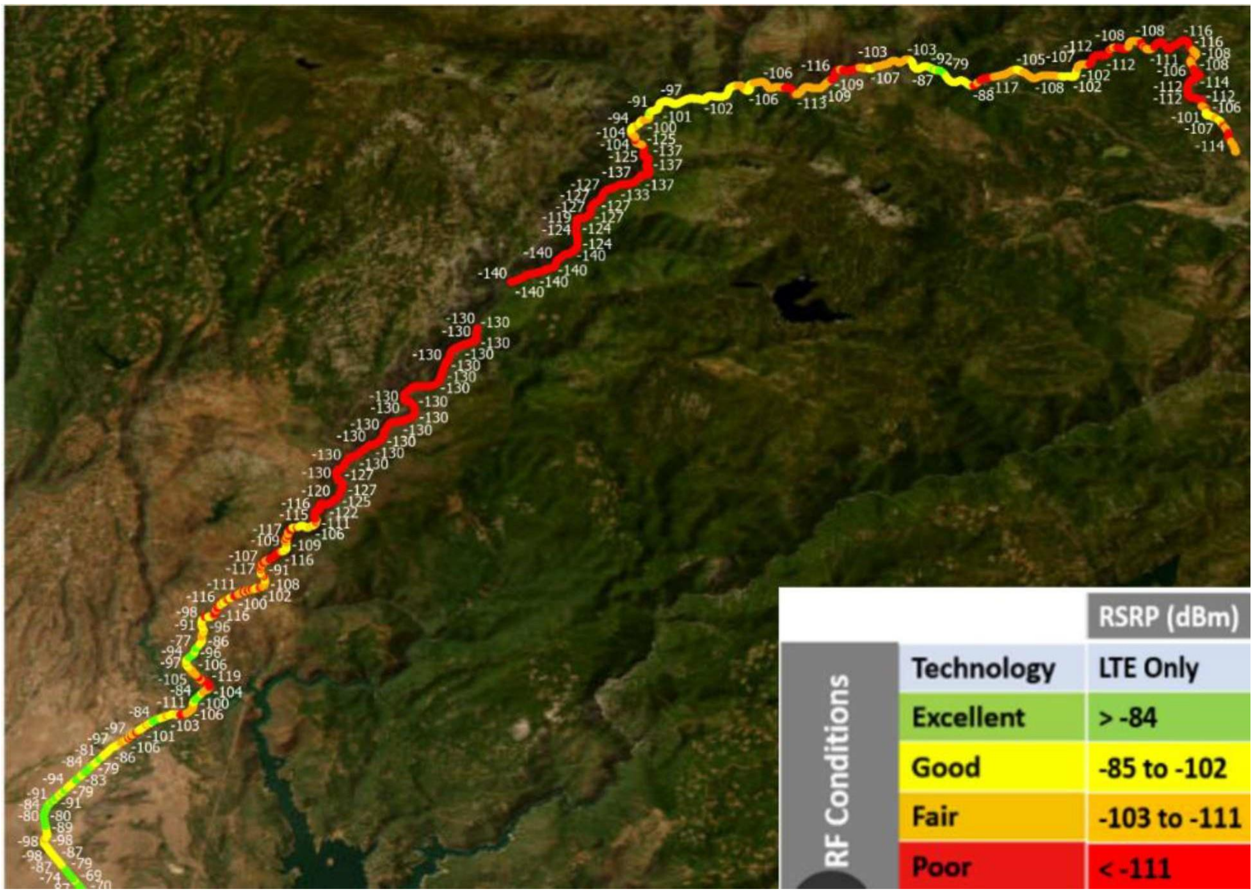

Figure A.27: Trial 1 – Verizon RSRP mapping result along Highway 70. Map generated using ArcGIS software by Esri.

SINR

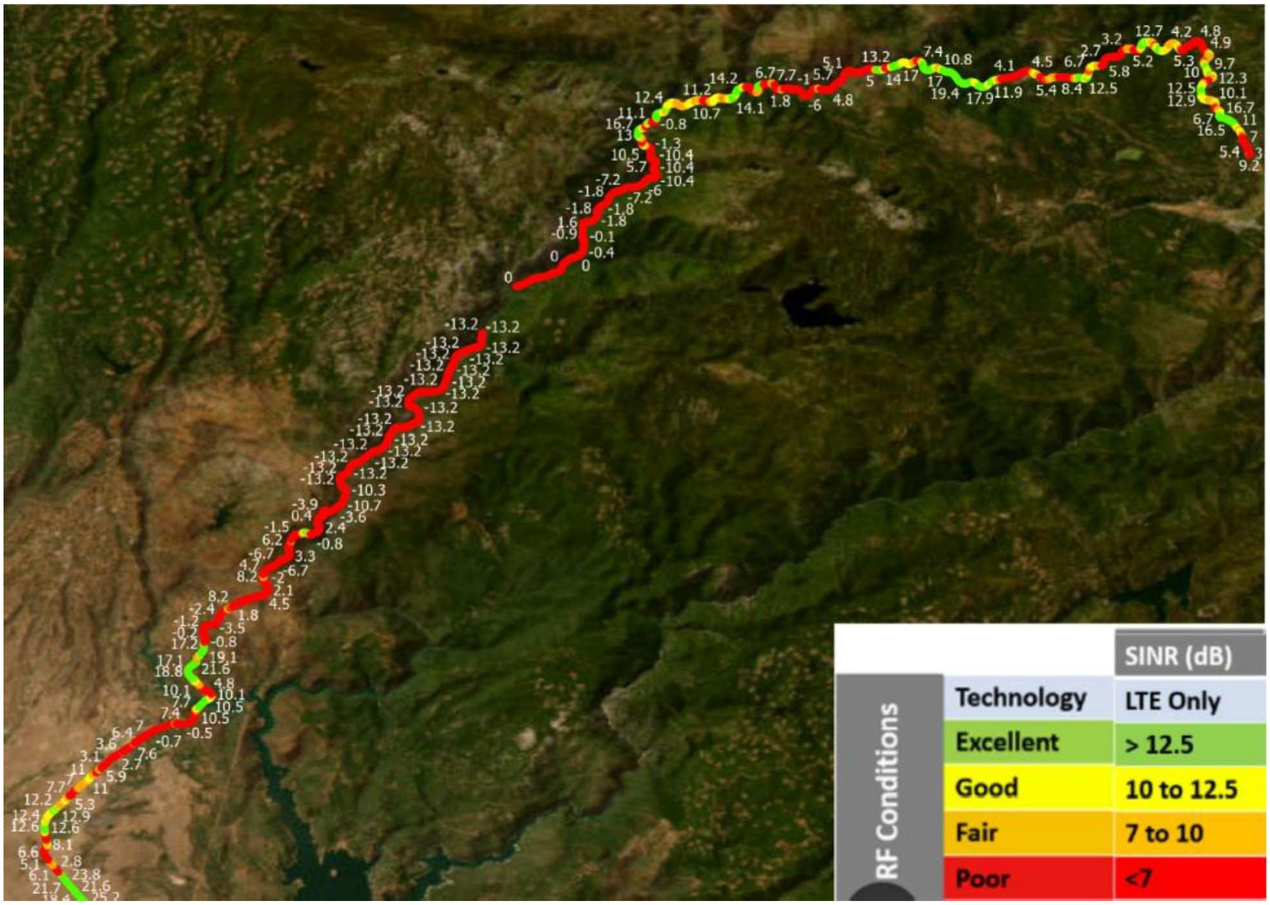

Figure A.28: Trial 1 – Verizon SINR mapping result along Highway 70. Map generated using ArcGIS software by Esri.

Trial 2

RSSI

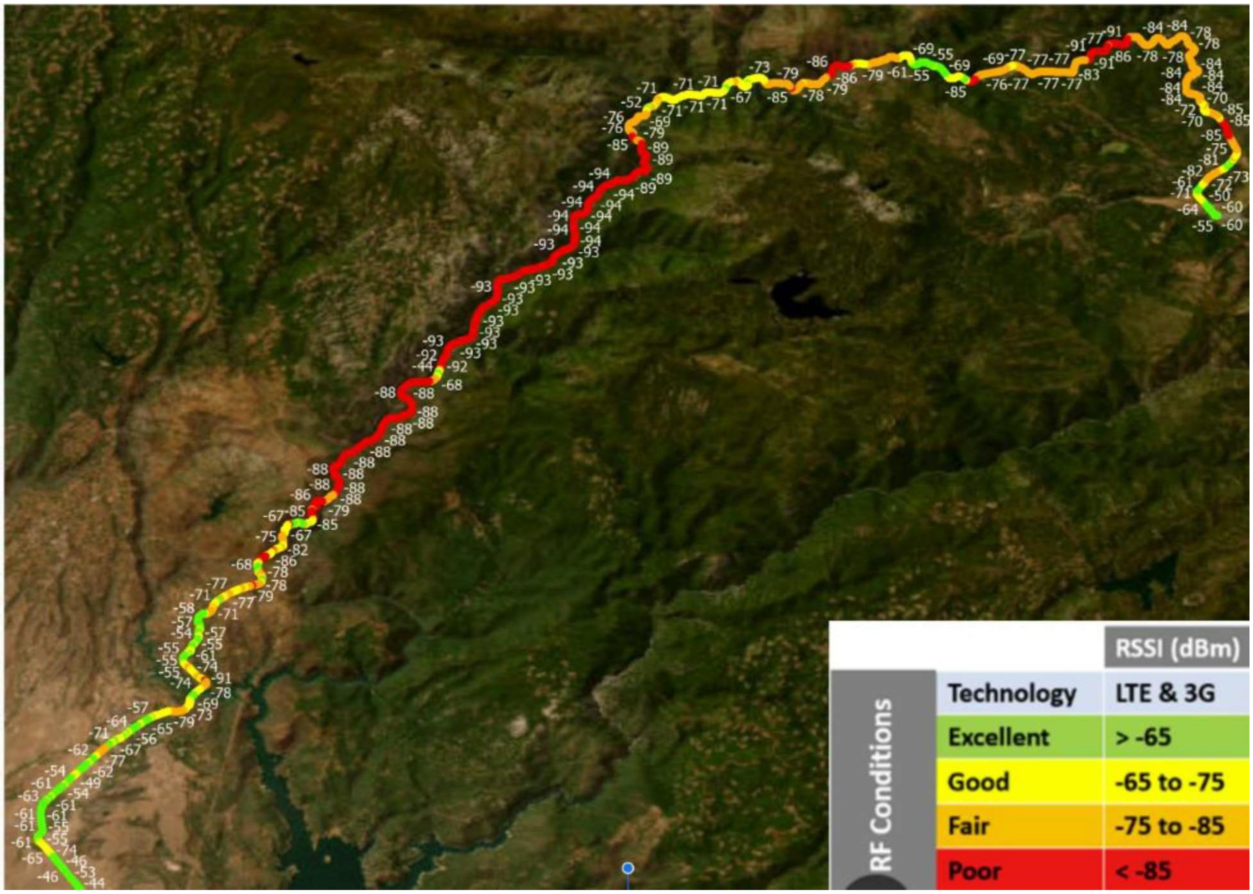

Figure A.29: Trial 2 – Verizon RSSI mapping result along Highway 70. Map generated using ArcGIS software by Esri.

RSRQ

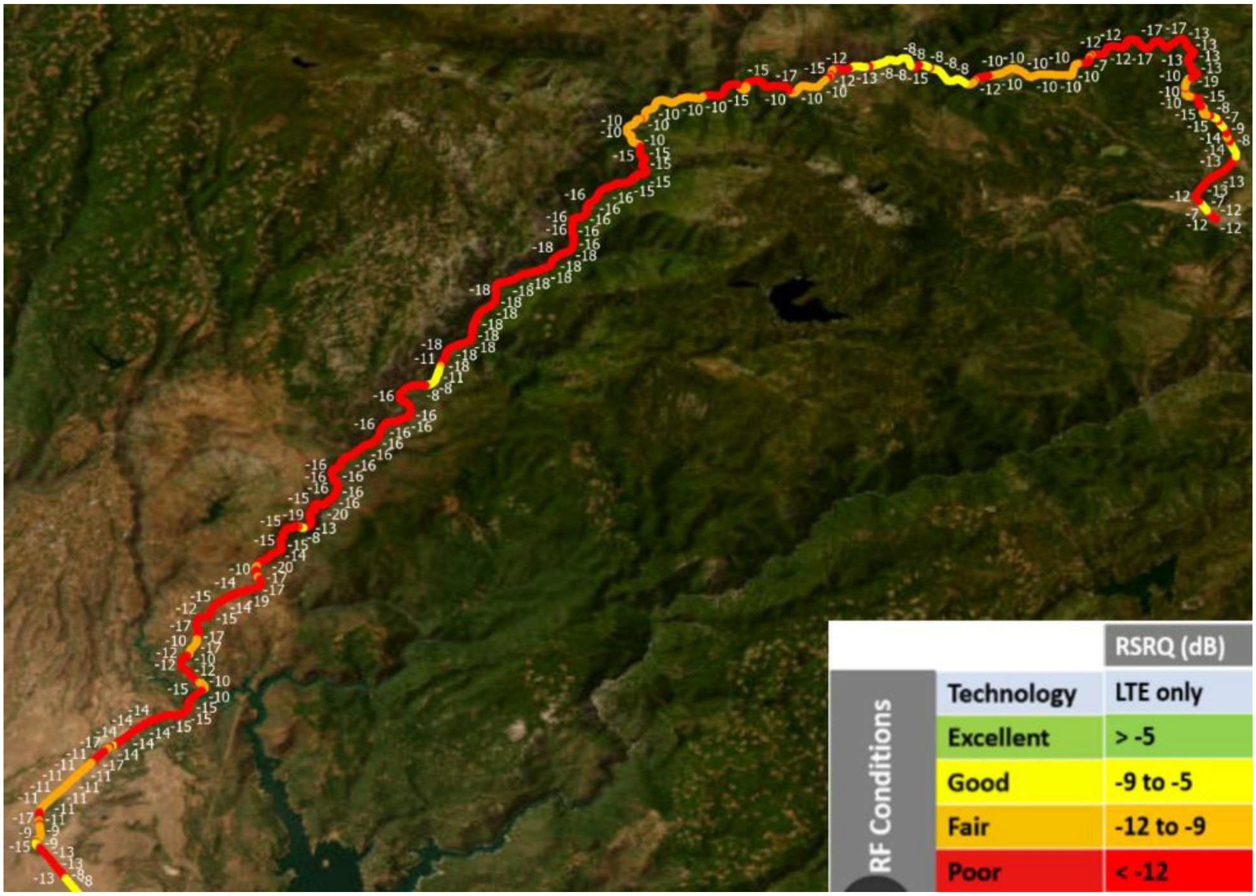

Figure A.30: Trial 2 – Verizon RSRQ mapping result along Highway 70. Map generated using ArcGIS software by Esri.

RSRP

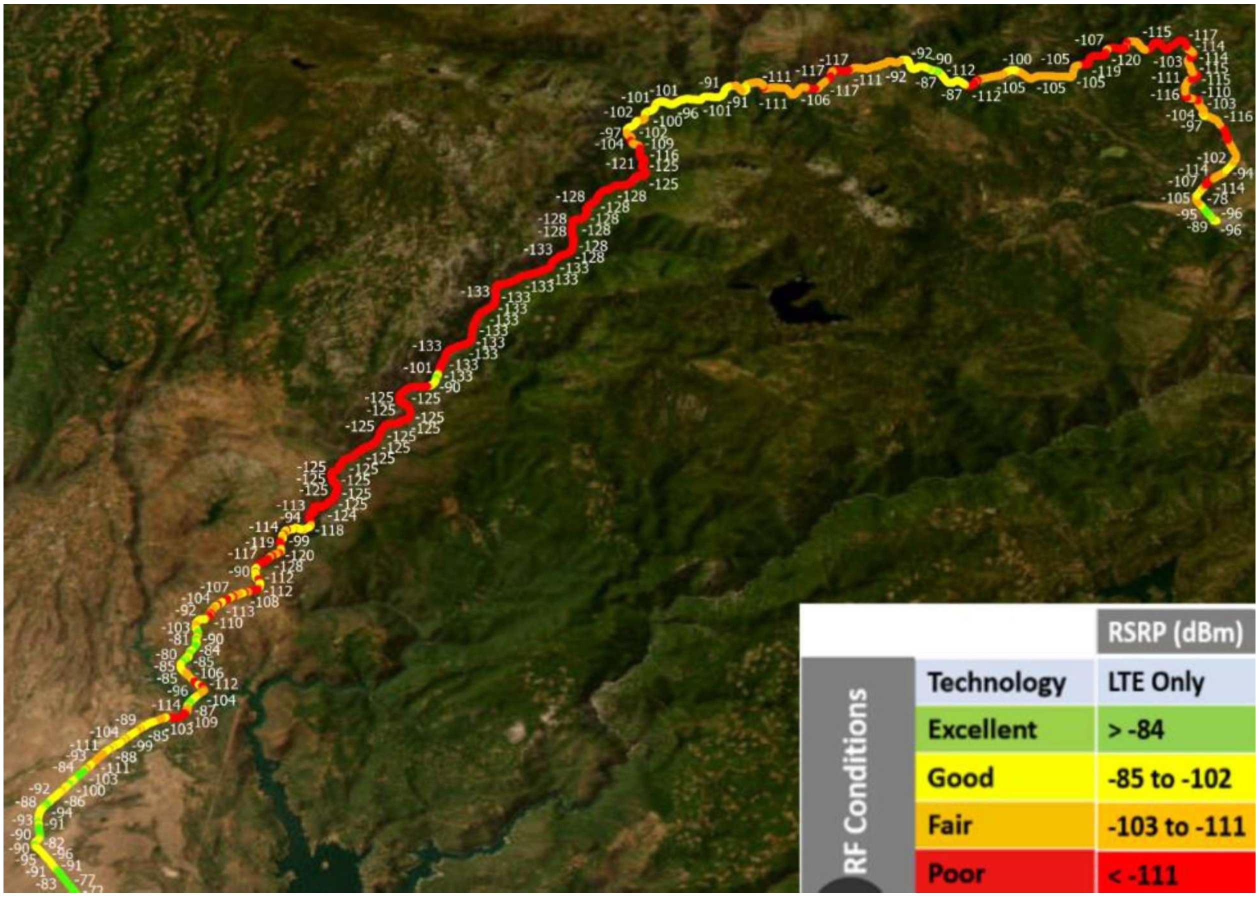

Figure A.31: Trial 2 – Verizon RSRP mapping result along Highway 70. Map generated using ArcGIS software by Esri.

SINR

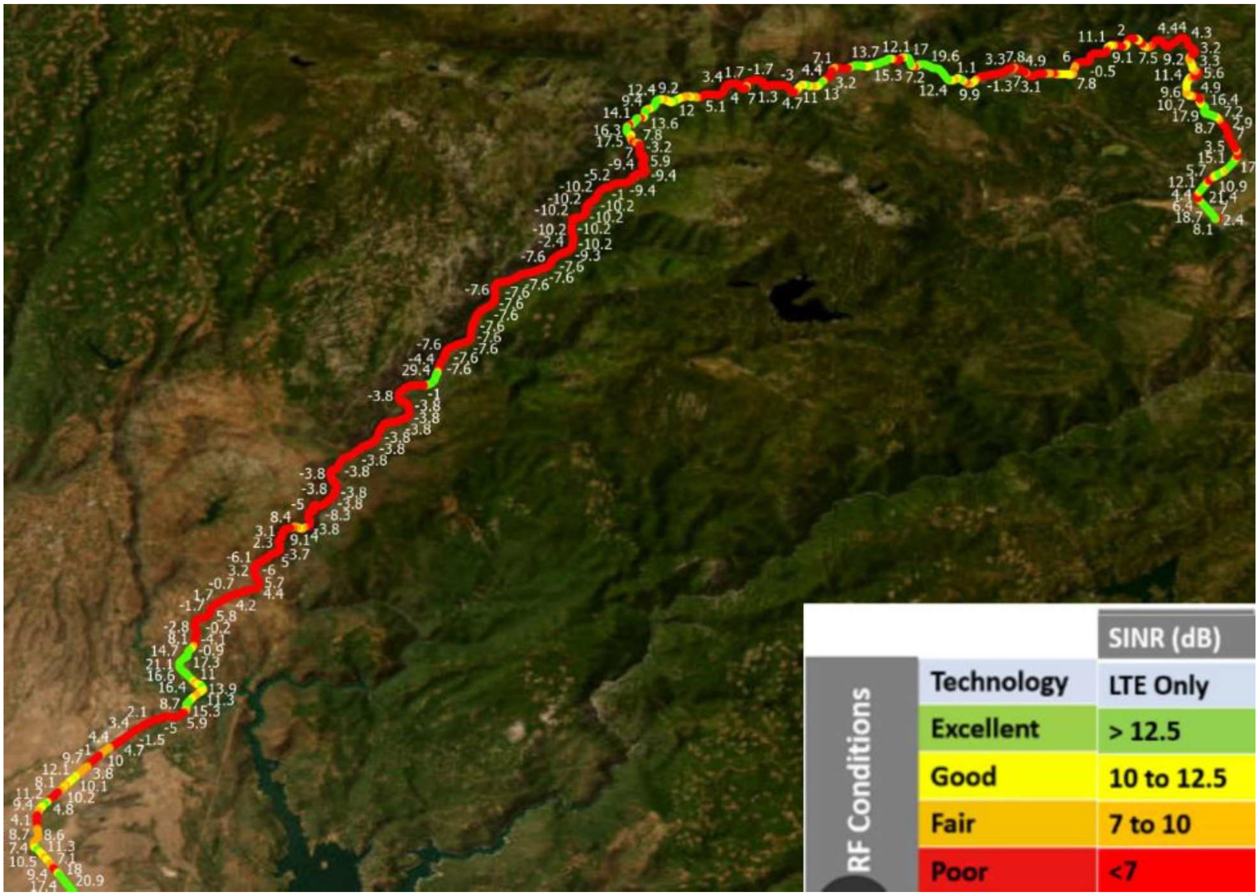

Figure A.32: Trial 2 – Verizon SINR mapping result along Highway 70. Map generated using ArcGIS software by Esri.

Appendix D: Interim Report for Task 5

STATE OF CALIFORNIA • DEPARTMENT OF TRANSPORTATION

TECHNICAL REPORT DOCUMENTATION PAGE

TR-0003 (REV 04/2024)

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16. ABSTRACT

This report is part of AHMCT's research project "Development and Testing of an Unmanned Aerial System (UAS) Cellular & Wi-Fi Repeater: Phase 2." The goal of this research is to expand upon the successful UAS aerial repeater that was created in Task 3280. The researchers evaluated several commercial off-the-shelf (COTS) routers and antennas to improve the ground Wi-Fi network. After the components were selected, an easily assembled payload package was designed to mount to the UAS to create a useable communication network. The goal of the research is to evaluate the benefits and drawbacks of the aerial repeater concept through field testing. This document provides the UAS system performance results.

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Unmanned Aerial System, Drone, Communications Repeater, Field Testing, LTE Network Performance, Wi-Fi Network Performance, Email and VoIP Testing, AGL Signal Testing, ArcGIS mapping	No restrictions. This document is available to the public through the National Technical Information Service, Springfield, Virginia 22161.

19. SECURITY CLASSIFICATION *(of this report)*	20. NUMBER OF PAGES	21. COST OF REPORT CHARGED
Unclassified	66	N/A

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Advanced Highway Maintenance and Construction Technology Research Center

Department of Mechanical and Aerospace Engineering
University of California at Davis

Development and Testing of an Unmanned Aerial System (UAS) Cellular & Wi-Fi Repeater: Phase 2 – Field Trials and Survey of the Outcomes

Anh Duong, Dave Torick, Evan Sim, Kin Yen, and Shima Nazari

Report Number: CA25-4297
AHMCT Research Report: UCD-ARR-25-04-30-05
Interim Report of Contract: 65A0749 Task 4297

April 28th, 2025

California Department of Transportation

Division of Research, Innovation and System Information

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List of Acronyms and Abbreviations

Acronym	Definition
AGL	Above Ground Level
APA	Active-Passive Antennas
AHMCT	Advanced Highway Maintenance and Construction Technology Research Center
Caltrans	California Department of Transportation
COTS	Commercial Off–The-Shelf
DJI	Da-Jiang Innovations (Drone Company)
DOT	Department of Transportation
DRISI	Caltrans Division of Research, Innovation and System Information
GPS	Global Positioning System
LTE	Long Term Evolution
PPE	Personal Protective Equipment
RSRP	Reference Signal Received Power
RSRQ	Reference Signal Received Quality
RSSI	Received Signal Strength Indicator
SINR	Signal-to-Interference plus Noise Ratio
SIM	Subscriber Identity Module
SR	State Route
UAS	Uncrewed Aerial Systems
UASRE	Uncrewed Aerial Systems Repeater

Acronym	Definition
VoIP	Voiceover Internet Protocol
Wi-Fi	Wireless Fidelity

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Chapter 1: Introduction- Field Trials Results and Analysis

Caltrans has many rural use cases where no current network communications exist outside of satellite services. Based on prior Advanced Highway Maintenance and Construction Technology (AHMCT) research, the cellular range of typical sites in rural areas is significantly limited by surrounding terrain and foliage. There is a need to provide enhanced communications availability outside of current cellular offerings without the requirement of a full-fledged investment in satellite equipment. Research performed under Phase 1 of Task 3280, showed that a UAS can elevate a payload into the cellular signal that is typically blocked by terrain and create a Wi-Fi network on the ground for worker communications. Refinement of the UAS payload is necessary to minimize deployment time and reduce the number of components necessary to establish a usable network. After the payload package has been optimized, it is necessary to conduct field trials to verify the technology's success in various terrain situations with limited to no cellular network coverage. With a temporary Wi-Fi network in construction and emergency response areas, communication can occur through emails and Wi-Fi calling, assisting in efficiency, resource management, and accurate equipment deployment for the first time in some rural districts.

The purpose of this document is to provide the results from the field trials, analyze the performance of the UAS aerial repeater system, and provide recommendations.

Chapter 2: Summary of Results

Major Results

All results collected from Highways 299 and 70 are summarized in Tables 2.1 and 2.2. Tables 2.1 and 2.2 include eleven test runs: five on Highway 299 and on Highway 70.

Table 2.1: All testing results from field trials on Highways 299

Location	Original Internet Quality (based on Verizon service)	AGL (feet)	LTE Signal RSSI Reading (dBm)	Internet Connection Download Speed (Mb/s)	Internet Connection Upload Speed (Mb/s)	Latency (millisecond)	Retransmission (%)	Email latency or possibility (in second or Y/N)	VOIP (Yes or No)
1 (First run – using Bingfu antenna)	1 bar, un-usable internet	0	-86	Took too long to respond					No
		200	-84	Took too long to respond				7.58	Yes
		350	-67	42.93	2.88	70	1.46	3.9	Yes
1 (Second run– using Proxicast antenna)	1 bar, un-usable internet	0	-83	Did not perform testing at this height					N/A
		200	-77	20.73	3.26	78	18.96	Yes	Yes
2	No service	0	-125	No signal captured					No
		350	-125						No
3	No service	0	-125	Signal captured, but was unusable					No
		400	-84						No
4	1 bar, slow internet	0	-76	Internet data was not recorded as the signal at ground level was already strong after connecting to the UAS system					Yes
		100	-76						Yes
		200	-76						Yes

Location	Original Internet Quality (based on Verizon service)	AGL (feet)	LTE Signal RSSI Reading (dBm)	Internet Connection Download Speed (Mb/s)	Internet Connection Upload Speed (Mb/s)	Latency (millisecond)	Retransmission (%)	Email latency or possibility (in second or Y/N)	VOIP (Yes or No)
5	1 bar, un-usable internet	0	-72	41.58	1.44	62	0.01	5.38	Yes
		100	-53	32.33	4.81	63	0.13	13.53	Yes
		200	-47	95.81	14.22	51	0.01	8.88	Yes

Notes: 1) With the exception of Location 1, where both Bingfu and Proxicast LTE antennas were tested, Proxicast was used for all other locations. Proxicast is a better LTE antenna than Bingfu, according to AHMCT testing data; and 2) When the data collection system took too long to respond, the AHMCT team was not able to record data.

Table 2.2: All testing results from field trials on Highways 70

Location	Original Internet Quality (based on Verizon service)	AGL (feet)	LTE Signal RSSI Reading (dBm)	Internet Connection Download Speed (Mb/s)	Internet Connection Upload Speed (Mb/s)	Latency (millisecond)	Retransmission (%)	Email latency or possibility (in second or Y/N)	VOIP (Yes or No)
6	1 bar, slow internet	0	-70	14.97	2.41	59	0.22	5.31	Yes
		200	-58	5.30	2.76	59	0	2.46	Yes
		350	-58	9.45	5.12	105	0.04	8.44	Yes

Location	Original Internet Quality (based on Verizon service)	AGL (feet)	LTE Signal RSSI Reading (dBm)	Internet Connection Download Speed (Mb/s)	Internet Connection Upload Speed (Mb/s)	Latency (millisecond)	Retransmission (%)	Email latency or possibility (in second or Y/N)	VOIP (Yes or No)
7	1 bar, un-usable internet	0	-78	3.17	0.28	69	0	5.31	Yes
		200	-78	2.16	0.15	65	0.06	2.46	Yes
		350	-72	1.04	0.60	64	0	8.44	Yes
8	1 bar, un-usable internet	0	-76	2.10	0.83	71	0	9.14	Yes
		200	-76	6.24	1.62	61	1.47	9.82	Yes
		350	-70	3.90	1.87	62	0	9.66	Yes
9	1 bar, un-usable internet	0	-82	6.05	0.08	65	1.40	5.46	Yes
		200	-78	4.59	2.60	65	0	6.98	Yes
		350	-72	3.15	1.89	59	0	13.33	Yes
10	No service	0	-125	Took too long to respond					No
		200	-90	1.42	0.01	84	0	17.16	Yes
		350	-90	Took too long to respond					No
11	No service	0	-89	Helicopter drill, had to stop testing					No
		200	-89						No

Notes: 1) With the exception of Location 1, where both Bingfu and Proxicast LTE antennas were tested, Proxicast was used for all other locations. Proxicast is a better LTE antenna than Bingfu, according to AHMCT testing data; and 2) When the data collection system took too long to respond, the AHMCT team was not able to record data.

The locations of the test runs are shown in Figures 2.1 and 2.2. The numbering of the locations is based on the order of testing (e.g., Location 1 means the place where testing was first conducted).

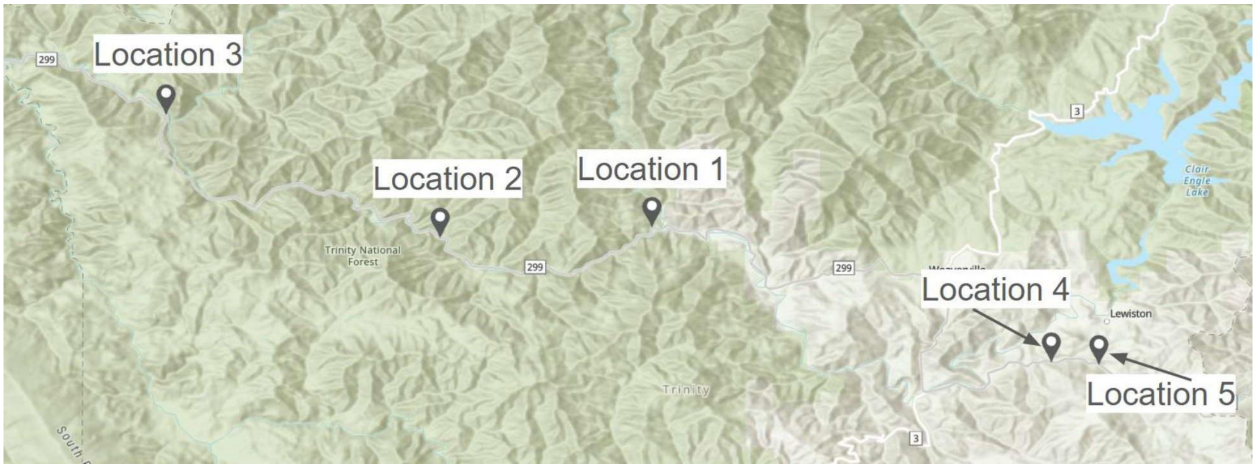

Figure 2.1: Highway 299 testing locations. Map generated using ArcGIS software by Esri.

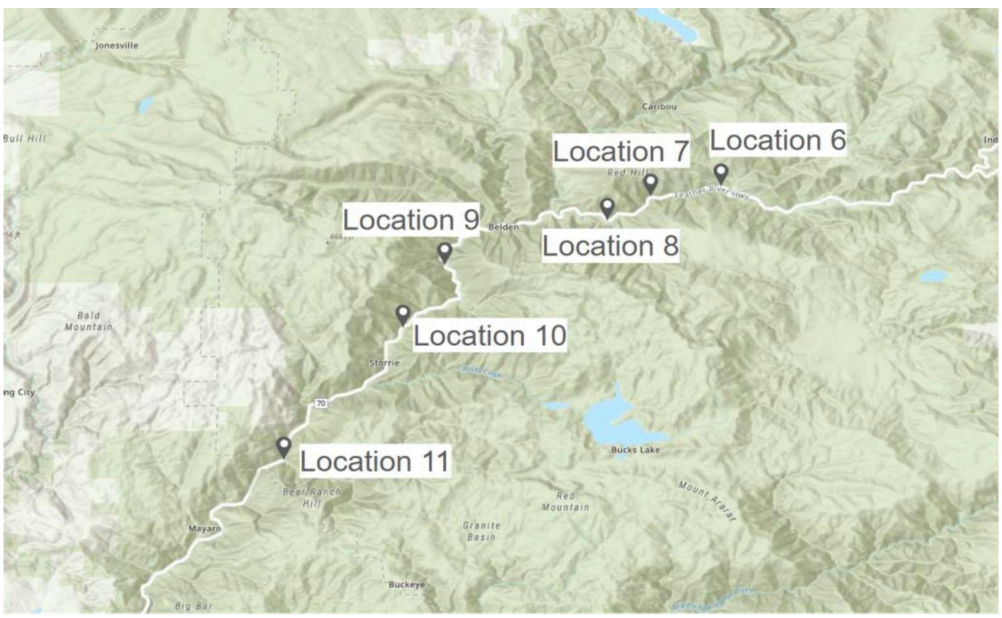

Figure 2.2: Highway 70 testing locations. Map generated using ArcGIS software by Esri.

Conclusion

From the major results, the conclusions for the UAS repeater system are:

- The system extends the signal range, provided that a cell tower signal is within approximately 10 miles and the location is within the signal sector.
- There was no need for the drone to ascend to 350 feet AGL to send emails or use VOIP if there was no broadband shadow; these tasks were successfully carried out at both zero (0) and 200 feet AGL.
- Having a strong cellular antenna and a reliable modem helps improve signal without the need to deploy the drone
    - Only once on Highway 299 and once on Highway 70 did the drone need to fly to create a usable network.

Figures 2.3 and 2.4 illustrate the performance of the UAS, with a focus on the primary objective: enabling the user to send emails and perform VoIP. These figures demonstrate whether the system supports these tasks at various altitudes above ground level (AGL). Red indicates that the UAS system failed to detect an LTE signal, therefore the Wi-Fi client was unable to send emails and perform VoIP (Locations 2 and 3 on Highway 299; Location 11 on Highway 70). Green indicates that the UAS system successfully detected an LTE signal at least once, therefore the Wi-Fi client was able to send emails and perform VoIP (Locations 1, 4, and 5 on Highway 299; Locations 6, 7, 8, 9, and 10 on Highway 70).

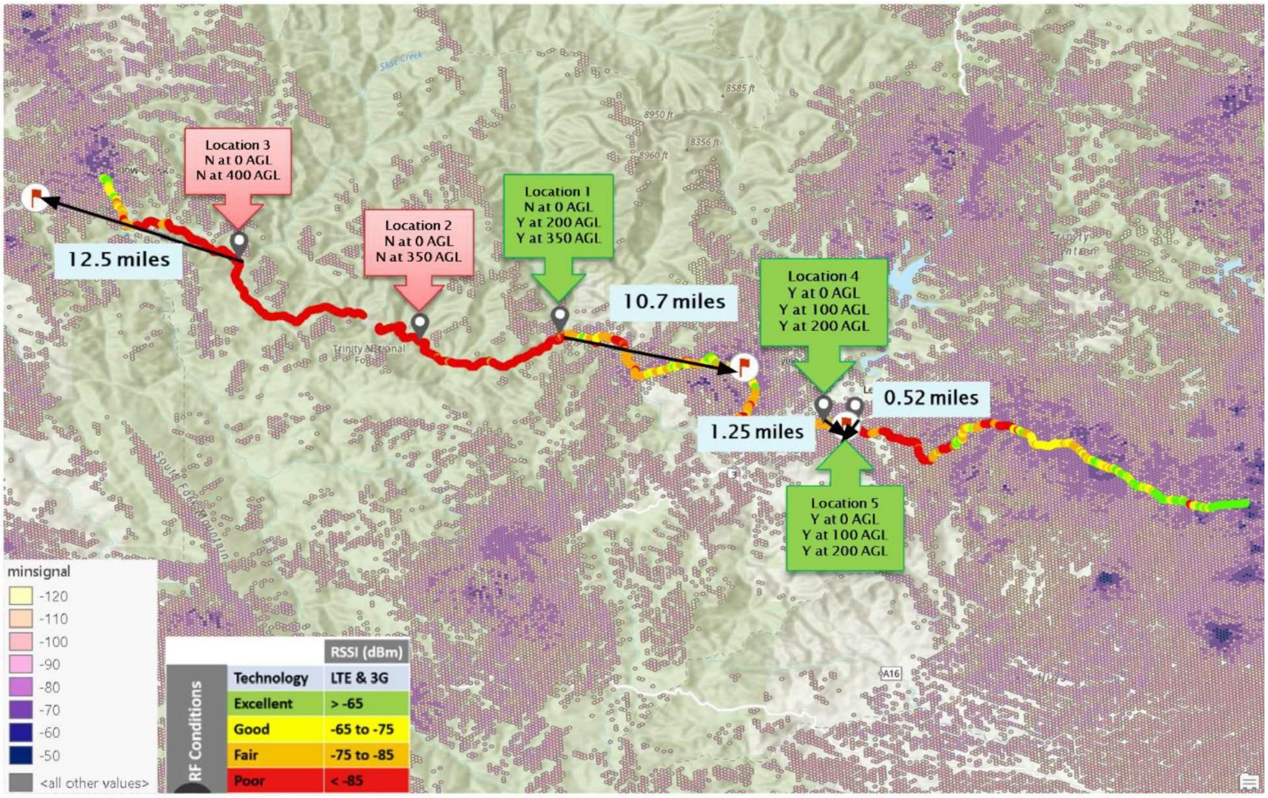

Figure 2.3: UAS repeater performance for email sending and VOIP at different AGLs on Highway 299. Map generated using ArcGIS software by Esri.

From the data shown in Figure 2.3, the following conclusions can be made:

- For Location 1, email sending and VoIP were not successful at zero (0) AGL but were successful at 200 and 350 AGL. The signal source connected to the modem was 10.7 miles away from the test site.
- For Locations 2 and 3, email sending and VoIP were not successful at all AGLs (the maximum AGL requirement is 400). At Location 2, the modem was unable to connect to a signal source. At Location 3, the signal source connected to the modem was 12.5 miles away from the test site.
- For Locations 4 and 5, email sending and VoIP were successful at zero (0), 100 and 200 AGL. At Location 4, the signal source connected to the modem was 1.25 miles away from the test site. At Location 5, the signal source connected to the modem was 0.52 miles away from the test site.

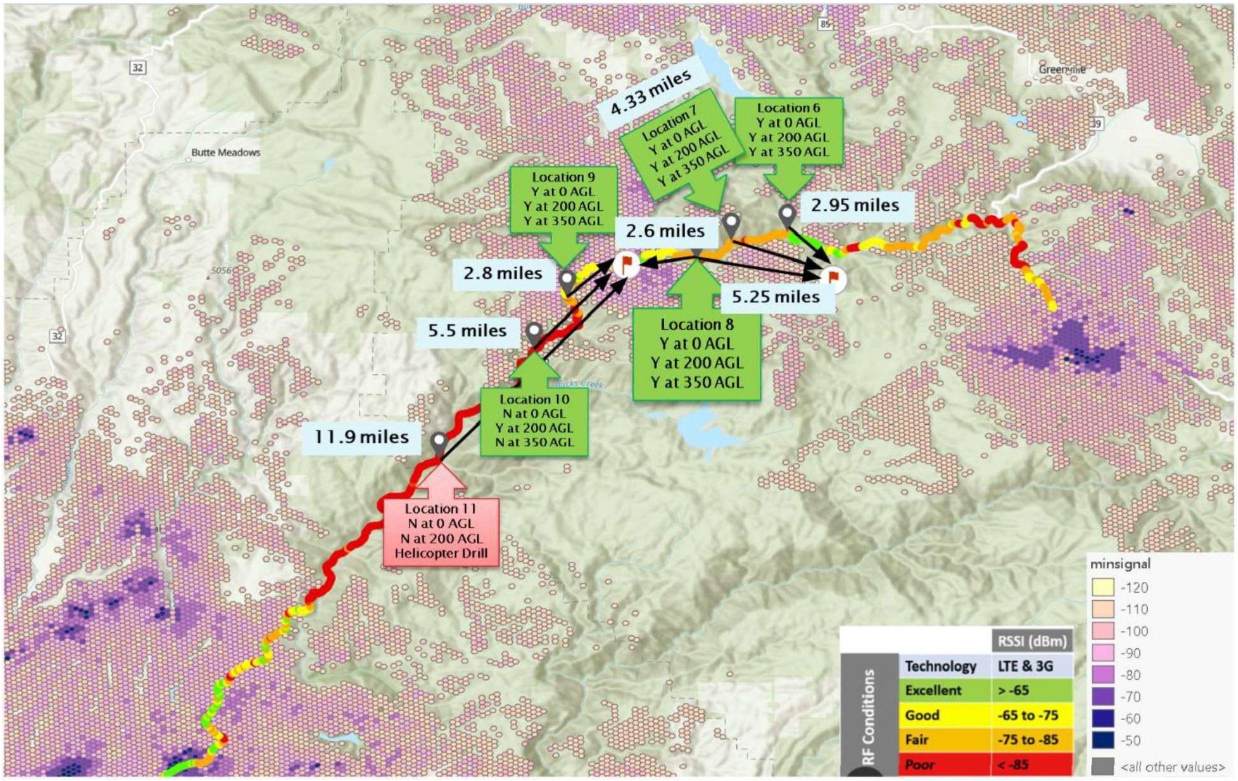

Figure 2.4: UAS repeater performance for email sending and VoIP at different AGLs on Highway 70. Map generated using ArcGIS software by Esri.

From the data shown in Figure 2.4, the following conclusions can be made:

- For Locations 6, 7, 8, and 9, email sending and VoIP were successful at zero (0), 200, and 350 AGL. At Location 6, the signal source connected to the modem was 2.95 miles away from the test site. At Location 7, the signal source connected to the modem was 4.33 miles away from the test site. At Location 8, the two (2) signal sources connected to the modem were 2.6 and 5.25 miles away from the test site. These two signal sources were alternately connected to the modem. At Location 9, the signal source connected to the modem was 2.8 miles away from the test site.
- For Location 10, email sending and VoIP were not successful at 0 and 350 AGL but were successful at 200 AGL. The signal source connected to the modem was 5.5 miles away from the test site.
- For Location 11, email sending and VoIP were not successful at all AGLs. Due to a helicopter operating in the vicinity, the AHMCT was unable to continue testing at a higher AGL.

Recommendations

Based on the results, the AHMCT team offers the following recommendations for the effective utilization of the UAS system:

- **Recommendation**: For optimal performance, the UAS system should be located within approximately 10 miles of a cellular tower.
    - On Highway 299, the UAS system failed to capture a usable signal in two out of five test runs when flown between 200 and 400 feet AGL, due to the test sites being more than 10 miles from the nearest cellular tower. Without proximity to a tower, the system's performance is significantly reduced.
    - Similarly, on Highway 70, the UAS system failed to capture a usable signal when flown at 200 feet AGL, as the test site was more than 10 miles from the nearest cellular tower. The UAS system did not fly higher than 200 feet AGL due to a helicopter drill taking place at the time.
- **Recommendation**: For safety, the UAS system should be operated under the supervision of a Remote Pilot in Command (RPIC) throughout the duration of the flight.
    - Terrain conditions can produce potentially strong gusts of wind. Therefore, it is highly recommended to supervise the UAS system at all times to ensure the UAS system does not crash into the path of traffic.
    - The limited space between the shoulder and the road also poses challenges that require careful monitoring.
- **Recommendation:** To ensure uninterrupted operation during a two-hour mission, it is recommended to have eight (8) backup batteries available.
    - During the test runs, the UAS system required two (2) batteries to operate for 30 minutes.

The AHMCT team **does not recommend deploying the UAS system if the Wi-Fi client:**

- Can reliably obtain a usable LTE signal on the ground when connecting to the UAS system. The Wi-Fi client can place a phone call to verify signal availability.
    - The Wi-Fi clients should be able to place a phone call to verify signal availability. The results show that utilizing a Sierra Wireless MP70 modem and Proxicast antennas can provide a usable network that enables the user to send emails and perform VoIP on the ground in many situations.
- Do not meet safety requirements
    - The user should be able to observe the UAS system at all times.
    - Shoulders should have enough clearance to land the system.

Future Work

During the development of the test plan, the AHMCT team explored the possibility of extending the UAS systems flight time by using a tether. The tethered unit requires a generator to operate, as it is designed to provide continuous power during extended flight times. During field testing at the Woodland Davis Aeromodellers field, the UAS sustained flights up to 2 hours and 48 minutes long. The UAS could have stayed in the air longer; however, the research team concluded their tests and landed the UAS. Due to current limitations within Caltrans, tethered flights are more restrictive than untethered flights. Should Caltrans' policies change, revisiting a tethered system could enable extended flight durations, offering a reliable network for Caltrans and other responders during major incidents. Figure 2.5 illustrates the UAS system connected to the tethered system.

Figure 2.5: The UAS system connected to a third-party tethered unit.

The UAS test results demonstrate that a Sierra Wireless 70 modem with a pair of Proxicast antennas can enhance the LTE signal without requiring the drone to be deployed. The AHMCT team can conduct further research into alternative modems and antennas to optimize the system on the ground. This approach allows for exploration of better modem and antenna options without the concern of weight limitations.

Additionally, based on the current technology market, the AHMCT team recommends focusing on a Starlink network system, instead of a UAS-based network system in rural areas. The Starlink network system setup is straightforward and does not require a certified drone pilot. Caltrans has already utilized the Starlink satellite network system in recent years and yielded positive results. Figure 2.6 shows Caltrans use of the Starlink network in a separate project.

Figure 2.6: The Starlink satellite system set-up for AHMCT Task 4059 - Caltrans project. As long as the system is powered, it can serve as a hotspot for multiple devices.

Deviations from Research Proposal

The AHMCT team was scheduled to provide guidance on using the UAS system for Caltrans personnel in a workshop forum. However, after evaluating the system, the team determined that the UAS offers minimal benefits relative to its high deployment efforts and concluded that it is incompatible with Caltrans' daily operations.

1. **Personnel Requirements:** A minimum of two Caltrans personnel is required per shift during drone deployment, one of whom must be a certified Part 107 pilot. Per Federal Aviation Administration (FAA) regulations, any UAS operation above 150 feet AGL requires a Part 107–certified pilot and a visual observer. Although the FAA does not mandate a visual observer for flights below 150 feet, Caltrans safety policy does. Given Caltrans safety standards, the terrain, the potential for strong gusts, and the UAS's optimal performance often at approximately 200 feet AGL, a visual observer is mandatory.
2. **Deployment Location and Direction Limitations:** The UAS system performs optimally within 10 miles of a cellular tower. Caltrans personnel should remain within 10 miles of a cellular tower and ensure the drone captures a usable LTE signal (by checking if their phones are able to send emails and conduct calls). About 10 minutes are required for drone deployment and for the payload package to stabilize and provide usable signal. Each time the personnel relocate, this process must be repeated. Additionally, a safe deployment area must have a shoulder that is at least 25 feet wide and 100 feet long to allow the pilot to maintain a clear line of sight of the UAS. All these factors may limit the system effectiveness in rural areas.
3. **Limited LTE Signal Gain:** The UAS system successfully detected usable LTE signals on the ground due to its strong cellular antenna (Proxicast) and reliable modem (Sierra Wireless 70). During testing on Highways 299 and 70, the UAS only needed to ascend twice out of eleven trial runs to capture a usable LTE signal. Therefore, Caltrans personnel are more likely to obtain a usable LTE signal with a higher gain antenna and/or a higher sensitivity modem mounted on their vehicles as opposed to relying on the UAS for signal capture.
4. **Short Flight Durations:** Each UAS deployment requires two (2) batteries, providing approximately 30 minutes of flight time. With eight (8) batteries stored in the charging case, the UAS system can operate for a total of about two hours. Although the UAS system was tested with a third party tethered system, the tether was not implemented.

Given these limitations, the AHMCT team and the Caltrans panel agreed that organizing a workshop would not be practical.

Moving forward, the AHMCT team recommends that the UAS system will be supplemented by improving modems and antennas on the ground based on the results of the UAS system testing.

Chapter 3:
System Design and Operating Procedures

Experimental Set-up

System Overview

There are two systems responsible for collecting data: the UAS system and a ground communication system. First, the UAS system captures signals from the cellular tower. Then, Raspberry Pi 4 records data output from the modem. Raspberry Pi 5 is set up to communicate with Raspberry Pi 4 at a ground communication apparatus. From the ground, Raspberry Pi 5 displays the data output collected from Raspberry Pi 4 through a monitor. A demonstration of the UAS system communicating with the ground communication system is shown in Figure 3.1.

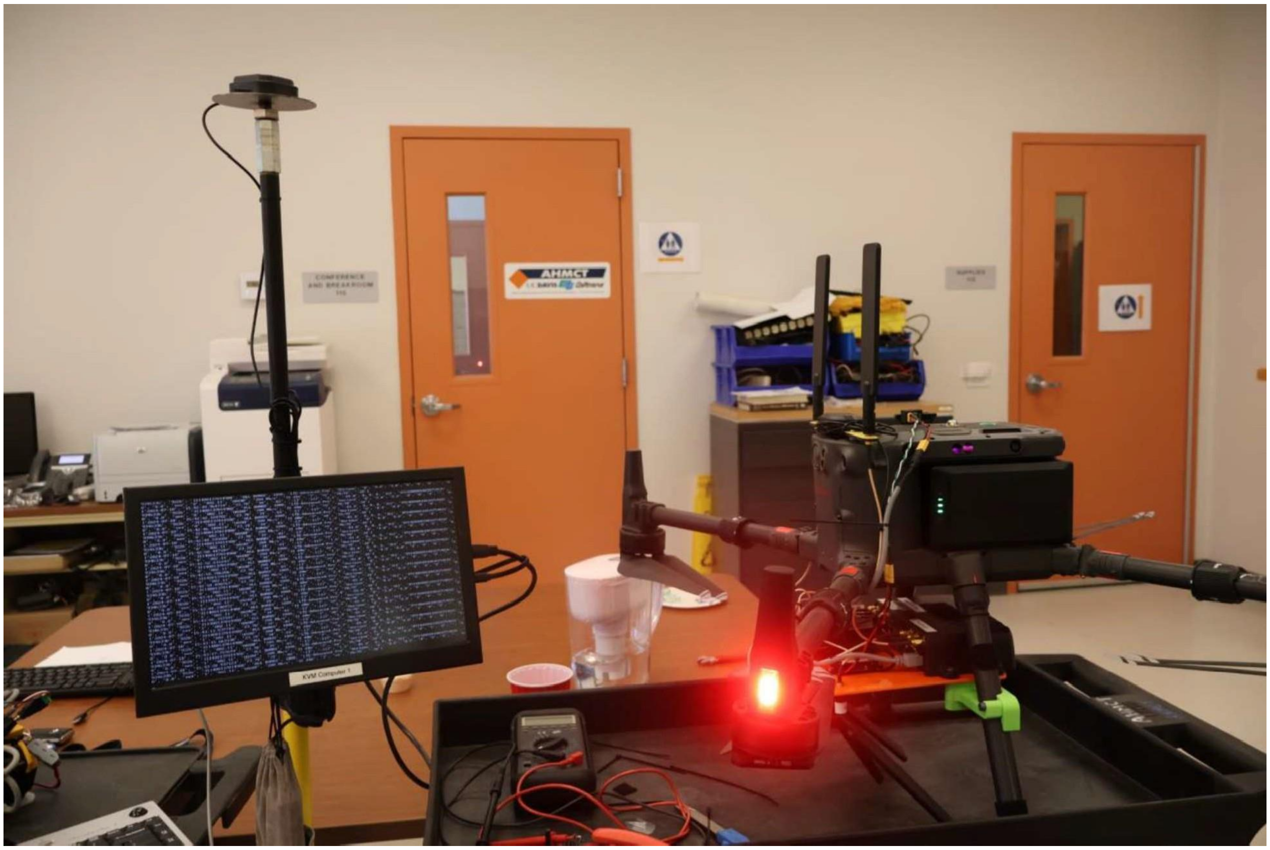

Figure 3.1: UAS system on the right and ground communication system on the left. Two Raspberry Pis communicate with each other to display data read from the modem.

The UAS system consists of the following components:

- One (1) DJI Matrice 300 drone
- One (1) Sierra Wireless MP70 modem
- One (1) Raspberry Pi 4 (name as Pi 1 throughout the context of this report)
- Two (2) LTE antennas
- Two (2) Wi-Fi antennas
- One (1) GPS antenna
- Cables to connect the components
- Fixtures and hardware parts to hold the components in place

Objective for the UAS system: Route network data traffic between the Wi-Fi clients to the LTE network at a height (maximum 400 feet AGL). Ultimately, the UAS system serves as a network hotspot while hovering in the air.

The ground communication system consists of the following components:

- One (1) Raspberry Pi 5 (name as Pi 2 throughout the context of this report)

- One (1) GPS module
- One (1) GPS antenna
- One (1) DeWalt portable battery
- One (1) monitor
- One (1) portable battery (to power the monitor)
- Cables to connect the components
- Fixtures and hardware parts to hold the components in place

Objective for the ground communication system: Communicate with Pi 1 to obtain the signal metrics recorded. The ground personnel can monitor the cellular and Wi-Fi signal performance generated from the UAS system via the monitor.

Figure 3.2 illustrates the connection between the UAS system components and the ground communication system components. The highlighted sections indicate the signal metrics that were collected. Table 3.1 provides a detailed breakdown of the communications between the components.

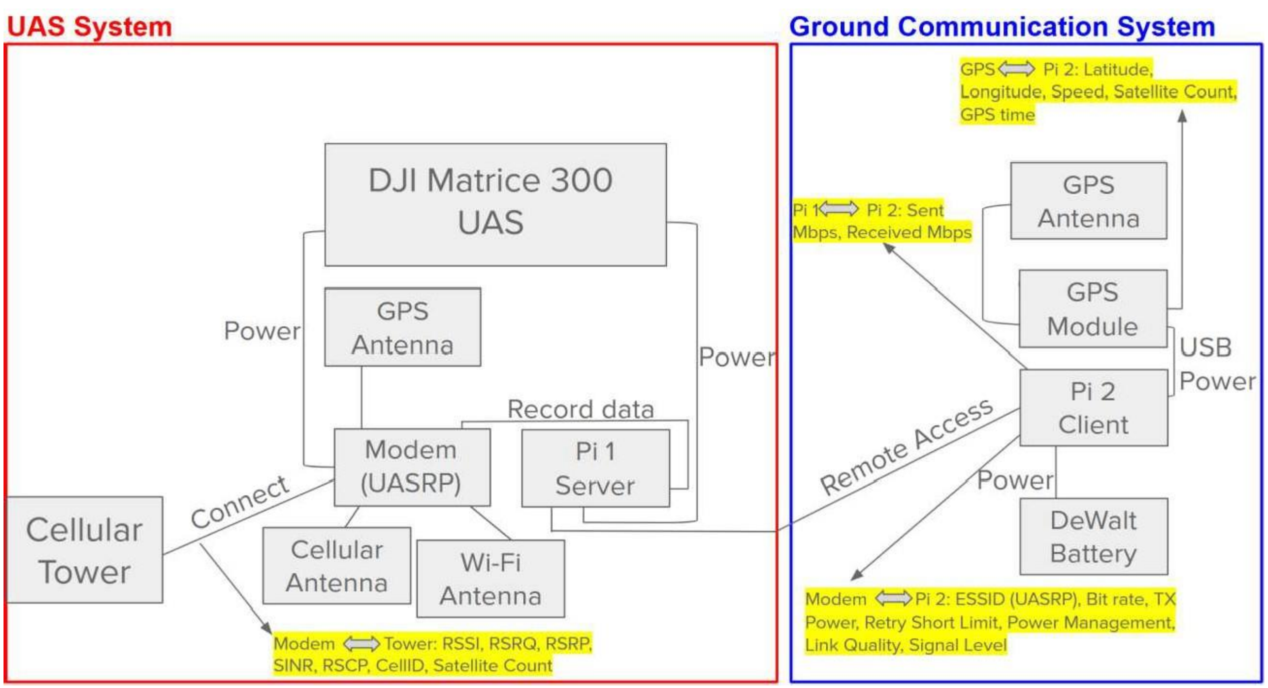

Figure 3.2: Connection diagram between the UAS system and the ground communication system.

Table 3.1: Data collected from the communication systems

Communication	Signal Metrics Collected from the Communication
Modem communicates with the cellular tower via the LTE antenna. The data output from the modem is recorded by Pi 1	Modem LTE signal performance: RSSI, RSRQ, RSRP, SINR, RSCP, cell ID, satellite count, etc.
Pi 2 communicates with Pi 1 via remote access	Communication performance between server and client: sent Mbps, received Mbps
GPS antenna communicates with Pi 2 via programmed GPS module	GPS location of the ground communication system: latitude, longitude, speed, satellite count, and time
Pi 2 communicates with the modem via remote access	Modem characteristics: ESSID (UASRP is the network name), bit rate, TX power, retry short limit, power management, link quality, and signal level

LTE Network Analysis

Based on previous tests, the Bingfu and Proxicast LTE antennas were evaluated and selected for the field trial. Initially, the Bingfu antenna was chosen as the primary option, due to its lightweight and compact design. However, after assessing performance, the Proxicast antenna was utilized instead of the Bingfu antenna because despite the Proxicast's larger size, it provided better LTE signal capture.

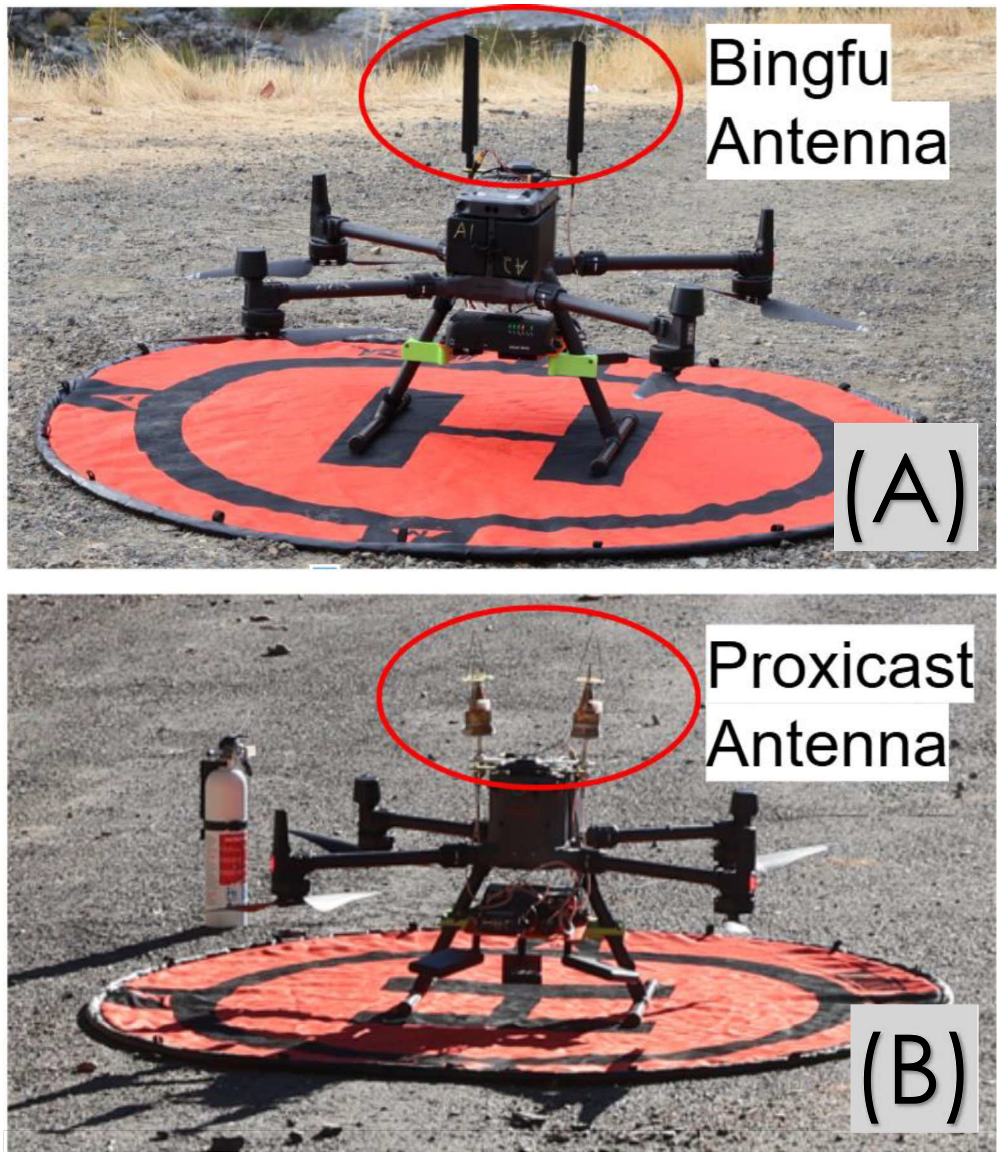

Figure 3.3: (A) Bingfu LTE antenna on the UAS system. (B) Proxicast LTE antenna on the UAS system.

The Proxicast LTE antenna serves the purpose of routing a usable signal from the cellular tower to the Wi-Fi client. **In this context, a "usable signal" is defined as the ability to send emails and perform VOIP.**

Wi-Fi Network Analysis

When the UAS system is deployed, it may be as far as 400 feet from the ground. As the distance from the Wi-Fi client increases, the Wi-Fi strength diminishes. To mitigate this issue, Wi-Fi antennas were installed to enhance signal reliability and coverage.

Based on previous tests, the Active-Passive Antennas (APA) Wi-Fi antenna was evaluated and chosen for the field trial. The APA antenna performs optimally when the Wi-Fi client is directly beneath the UAS system. However, as the client moves farther from the antenna, Wi-Fi performance gradually declines. **The performance characteristics of the APA antenna align well with Caltrans needs, as workers typically do not move beyond 100 feet from their vehicles in this context.**

Table 3.2 demonstrates the APA Wi-Fi antenna performance metrics at different vertical and horizontal distances when communicating with a Wi-Fi client. From the testing results, the APA antenna's signal strength is stronger the closer the client is to the system, and weaker as the distance increases.

Table 3.2: Performance metrics of the APA Wi-Fi antenna at altitudes of 100 and 350 feet AGL, measured while communicating with a Wi-Fi client at varying horizontal distances

Location of UAS System and Wi-Fi Client	APA Wi-Fi Antenna Performance Metrics
UAS system at 100 feet AGL Wi-Fi client stands 10 feet away from the UAS system	Signal Level: -56.1 dBm Upload speed: 117.9 Mbps Download speed: 117.2 Mbps
UAS system at 100 feet AGL Wi-Fi client stands 100 feet away from the UAS system	Signal Level: -72.9 dBm Upload speed: 55.3 Mbps Download speed: 47.0 Mbps
UAS system at 100 feet AGL Wi-Fi client stands 200 feet away from the UAS system	N/A, Unable to connect
UAS system at 350 feet AGL Wi-Fi client stands 10 feet away from the UAS system	Signal Level: -67.8 dBm Upload speed: 65.2 Mbps Download speed: 84.6 Mbps
UAS system at 350 feet AGL Wi-Fi client stands 100 feet away from the UAS system	Signal Level: -73.2 dBm Upload speed: 58.2 Mbps Download speed: 39.7 Mbps
UAS system at 350 feet AGL	Signal Level: -81.0 dBm

Location of UAS System and Wi-Fi Client	**APA Wi-Fi Antenna Performance Metrics**
Wi-Fi client stands 200 feet away from the UAS system	Upload speed: 1.28 Mbps Download speed: 2.51 Mbps

Standard Operating Procedures of UAS Repeater

UAS Pre-flight

Testing Procedures for Data Collection

A procedure was implemented to ensure that field personnel could carry out testing safely and efficiently.

General instruction for the entire data collection system setup

1. Put on PPE before exiting the car.
2. Set up the orange cones around the testing perimeter.
3. Set up the UAS system. See (a) below for more details.
4. Set up the ground-based communication system. See (b) below for more details.

a. UAS system
- Connect the power cable so modem and Pi 1 can draw power from the drone.
- Connect all the antenna cables. Make sure all antennas are secured.
- Make sure the modem and the Pi 1 are powered before launching.

b. Ground communication system
- Turn on the DeWalt battery. Make sure that Pi 2 is powered, and the GPS module is receiving pulse (blinking LED).
- Turn on the monitor screen using the portable battery charger.
- Log in to Pi 2.
- Use established commands to execute the code.
- After the data is sufficiently collected, command ctrl-C to exit the code.
- Use the established commands to execute the code and collect communication characteristic (upload and download speed) between two Pis.

- After the data is sufficiently collected, exit the code.
- Repeat the code commands at other locations.

Ideally, field personnel should complete the entire data collection set-up in under 15 minutes. It is recommended that field personnel position the ground communication system behind a vehicle to provide protection from oncoming traffic.

General Operating Procedures

In the case of deploying the UAS system without collecting signal data, the procedures would be as follows:

General instruction for deploying the UAS system

1. Put on PPE before exiting the car.
2. Set-up the orange cones around the drone deployment perimeter.
3. Set-up the UAS system.
   - Connect the power cable so the modem can draw power from the drone.
   - Connect all the antenna cables. Make sure all antennas are secured.
4. Launch and monitor the UAS system.
5. Connect to the UAS system network if the system captures usable signal.

Ideally, field personnel should be able to launch the UAS system within 10 minutes. However, the signal output results may vary depending on the deployment location. More details are discussed later in this report.

Day of Flight

As outlined in the Task 4 report, the testing locations were chosen based on their potential to enhance LTE signals using the UAS, with each location providing a minimum of 25 feet of clearance from the road to safely deploy the UAS system. The AHMCT team traveled to these sites and followed the established procedures for data collection.

The following tools and equipment are required for the user when deploying the UAS system:

- Batteries for the UAS (fully charged)
- Batteries for the UAS remote control
- Wi-Fi antennas (APA)
- LTE antennas (Proxicast)
- Extra hardware as a backup
- Adjustable wrench

- Battery charging case with charging cable (for the UAS)
- Set of Metric and English allen keys
- Launching pad
- Orange cones

Since the AHMCT team was responsible for collecting data from the UAS system, additional tools and equipment were prepared for this purpose. However, if Caltrans is solely operating the UAS system, additional item such as extra hardware is optional.

In-Flight Responsibilities

Two members of the AHMCT team performed the field trials. One member was responsible for launching and monitoring the UAS system. The other member was responsible for the data collection process on the ground.

1. The member controlling the UAS system should:
    - Ensure that the UAS system can be observed at all times;
    - Keep a safe distance between themselves and the road;
    - Ensure that the UAS system moves only in a vertical direction (up and down) and avoid any lateral (sideways) movement.
2. The member collecting data on the ground should:
    - Stand within a 10-foot radius directly underneath the UAS system;
    - Ensure sufficient data is collected, while being mindful that the UAS system has a maximum flight time of 30 minutes after takeof.f

Safety is always the top priority. If at any point the team members feel that it is unsafe to continue data collection, the mission should be aborted immediately.

Figure 3.4: Field testing on Highway 70.

Post-Flight Maintenance

After a UAS deployment, the user should:

- Charge the UAS batteries and its remote control;
- Disassemble the system and store the UAS in the provided case.

For the AHMCT team, data should be extracted from Pi 2 for analysis.

Experimental Design Trade-off

Altitudes to be Flown

During the field trial, the AHMCT team discovered that the UAS system performs optimally at approximately 200 feet AGL. As the system ascends beyond 200 feet AGL, Wi-Fi antenna performance decreases. Therefore, a balance must be struck between reaching a sufficient altitude to connect to LTE signals and maintaining a vertical distance that preserves Wi-Fi antenna performance as much as possible. Figure 3.5 illustrates the relationship between the LTE antenna and Wi-Fi antenna performance as the UAS system ascends.

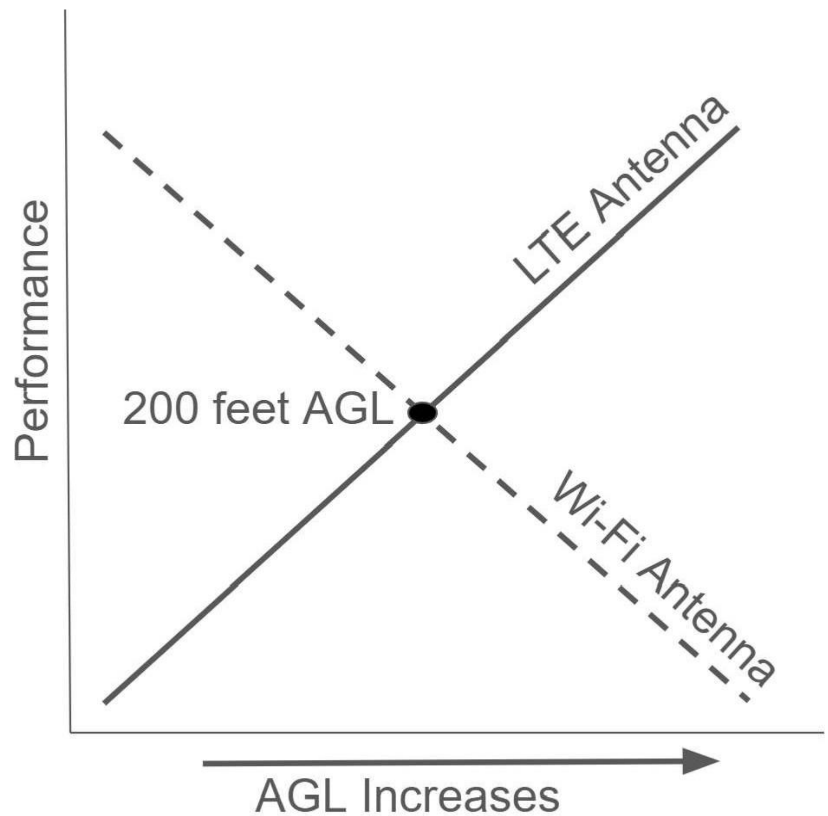

Figure 3.5: The relationship between the LTE antenna and Wi-Fi antenna as the UAS ascends. Note that this figure is for illustrative purposes only, as the relationship may not be strictly linear.

Distance Away from Take-off Location

Since the UAS pilot must maintain continuous visual observation of the system, they need to remain at a certain distance from the UAS. For example, during field trials, the pilot maintained a horizontal distance of approximately 100 feet from the UAS when it was at 350 feet AGL. Due to this safety requirement, deployment locations would be limited, as not all shoulders provide a minimum of 100 feet in length and 25 feet in width from the road.

Chapter 4: Location Summary and Field Trial Gross Reporting

The Task 4 interim report details the process of choosing testing locations. In this chapter, the AHMCT team focuses on the events that happened during field trials. In addition, Figures 2.1 and 2.2 can be referenced for the testing locations on the map.

Tables 4.1 and 4.2 outline the testing locations along Highways 299 and 70, respectively, along with the signal status at these sites prior to the deployment of the UAS system. The objective was to enhance the LTE signal using the UAS system. Results regarding any signal improvements at each testing location are presented in Chapter 5.

Table 4.1: Testing coordinates and flight start time on Highway 299

Location on the map and signal status before utilizing the UAS system	Latitude	Longitude	Start time (Recorded as the ground communication system is active)
1 Slow, un-usable LTE signal	40.76921	-123.1363	10:00:11 AM
2 No LTE signal	40.76164	-123.28784	11:04:39 AM
	40.76174	-123.28774	11:24:43 AM
3 No LTE signal	40.84979	-123.48385	11:46:58 AM
	40.84983	-123.48383	1:16:05 PM
	40.84988	-123.48391	1:22:11 PM
	40.84981	-123.4839	1:25:38 PM
	40.84985	-123.48399	1:26:25 PM
	40.84986	-123.48402	1:27:26 PM
	40.85005	-123.48395	1:29:46 PM

Location on the map and signal status before utilizing the UAS system	Latitude	Longitude	Start time (Recorded as the ground communication system is active)
1 Slow, un-usable LTE signal	40.76925	-123.13629	2:41:21 PM
	40.76939	-123.1361	2:43:39 PM
4 Slow LTE signal	40.6724	-122.85034	3:39:15 PM
5 Slow, un-usable LTE signal	40.67052	-122.81633	4:07:32 PM

Referencing Table 4.1, the events that happened during the field trail on Highway 299 are as follows:

- At 10:00 AM, the AHMCT team performed a trial run at Location 1 to confirm that the UAS and the ground communication systems were working.
- From 11:04 AM to 11:30 AM, the AHMCT team performed testing at Location 2. The AHMCT team provided the Caltrans team with a demonstration of how the entire system operates and how data are collected. Unfortunately, the UAS system was unable to pick up an LTE signal at Location 2.
- From 11:46 AM to 2:00 PM, the AHMCT team performed testing at Location 3. The UAS system was able to pick up an LTE signal. However, the signal strength was insufficient for sending emails or performing VOIP, despite the UAS ascending at the maximum allowable AGL. The AHMCT team waited to see if the signal would improve over time, but it did not. As a result, after more than an hour of waiting, the AHMCT team proceeded to the next location.
- From 2:20 PM to 3:20 PM, the AHMCT team returned to Location 1 to demonstrate to Caltrans personnel that the UAS system could enhance the LTE signal to a usable level for Wi-Fi clients, as it had been unable to do so at the two previous locations.
- From 3:40 PM to 4:00 PM, the AHMCT team performed testing at Location 4. The UAS system successfully detected sufficient LTE signals on the

ground, enabling email sending and VOIP functionality. Due to an aviation alert, the AHMCT team only ascended the UAS system to the maximum of 200 feet AGL as opposed to 350 feet AGL. Since the signal strength was already adequate and did not require improvement, the AHMCT team did not collect internet data for 100 and 200 feet AGLs. Following this, the team proceeded to the next location.

- At 4:07 PM, the AHMCT team performed testing at Location 5. Similar to Location 4, an aviation alert was active at the time. Hence, the AHMCT team only ascended to the maximum of 200 feet AGL as opposed to 350 feet AGL. After completing the data collection, the team concluded their work on Highway 299.

Table 4.2: Testing coordinates and flight start time on Highway 70

Location on the map	Latitude	Longitude	Start time (Recorded as the ground communication system is active)
6 Slow LTE signal	40.02943	-121.12689	10:00:10 AM
7 Slow, un-usable LTE signal	40.02347	-121.1666	11:01:24 AM
8 Slow, un-usable LTE signal	40.00924	-121.19105	11:39:03 AM
9 Slow, un-usable LTE signal	39.98303	-121.28269	12:19:17 PM
	39.98299	-121.28283	12:32:24 PM
10 No LTE signal	39.94624	-121.30634	12:46:13 PM
	39.94623	-121.3063	1:04:55 PM
	39.94628	-121.30633	1:11:57 PM
11 No LTE signal	39.86867	-121.37372	2:03:39 PM
	39.8686	-121.3734	2:14:16 PM

Referencing Table 4.2, the events that happened during the field trail on Highway 70 are as follows:

- At 10:00 AM, the AHMCT team performed a trial run at Location 6 to confirm that the UAS and the ground communication systems were working.
- From 11:01 AM to 11:30 AM, the AHMCT team performed testing and collected signal data at Location 7.
- From 11:39 AM to 12:00 PM, the AHMCT team performed testing and collected signal data at Location 8.
- From 12:19 PM to 12:35 PM, the AHMCT team performed testing and collected signal data at Location 9.
- From 12:46 PM to 1:30 PM, the AHMCT team performed testing and collected signal data at Location 10. The AHMCT team discovered that the UAS system was effective at 200 feet AGL, but not at 350 feet AGL, for this location.
- At 2:03 PM, the AHMCT team performed testing and collected signal data at Location 11. The AHMCT team was in the middle of testing when a helicopter drill began near the testing area. Hence, the AHMCT had to cut the testing short and conclude their work on Highway 70.

Chapter 5: Overall Results

Based on the cellular mapping results, the AHMCT team conducted testing at designated locations along Highways 299 and 70. Initially, the Bingfu LTE antenna was used, due to its lightweight and compact design, which was preferred over the Proxicast LTE antenna. **However, after the AHMCT team was unable to pick up an LTE signal at Location 2 using the Bingfu antenna, they decided to switch to the Proxicast antenna for the remainder of the testing**. Although Proxicast also failed to pick up an LTE signal at Location 2, it performed well at other locations. The Proxicast antenna successfully picked up LTE signals at more rural areas, although, at some sites, the signal quality did not meet Caltrans' standards for usability.

Caltrans' standards for signal usability are:

- Ability to send emails,
- Ability to perform Wi-Fi calling, or VoIP.

If the LTE signal picked up by the UAS system failed to meet Caltrans' signal criteria, it was considered "unusable". Out of the eleven (11) test runs, the UAS system detected an unusable LTE signal twice, at Locations 3 and 11.

On Highway 299, the UAS successfully improved the LTE signal in three out of five test runs. At Locations 1 and 5, the UAS system was able to provide usable LTE signals for the Wi-Fi clients. However, at Location 3, while the LTE signal improved over time, it was still deemed unusable as the Wi-Fi clients were unable to send emails or perform VoIP. At Location 2, the UAS system was unable to pick up an LTE signal. At Location 4, the UAS system was able to pick up a usable LTE signal on the ground (0 AGL), making the UAS deployment unnecessary at that location. Table 5.1 summarizes the impact of the UAS system on the LTE signal at testing locations on Highway 299.

Table 5.1: The impact of the UAS system on the LTE signal at testing locations on Highway 299

Location	Able to pick up LTE signal at 0 AGL?	Able to pick up LTE signal above 100 feet AGL?	Able to improve LTE signal?	Able to send email and perform VOIP?
1	No	Yes	Yes	Yes
2	No	No	No	No
3	No	Yes	Yes	No
4	Yes	Yes	No	Yes
5	Yes	Yes	Yes	Yes

On Highway 70, the UAS successfully improved the LTE signal in five out of six test runs. At Locations 6, 7, 8, 9, and 10, the UAS system was able to provide usable LTE signals for the Wi-Fi clients. At Location 11, the UAS system was unable to produce a usable LTE signal. Additionally, due to a helicopter drill occurring in the area during testing, the AHMCT team was unable to determine whether the LTE signal would improve over time. Table 5.2 summarizes the impact of the UAS system on the LTE signal at testing locations on Highway 70.

Table 5.2: The impact of the UAS system on the LTE signal at testing locations on Highway 299

Location	Able to pick up LTE signal at 0 AGL?	Able to pick up LTE signal above 100 feet AGL?	Able to improve LTE signal?	Able to send email and perform VOIP?
6	Yes	Yes	Yes	Yes
7	Yes	Yes	Yes	Yes
8	Yes	Yes	Yes	Yes
9	Yes	Yes	Yes	Yes
10	No	Yes	Yes	Yes

Location	Able to pick up LTE signal at 0 AGL?	Able to pick up LTE signal above 100 feet AGL?	Able to improve LTE signal?	Able to send email and perform VOIP?
11	No	Yes	Not enough time to evaluate due to a helicopter drill	Not enough time to evaluate due to a helicopter drill

Figures 5.1 through 5.10 provide illustrations depicting the testing results of the UAS system at each location for Highway 299. Observations on the data are noted for each location.

Highway 299

Location 1

Bingfu LTE Antenna

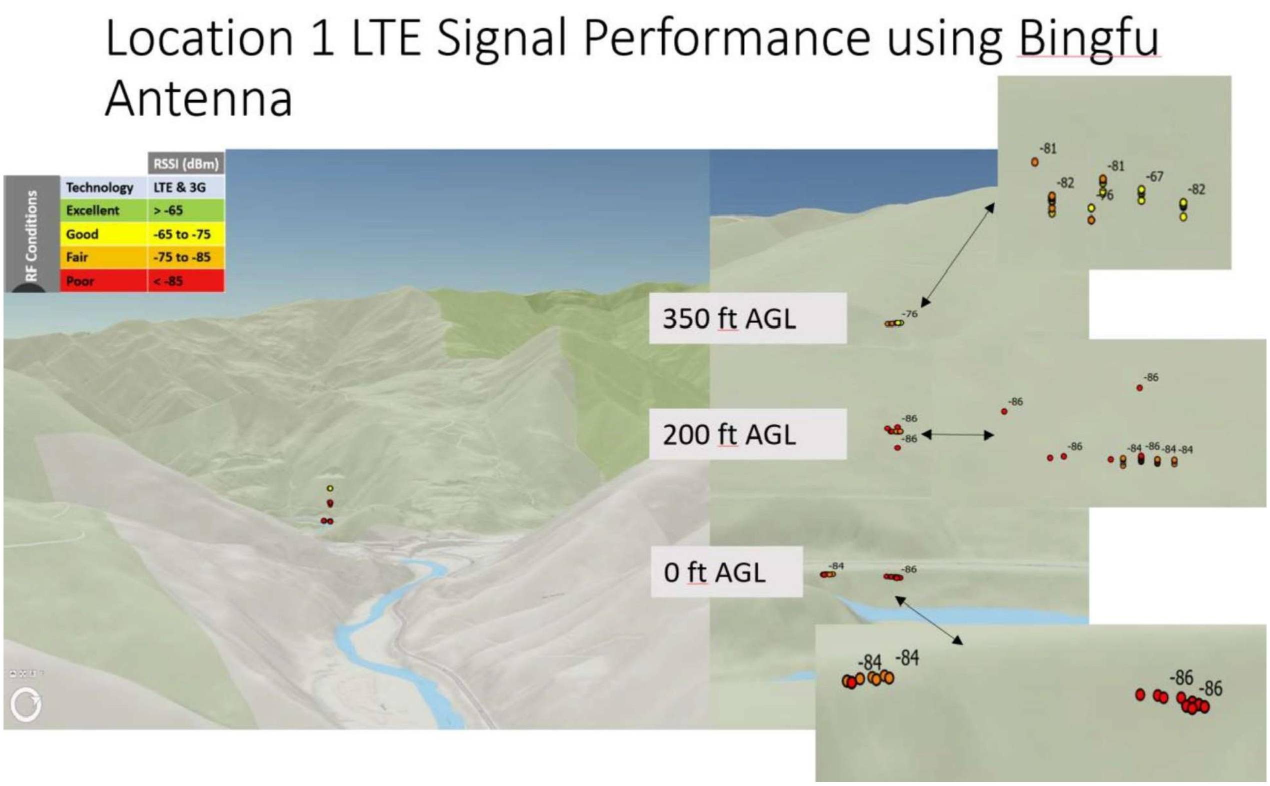

Figure 5.1: LTE signal performance using the UAS system with Bingfu antenna at Location 1. Map generated using ArcGIS software by Esri.

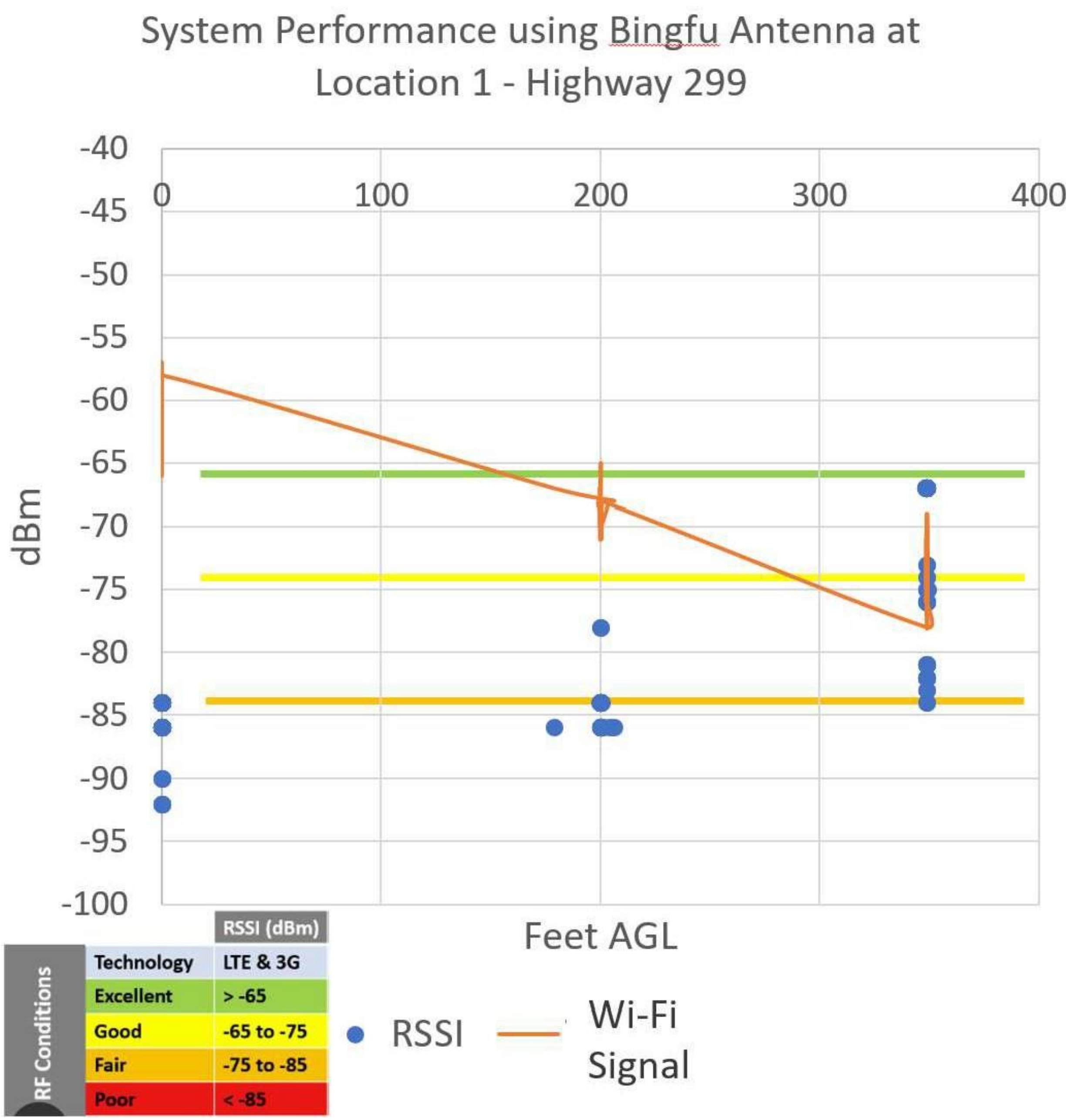

Figure 5.2: UAS system performance using Bingfu antenna at Location 1. RSSI data represents the LTE signal performance at various AGLs. Wi-Fi signal data represents the Wi-Fi connection performance from the modem to the Wi-Fi client.

Observation from Figures 5.1 and 5.2:

- As the UAS system ascended, LTE signal improved, but Wi-Fi connection degraded.
- LTE signal before using the UAS system: -92 dBm at 0 AGL.

- LTE signal after using the UAS system: -63 dBm at 350 feet AGL (best recorded value).

Proxicast LTE Antenna

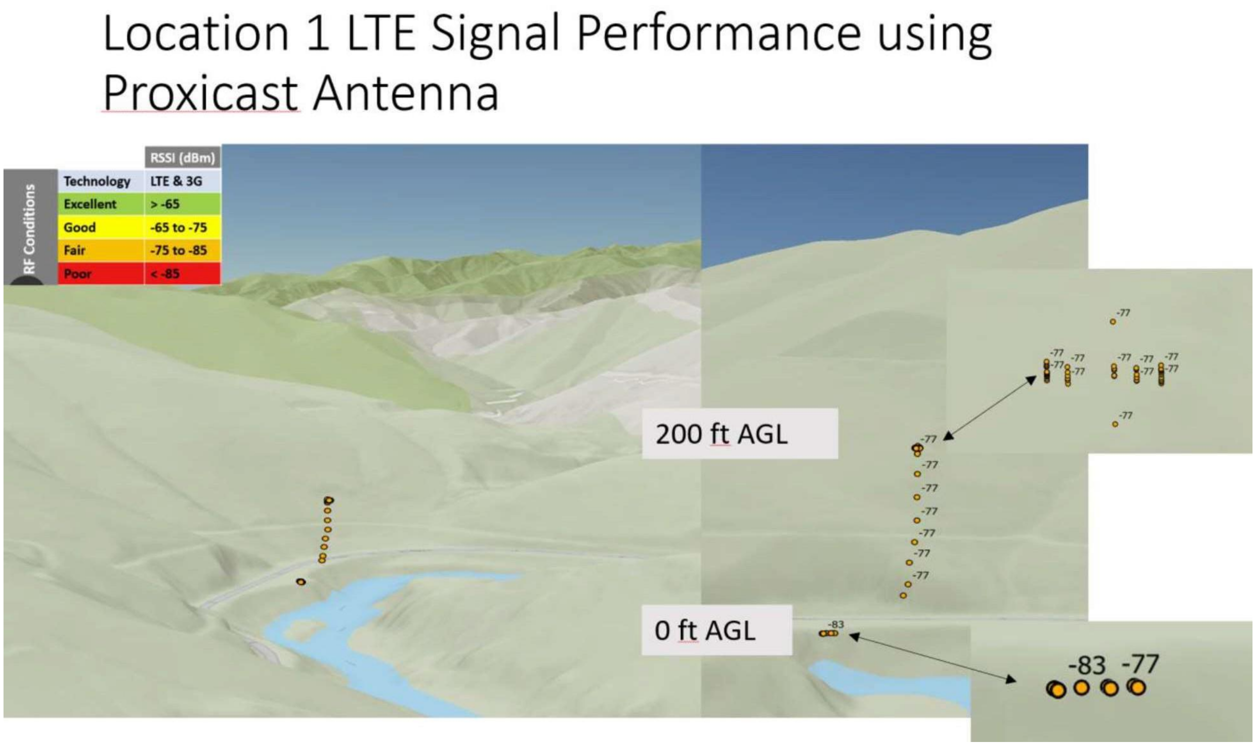

Figure 5.3: LTE signal performance using the UAS system with Proxicast antenna at Location 1. Map generated using ArcGIS software by Esri.

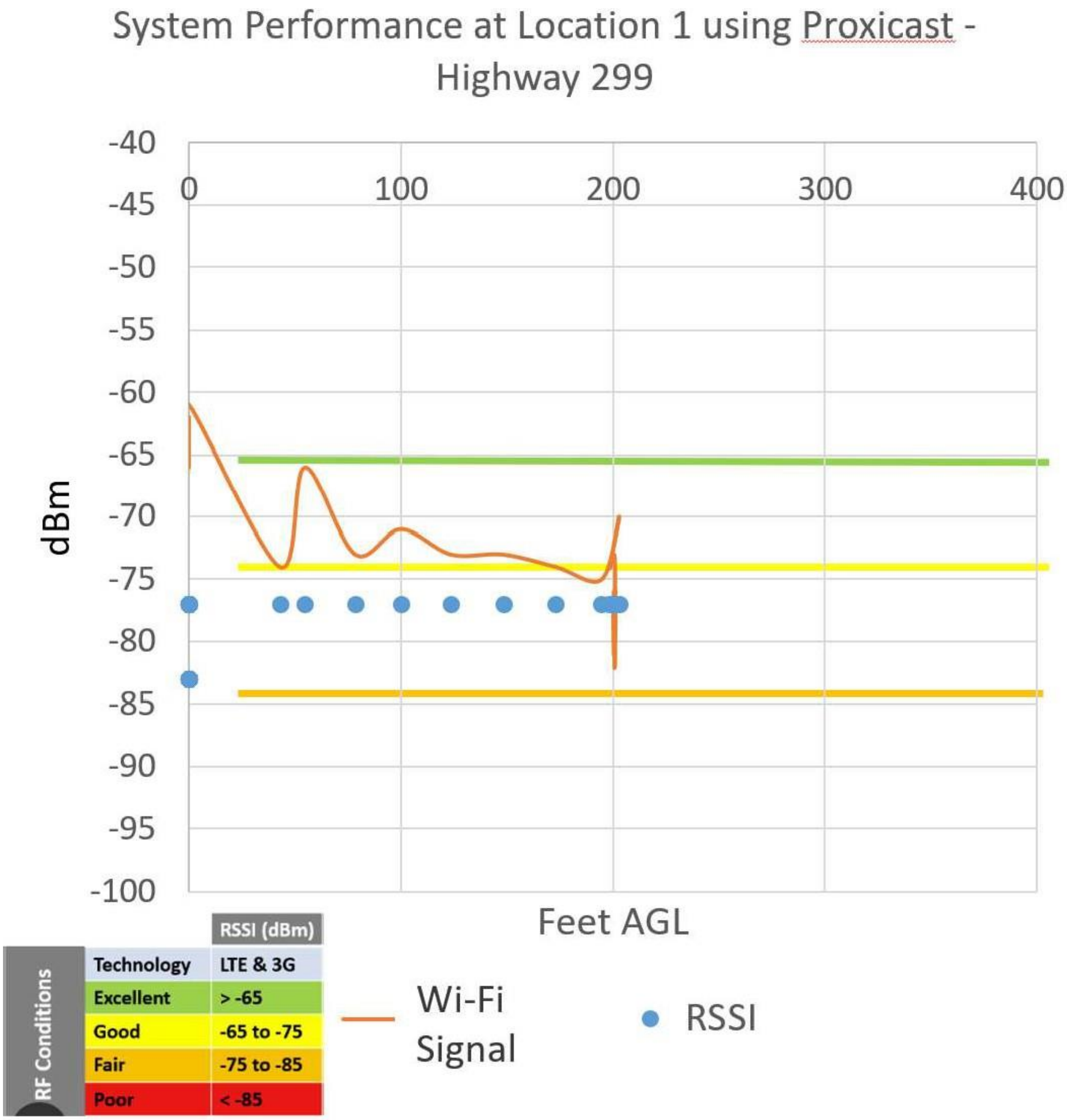

Figure 5.4: UAS system performance using Proxicast antenna at Location 1. RSSI data represents the LTE signal performance at various AGLs. Wi-Fi signal data represents the Wi-Fi connection performance from the modem to the Wi-Fi client.

Observation from Figures 5.3 and 5.4:

- As the UAS system ascended, LTE signal improved, but Wi-Fi connection degraded.
- LTE signal before using the UAS system: -83 dBm at 0 AGL.

- LTE signal after using the UAS system: -77 dBm at 200 feet AGL (best recorded value).
- The AHMCT team did not ascend the UAS system to 350 feet AGL as this test run was conducted for demonstration purposes for Caltrans.

Location 2

The AHMCT team does not have data to present for Location 2, due to the UAS system's inability to pick up an LTE signal.

Location 3

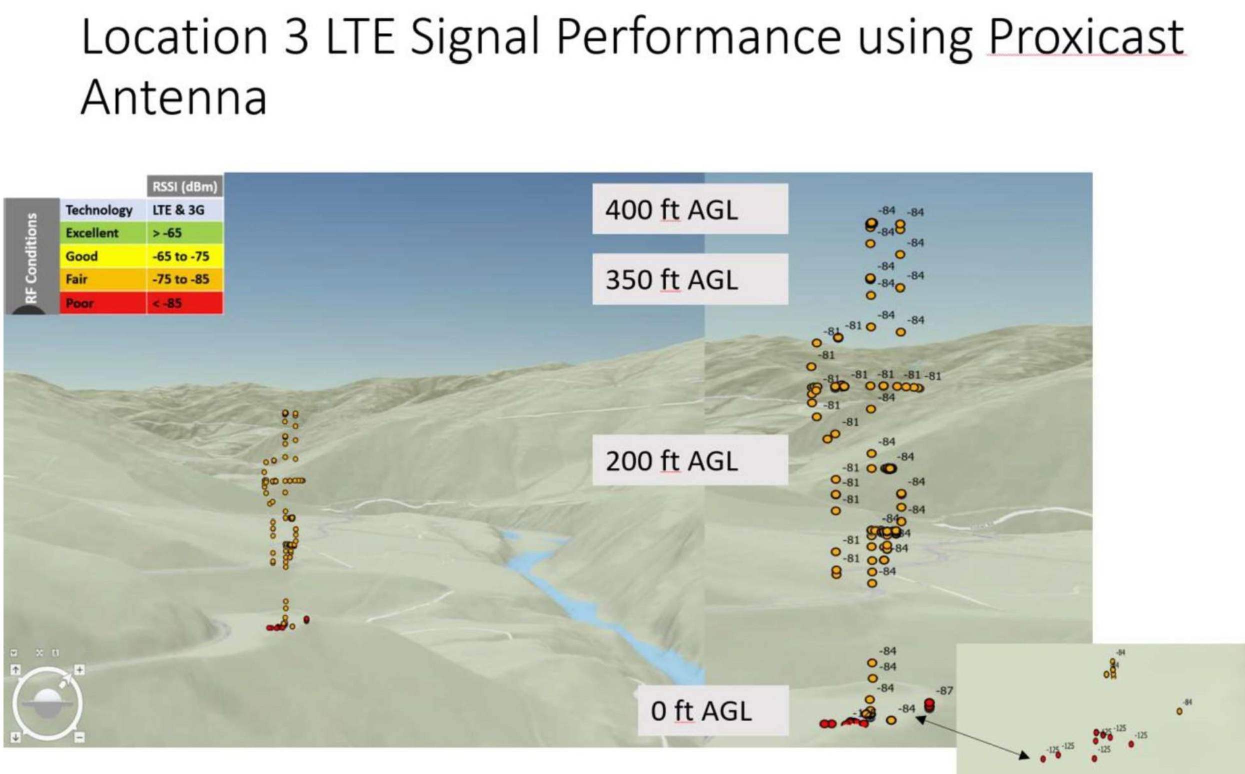

Figure 5.5: LTE signal performance using the UAS system with Proxicast antenna at Location 3. Map generated using ArcGIS software by Esri.

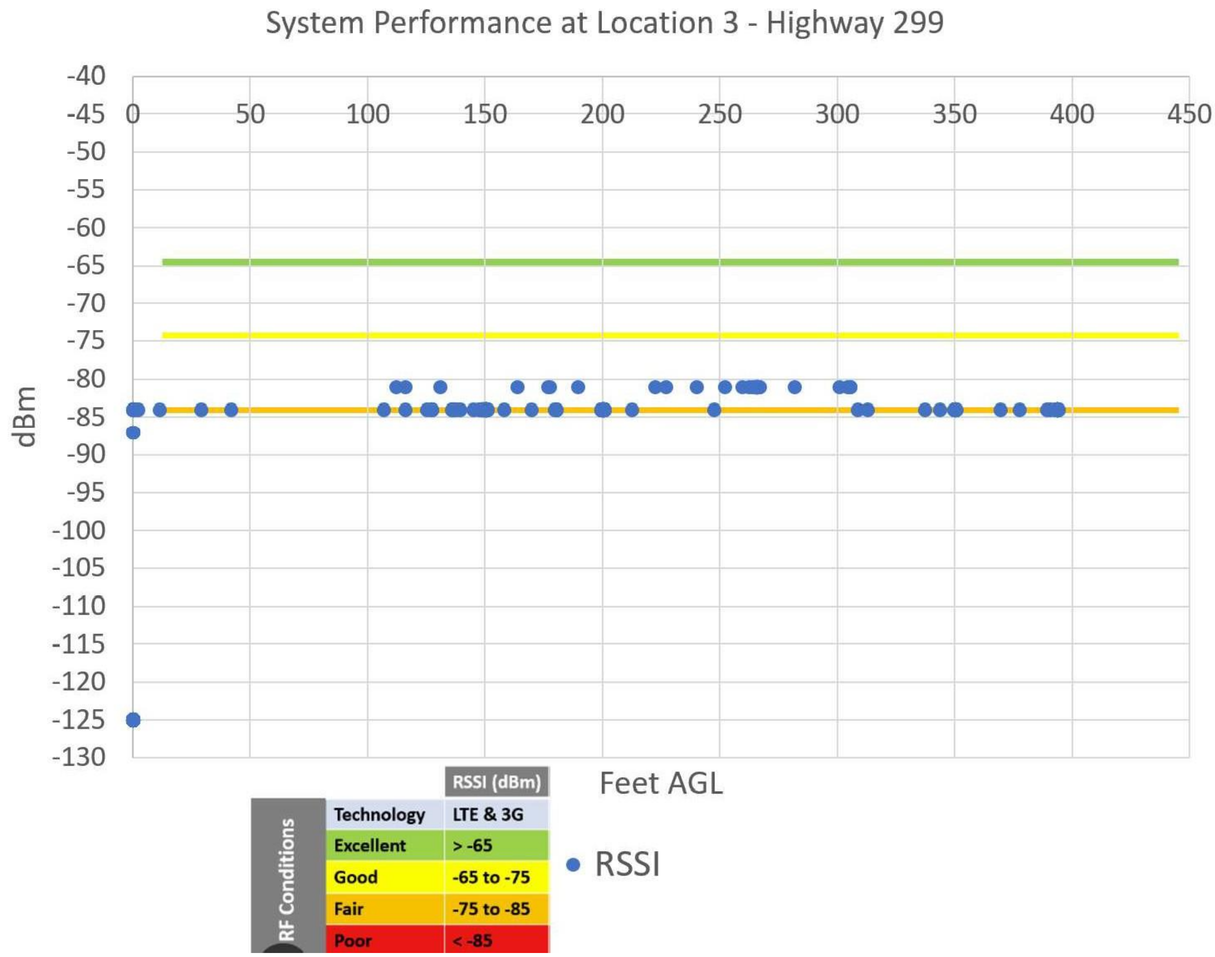

Figure 5.6: UAS system performance using Proxicast antenna at Location 3. RSSI data represents the LTE signal performance at various AGLs. Wi-Fi signal data is not presented as the LTE signal was deemed unusable according to Caltrans standards.

Observation from Figures 5.5 and 5.6:

- LTE signal before using the UAS system: -125 dBm at 0 AGL.
- LTE signal after using the UAS system: -81 dBm at around 250 feet AGL (best recorded value).
- The AHMCT team attempted to ascend the UAS system to a wider range of AGLs compared to Location 1, to determine if the LTE signal could be improved.

Location 4

Location 4 LTE Signal Performance using Proxicast Antenna

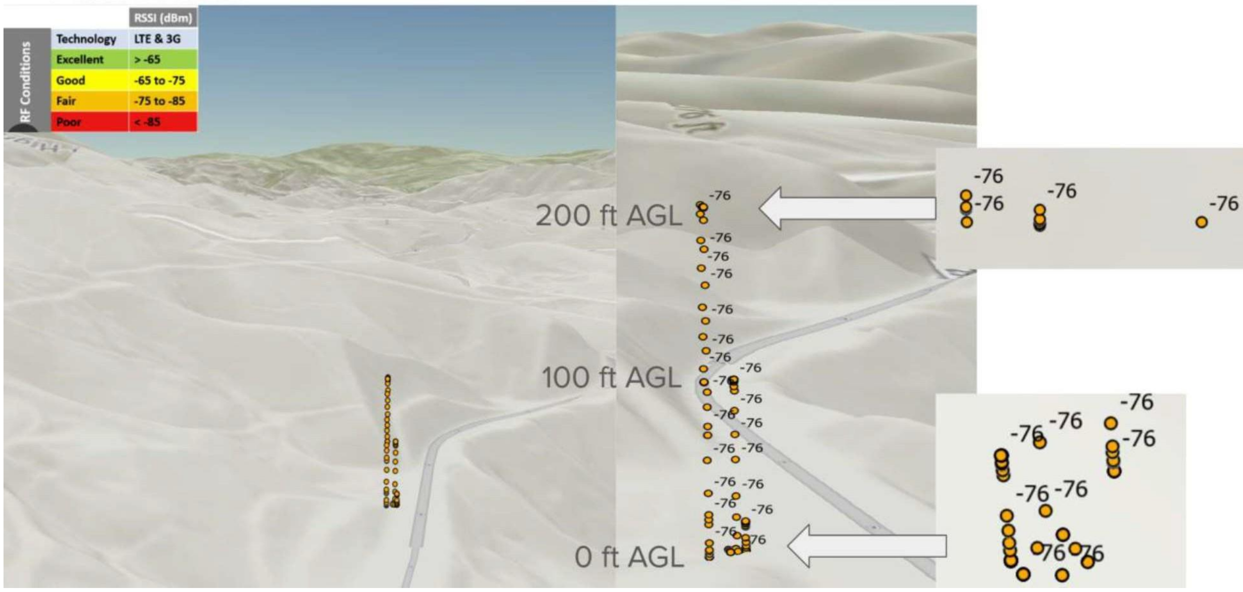

Figure 5.7: LTE signal performance using the UAS system with Proxicast antenna at Location 4. Map generated using ArcGIS software by Esri.

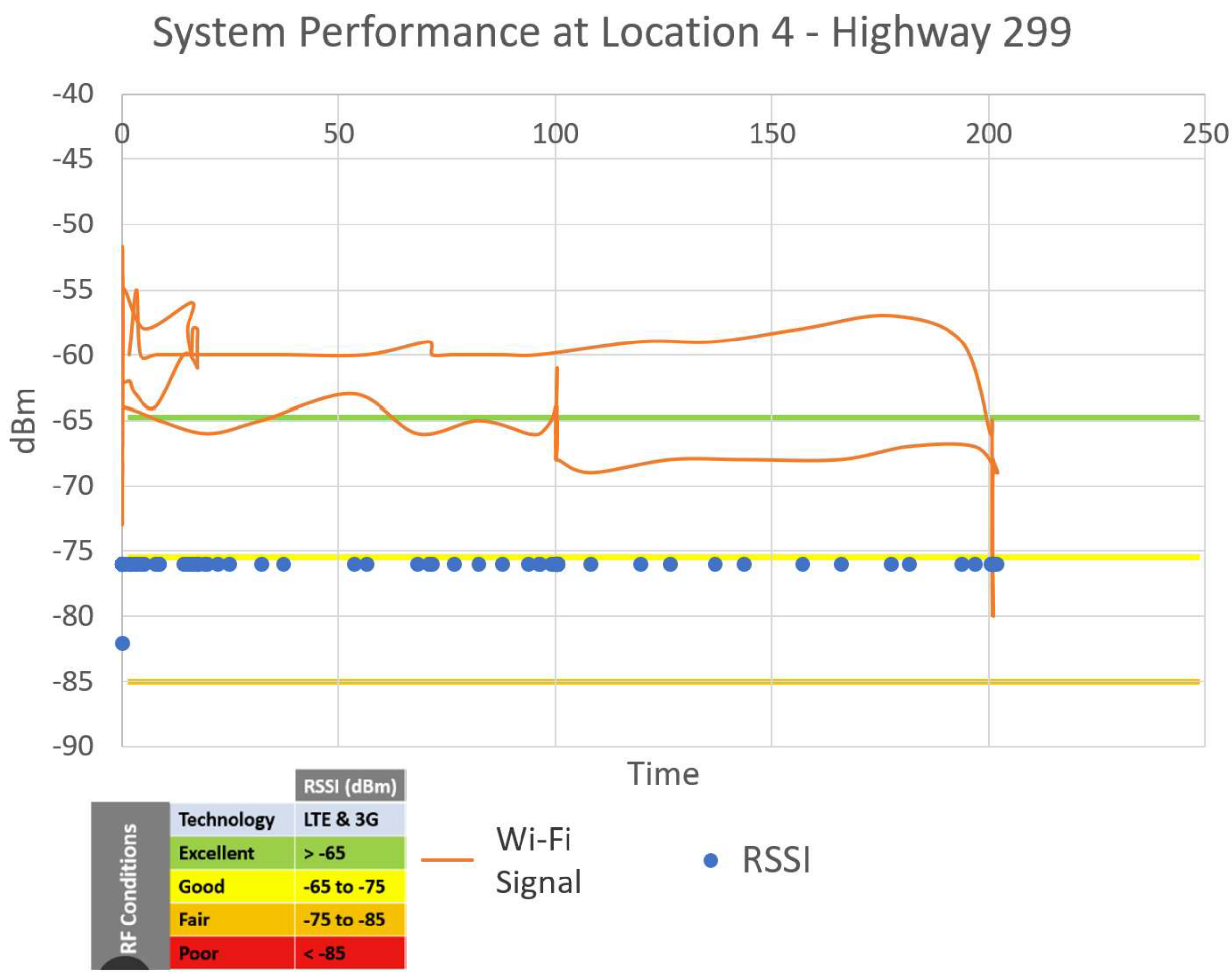

Figure 5.8: UAS system performance using Proxicast antenna at Location 4. RSSI data represents the LTE signal performance at various AGLs. Wi-Fi signal data represents the Wi-Fi connection performance from the modem to the Wi-Fi client.

Observation from Figures 5.7 and 5.8:

- LTE signal before using the UAS system: -76 dBm at 0 AGL.
- LTE signal after using the UAS system: -76 dBm at 200 feet AGL (best recorded value).
- Deployment of the UAS system did not result in any improvement to the LTE signal.
- The AHMCT team did not ascend the UAS system higher than 200 feet AGL, due to an aviation alert in the area.

Location 5

Location 5 LTE Signal Performance using Proxicast Antenna

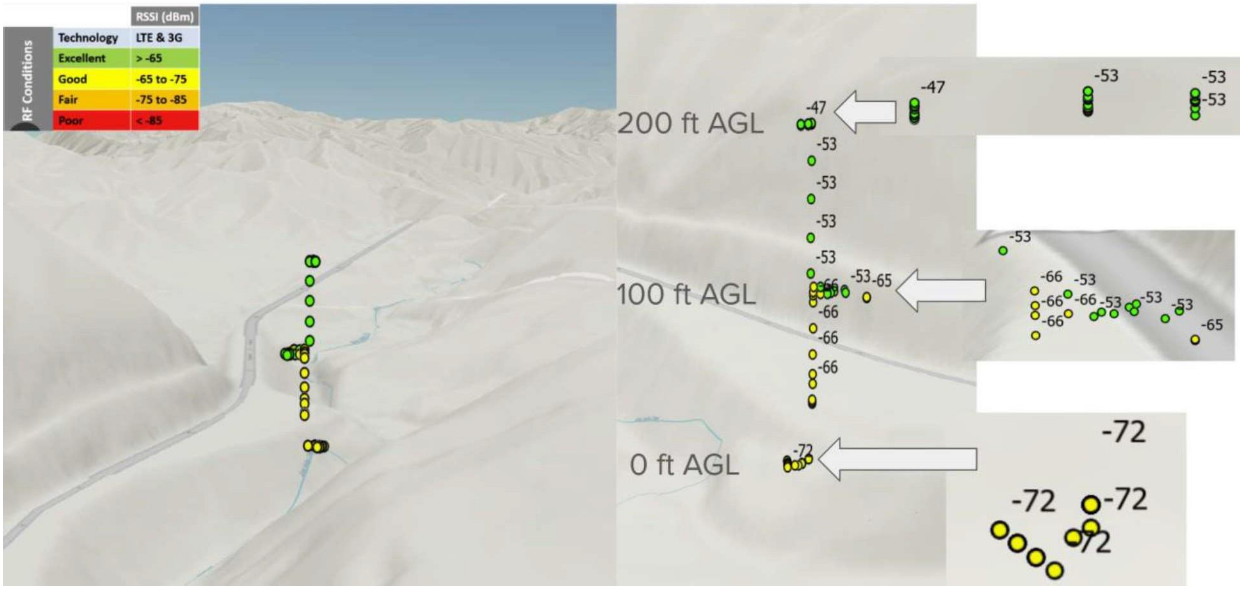

Figure 5.9: LTE signal performance using the UAS system with Proxicast antenna at Location 5. Map generated using ArcGIS software by Esri.

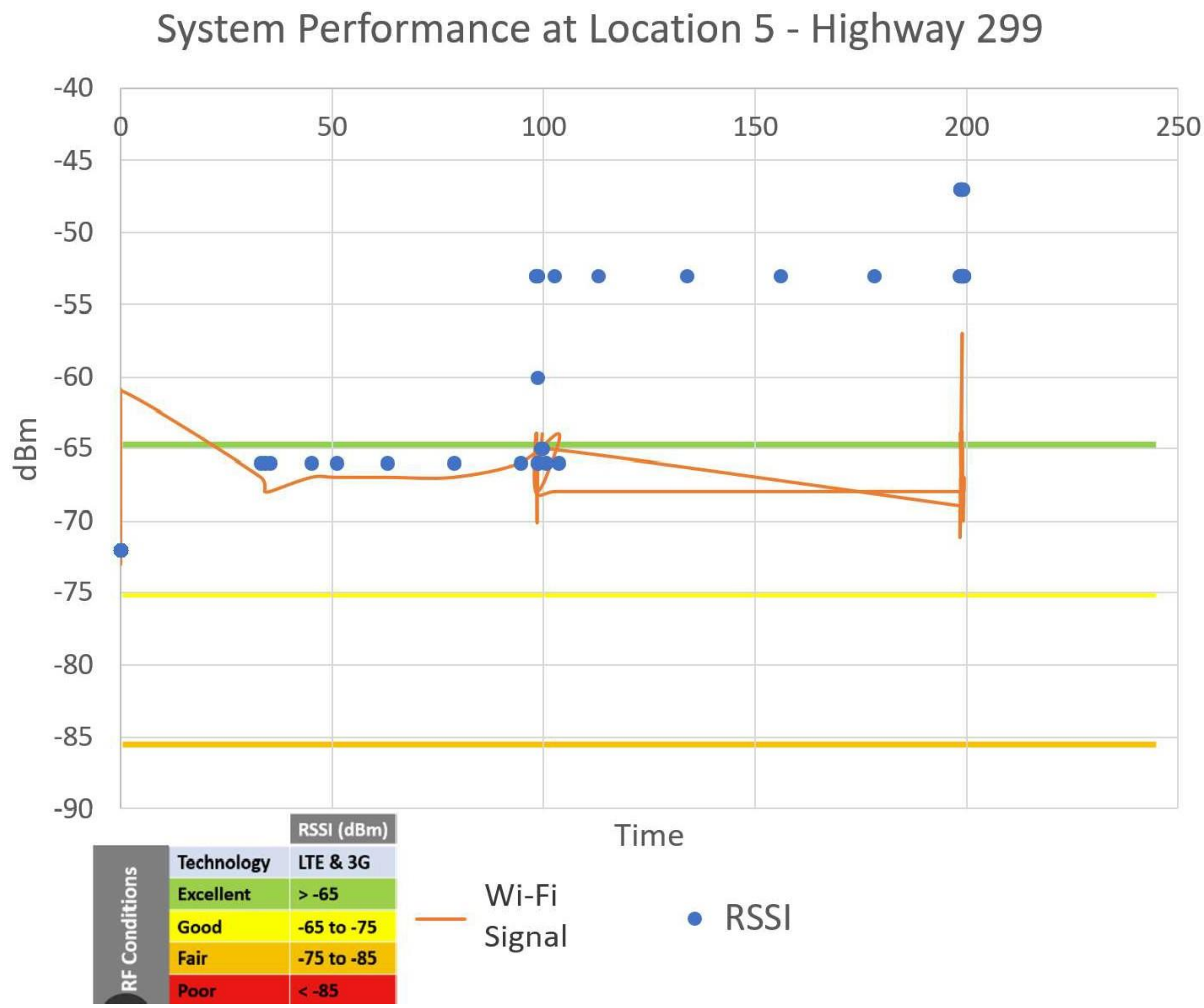

Figure 5.10: UAS system performance using Proxicast antenna at Location 5. RSSI data represents the LTE signal performance at various AGLs. Wi-Fi signal data represents the Wi-Fi connection performance from the modem to the Wi-Fi client.

Observation from Figures 5.9 and 5.10:

- LTE signal before using the UAS system: -72 dBm at 0 AGL.
- LTE signal after using the UAS system: -47 dBm at 200 feet AGL (best recorded value).
- The AHMCT team did not ascend the UAS system higher than 200 feet AGL, due to an aviation alert in the area.

Overall Result on Highway 299

Table 5.3 provides a summary of the data results for Highway 299.

Table 5.3: Summary of the data results for Highway 299

Location	Original Internet Quality (based on Verizon service)	AGL (feet)	LTE Signal RSSI Reading (dBm)	Internet Connection Download Speed (Mb/s)	Internet Connection Upload Speed (Mb/s)	Latency (millisecond)	Retransmission (%)	Email latency or possibility (in second or Y/N)	VoIP (Yes or No)
1 (First run – using Bingfu antenna)	1 bar, un-usable internet	0	-86	Took too long to respond					No
		200	-84	Took too long to respond				7.58	Yes
		350	-67	42.93	2.88	70	1.46	3.9	Yes
1 (Second run – using Proxicast antenna)	1 bar, un-usable internet	0	-83	Did not perform testing at this height					N/A
		200	-77	20.73	3.26	78	18.96	Yes	Yes
2	No service	0	-125	No signal captured					No
		350	-125						No
3	No service	0	-125	Signal captured, but was unusable					No
		400	-84						No
4		0	-76						Yes

Location	Original Internet Quality (based on Verizon service)	AGL (feet)	LTE Signal RSSI Reading (dBm)	Internet Connection Download Speed (Mb/s)	Internet Connection Upload Speed (Mb/s)	Latency (millisecond)	Retransmission (%)	Email latency or possibility (in second or Y/N)	VoIP (Yes or No)
	1 bar, slow internet	100	-76	Internet data was not recorded as the signal at ground level was already strong after connecting to the UAS system					Yes
		200	-76						Yes
5	1 bar, un-usable internet	0	-72	41.58	1.44	62	0.01	5.38	Yes
		100	-53	32.33	4.81	63	0.13	13.53	Yes
		200	-47	95.81	14.22	51	0.01	8.88	Yes

Notes: 1) The original internet quality was assessed using an iPhone with Verizon service. 2) The LTE signal strength was obtained from the RSSI reading collected from the modem. 3) Internet download and upload speeds, latency, and retransmissions were measured using the internet speed test application on an iPhone 16 browser while connected to the UAS system network, with no SIM card installed. 4) Email latency was recorded using a timer. The sender notified the receiver when the "send" button was pressed, and the receiver stopped the timer upon receiving the email. 5) VOIP performance was tested by having the caller place a call while using the UAS system network. The SIM card was removed or the service was disabled to ensure that the call connection relied solely on the UAS system.

Figures 5.11 through 5.22 provide illustrations depicting the testing results of the UAS system at each location for Highway 70. Observations on the data are noted for each location.

Highway 70

Location 6

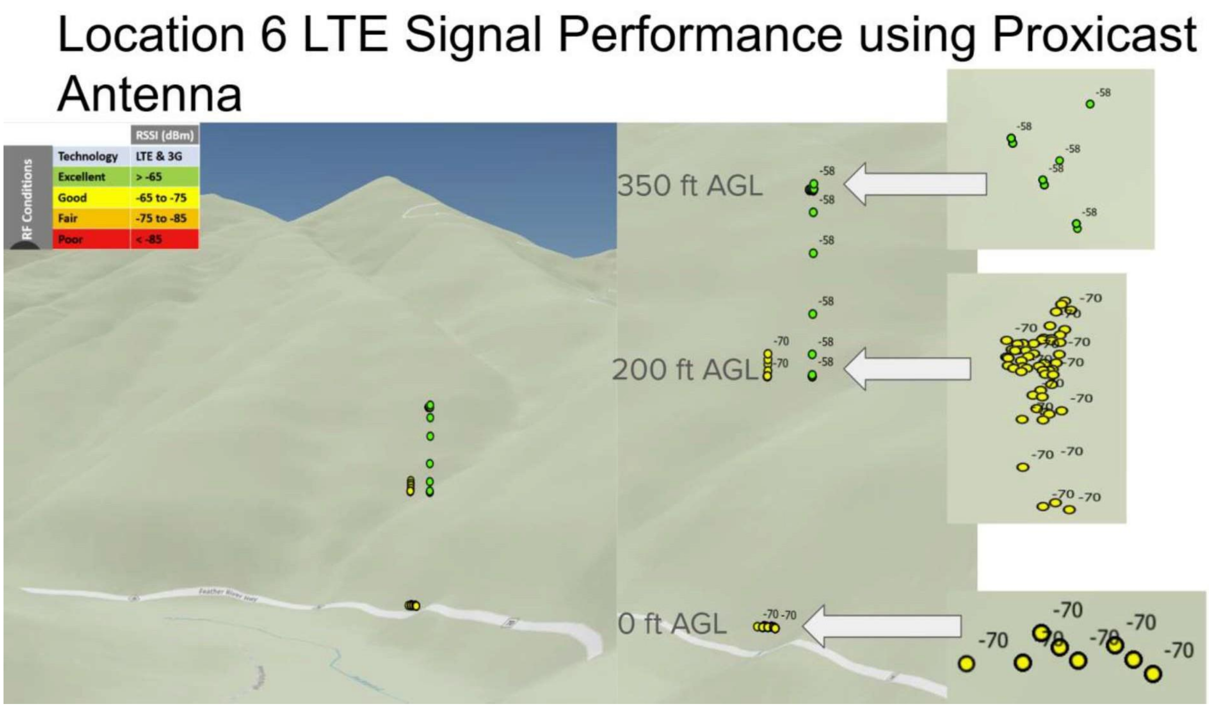

Figure 5.11: LTE signal performance using the UAS system with Proxicast antenna at Location 6. Map generated using ArcGIS software by Esri.

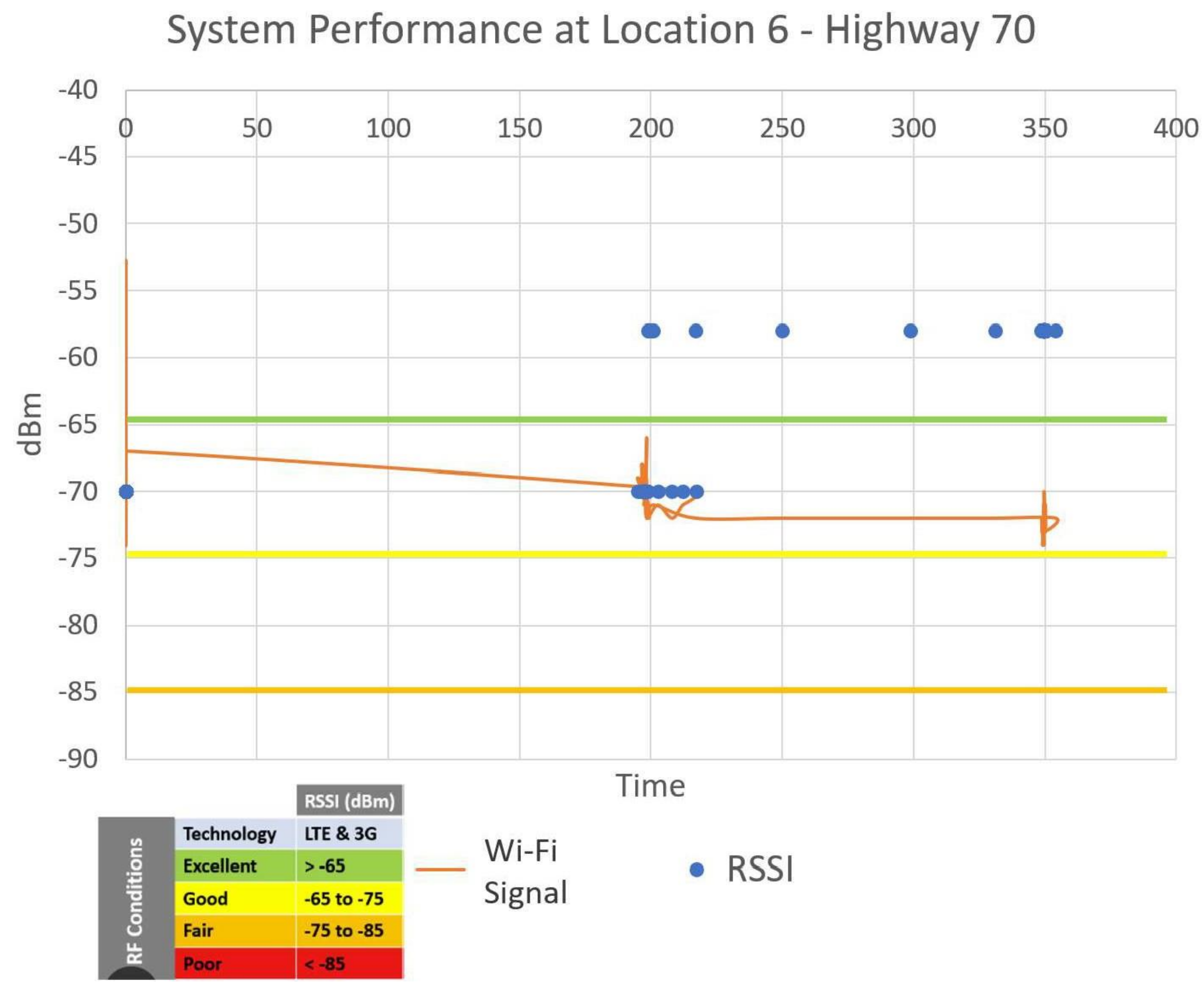

Figure 5.12: UAS system performance using Proxicast antenna at Location 6. RSSI data represents the LTE signal performance at various AGLs. Wi-Fi signal data represents the Wi-Fi connection performance from the modem to the Wi-Fi client.

Observation from Figures 5.11 and 5.12:

- As the UAS system ascended, LTE signal improved, but Wi-Fi connection degraded.
- LTE signal before using the UAS system: -70 dBm at 0 AGL.
- LTE signal after using the UAS system: -58 dBm at 200 feet AGL and stayed stable (at -58 dBm) at 350 feet AGL (best recorded value).

Location 7

Location 7 LTE Signal Performance using Proxicast Antenna

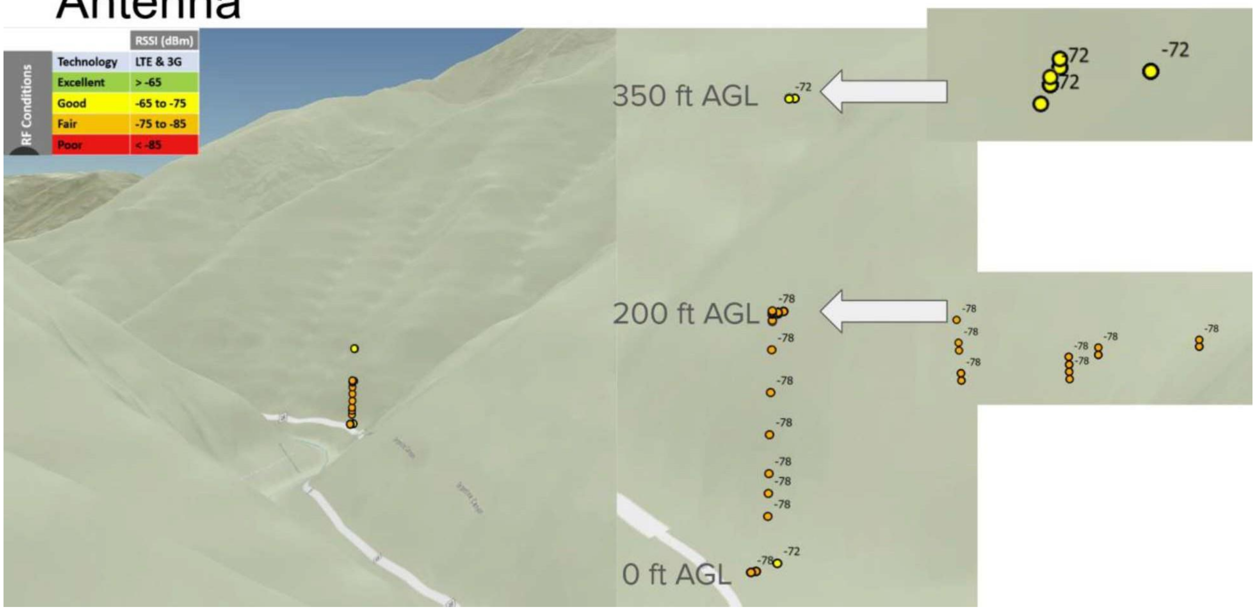

Figure 5.13: LTE signal performance using the UAS system with Proxicast antenna at Location 7. Map generated using ArcGIS software by Esri.

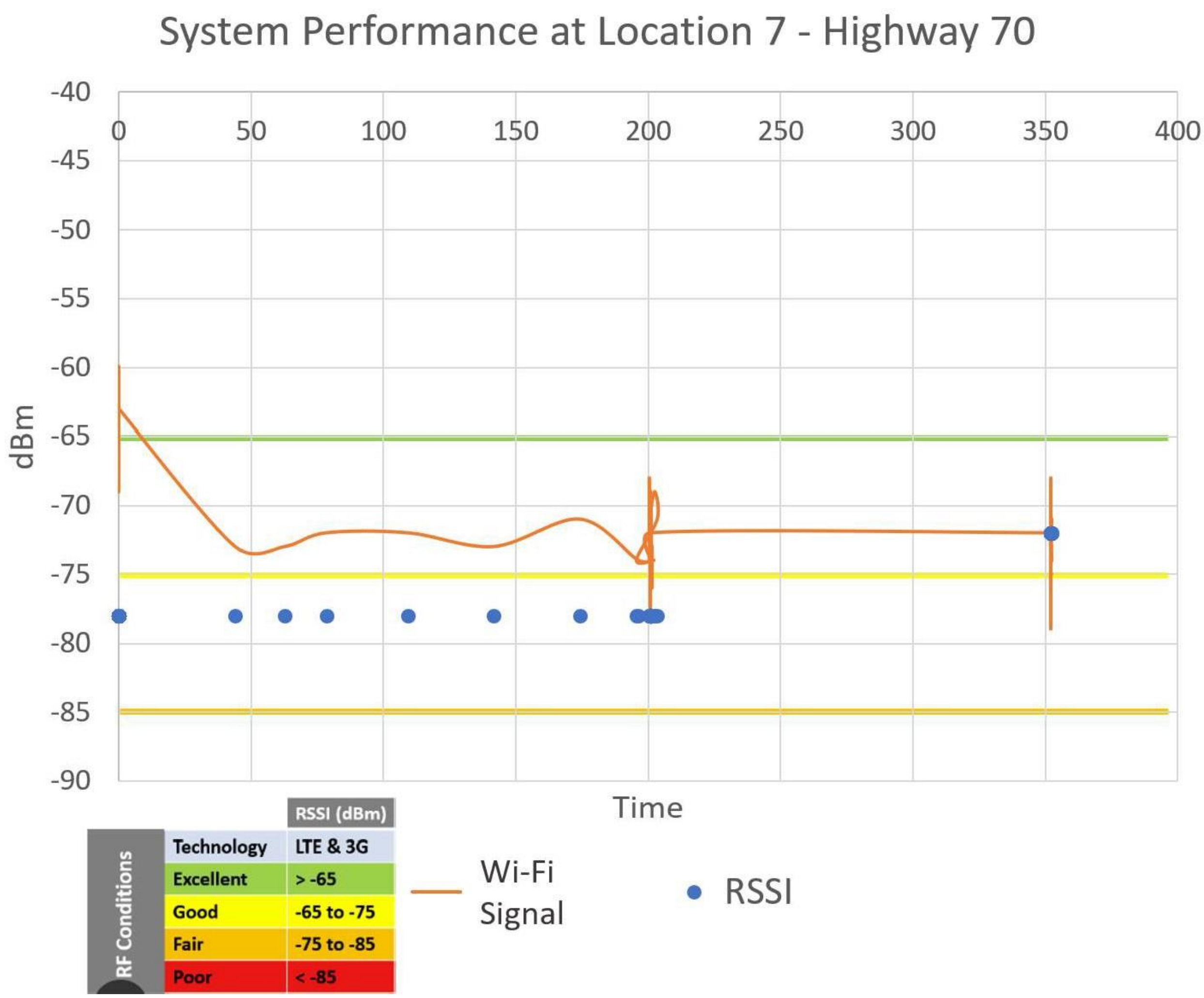

Figure 5.14: UAS system performance using Proxicast antenna at Location 7. RSSI data represents the LTE signal performance at various AGLs. Wi-Fi signal data represents the Wi-Fi connection performance from the modem to the Wi-Fi client.

Observation from Figures 5.13 and 5.14:

- As the UAS system ascended, LTE signal improved, but Wi-Fi connection degraded.
- LTE signal before using the UAS system: -78 dBm at 0 AGL.
- LTE signal after using the UAS system: -72 dBm at 350 feet AGL (best recorded value).

Location 8

Location 8 LTE Signal Performance using Proxicast Antenna

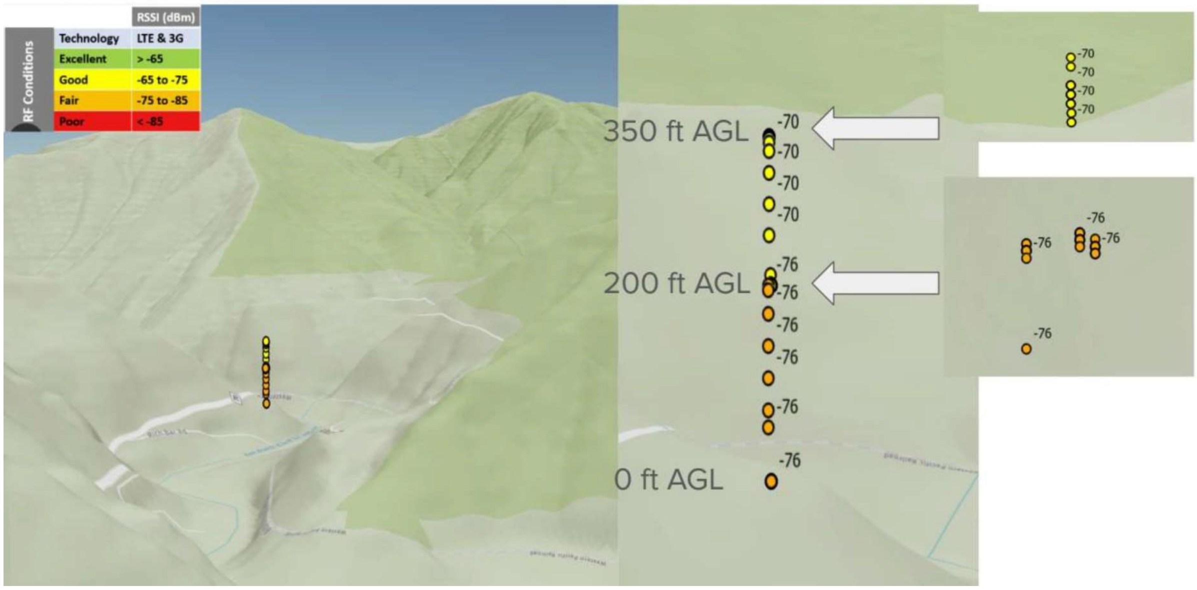

Figure 5.15: LTE signal performance using the UAS system with Proxicast antenna at Location 8. Map generated using ArcGIS software by Esri.

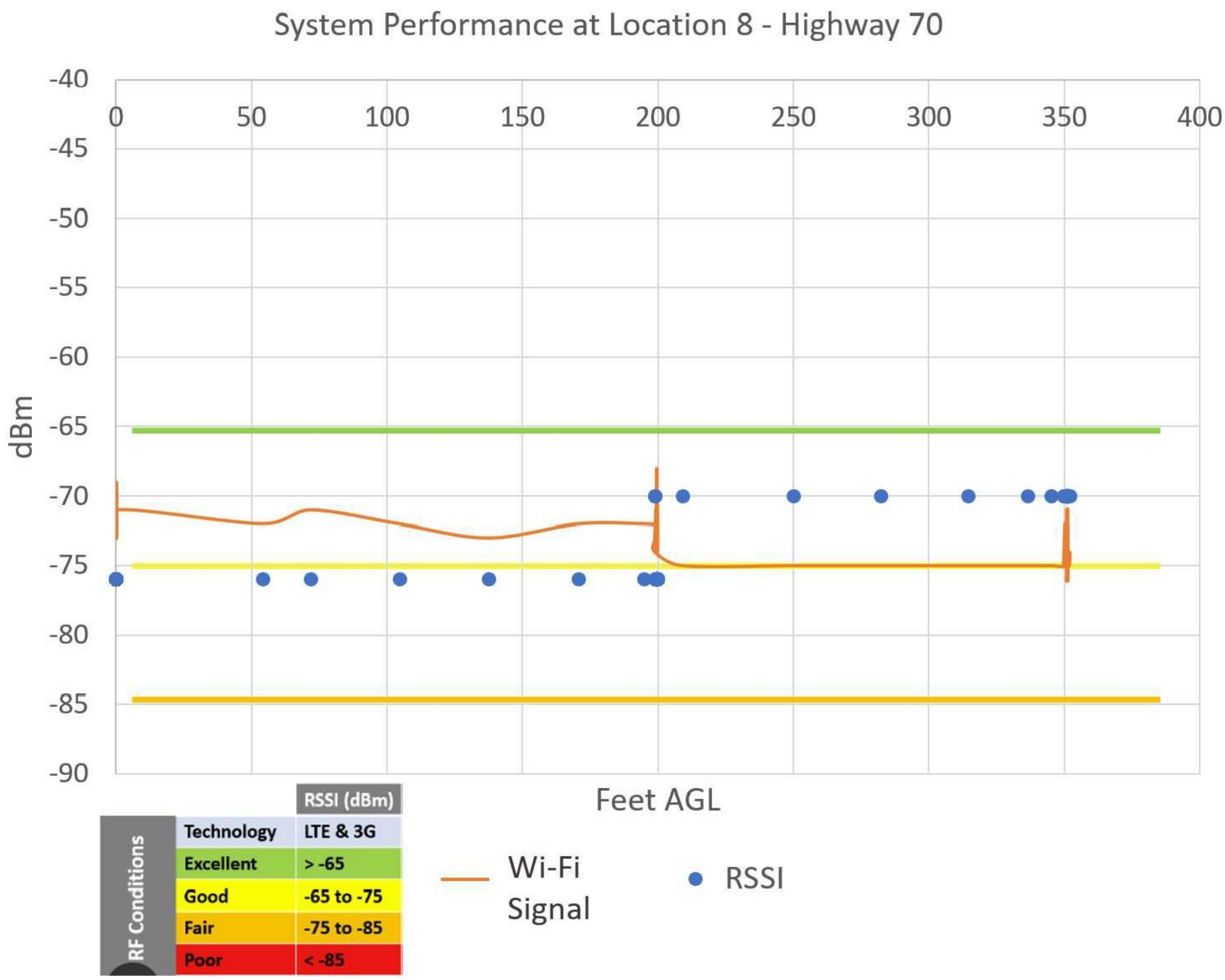

Figure 5.16: UAS system performance using Proxicast antenna at Location 8. RSSI data represents the LTE signal performance at various AGLs. Wi-Fi signal data represents the Wi-Fi connection performance from the modem to the Wi-Fi client.

Observation from Figures 5.15 and 5.16:

- As the UAS system ascended, LTE signal improved, but Wi-Fi connection degraded.
- LTE signal before using the UAS system: -76 dBm at 0 AGL.
- LTE signal after using the UAS system: -70 dBm at 200 feet AGL and stayed stable (at -70 dBm) at 350 feet AGL (best recorded value).

Location 9

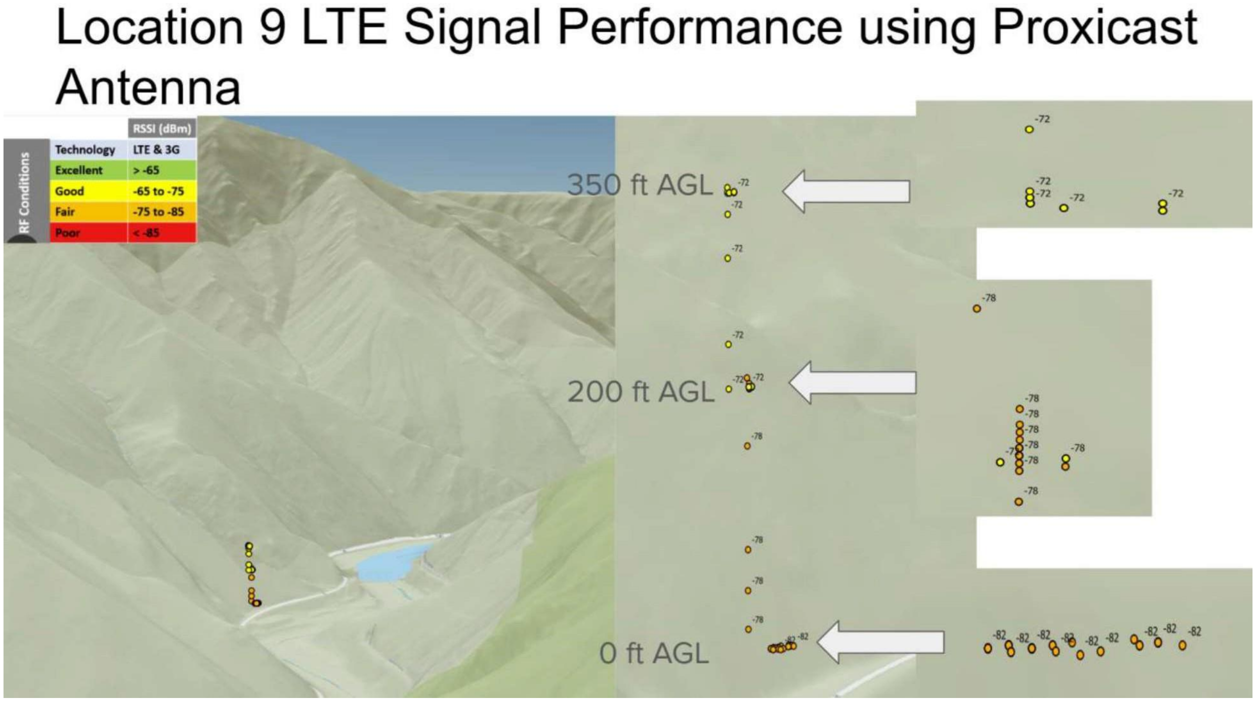

Figure 5.17: LTE signal performance using the UAS system with Proxicast antenna at Location 9. Map generated using ArcGIS software by Esri.

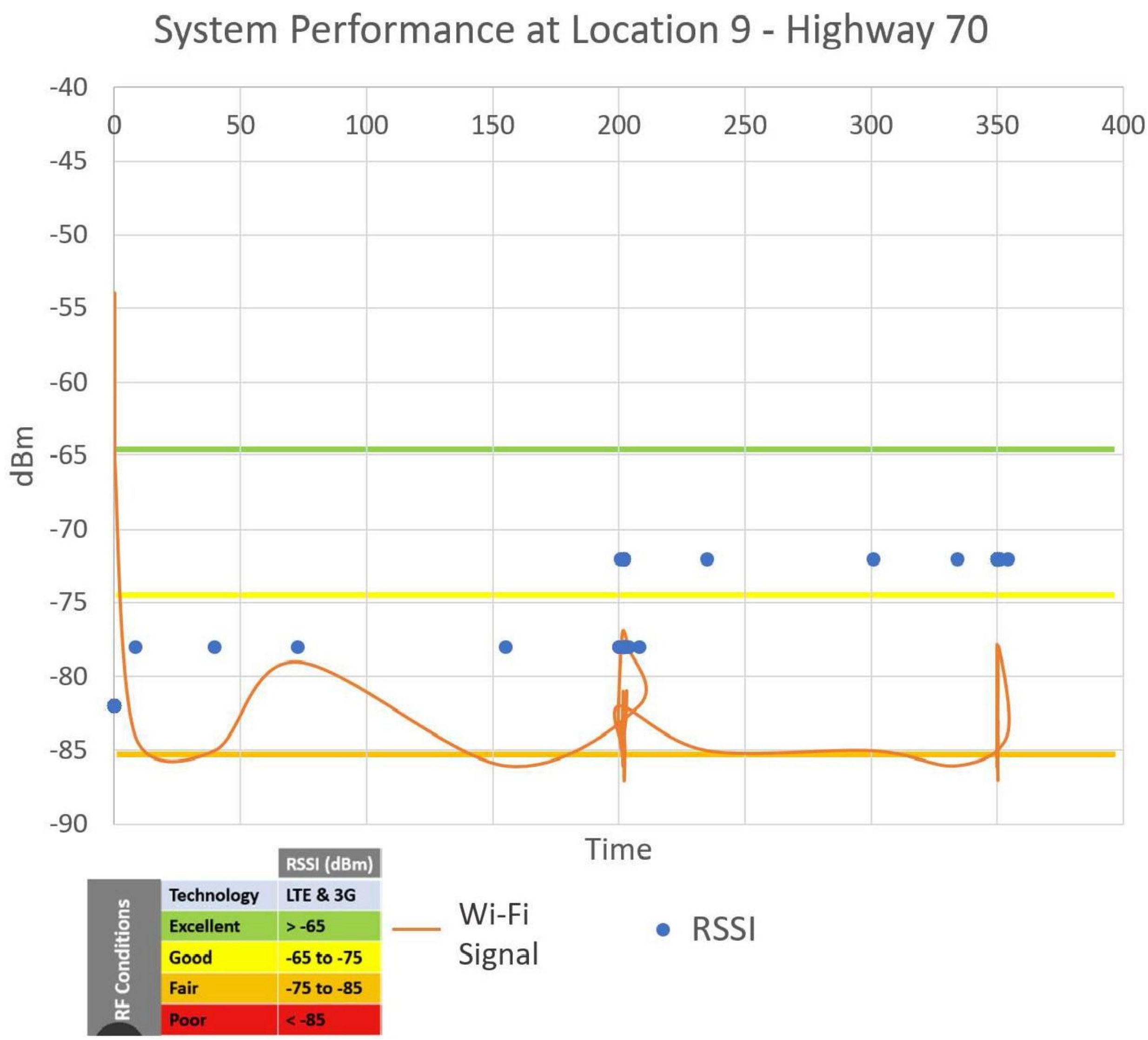

Figure 5.18: UAS system performance using Proxicast antenna at Location 9. RSSI data represents the LTE signal performance at various AGLs. Wi-Fi signal data represents the Wi-Fi connection performance from the modem to the Wi-Fi client.

Observation from Figures 5.17 and 5.18:

- As the UAS system ascended, LTE signal improved, but Wi-Fi connection degraded.
- LTE signal before using the UAS system: -82 dBm at 0 AGL.
- LTE signal after using the UAS system: -72 dBm at 350 feet AGL (best recorded value).

Location 10

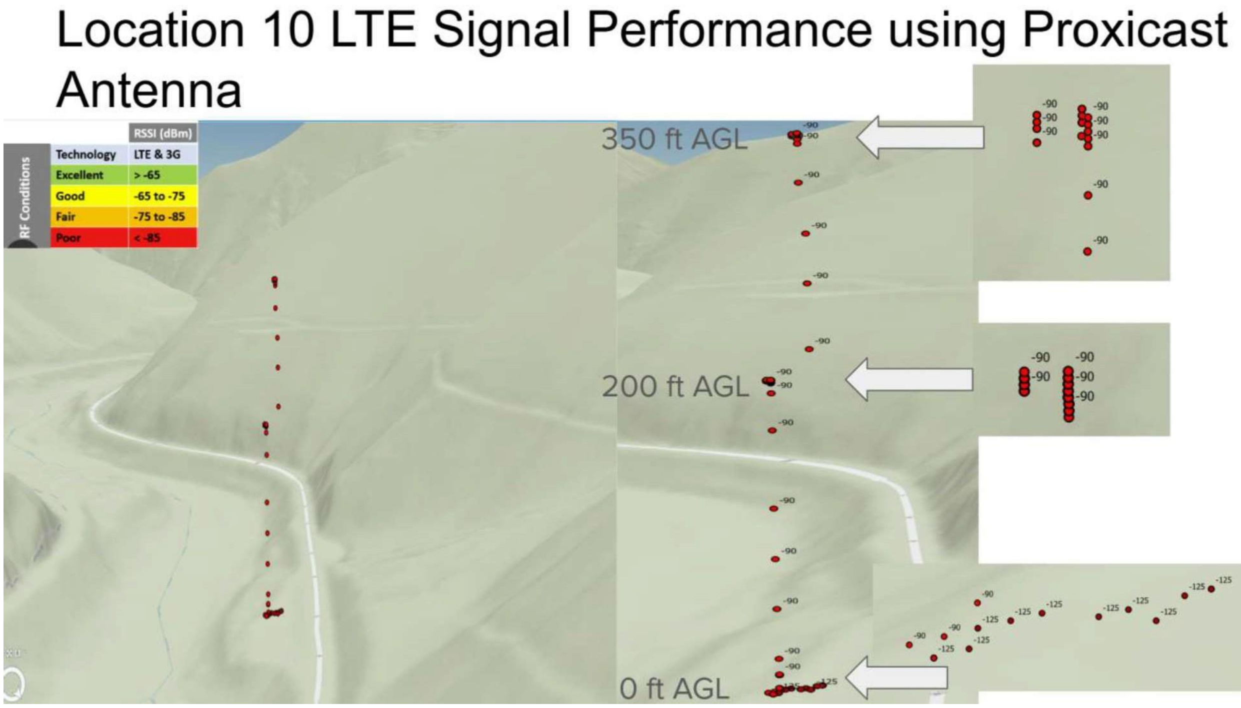

Figure 5.19: LTE signal performance using the UAS system with Proxicast antenna at Location 10. Map generated using ArcGIS software by Esri.

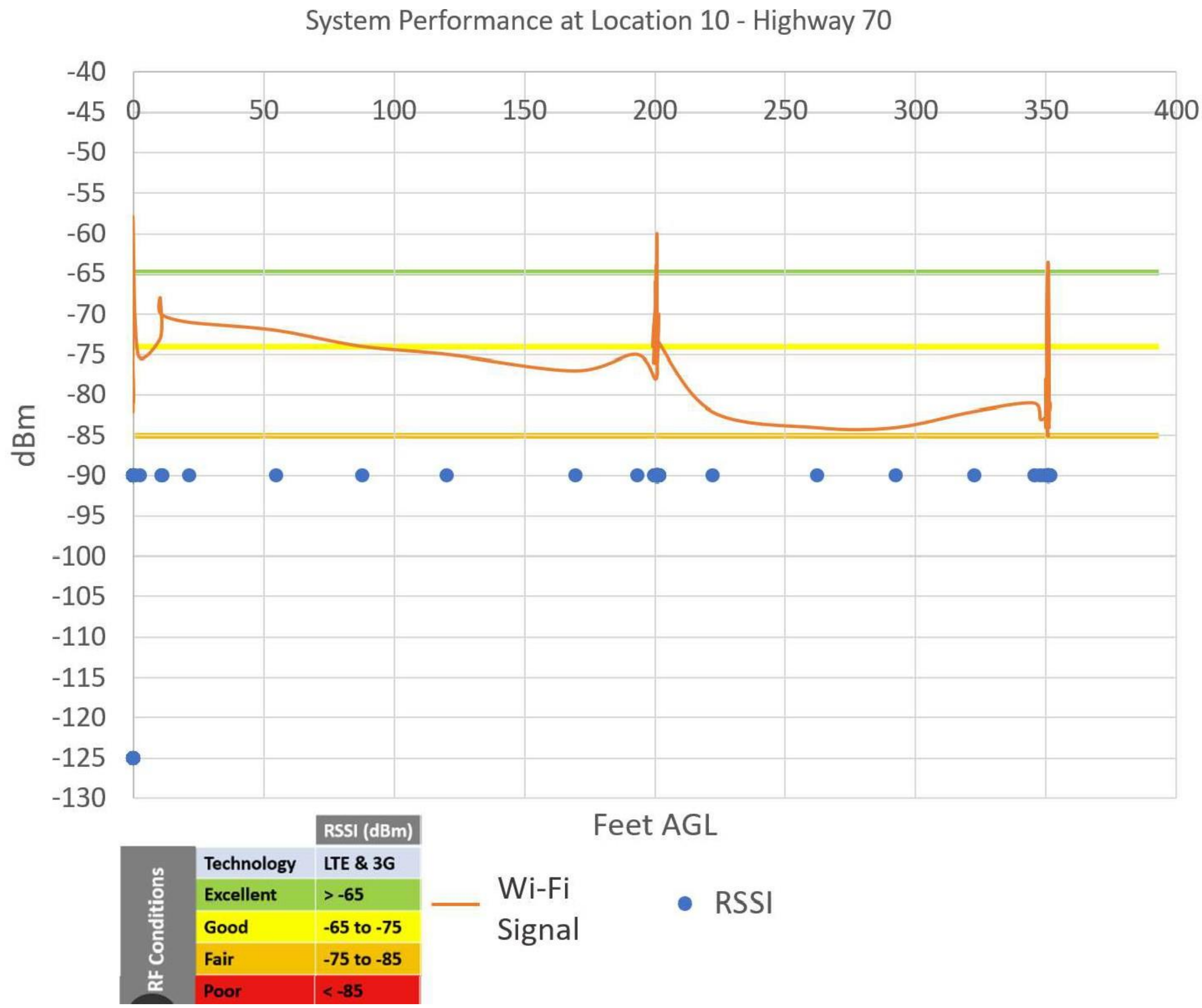

Figure 5.20: UAS system performance using Proxicast antenna at Location 10. RSSI data represents the LTE signal performance at various AGLs. Wi-Fi signal data represents the Wi-Fi connection performance from the modem to the Wi-Fi client.

Observation from Figures 5.19 and 5.20:

- As the UAS system ascended, LTE signal improved, but Wi-Fi connection degraded.
- LTE signal before using the UAS system: -125 dBm at 0 AGL.
- LTE signal after using the UAS system: -90 dBm at 200 feet AGL (best recorded value).
- LTE signal was usable at 200 feet AGL, but not at 350 feet AGL due to the Wi-Fi antenna performance degraded as the UAS system ascended.

Location 11

Location 11 LTE Signal Performance using Proxicast Antenna

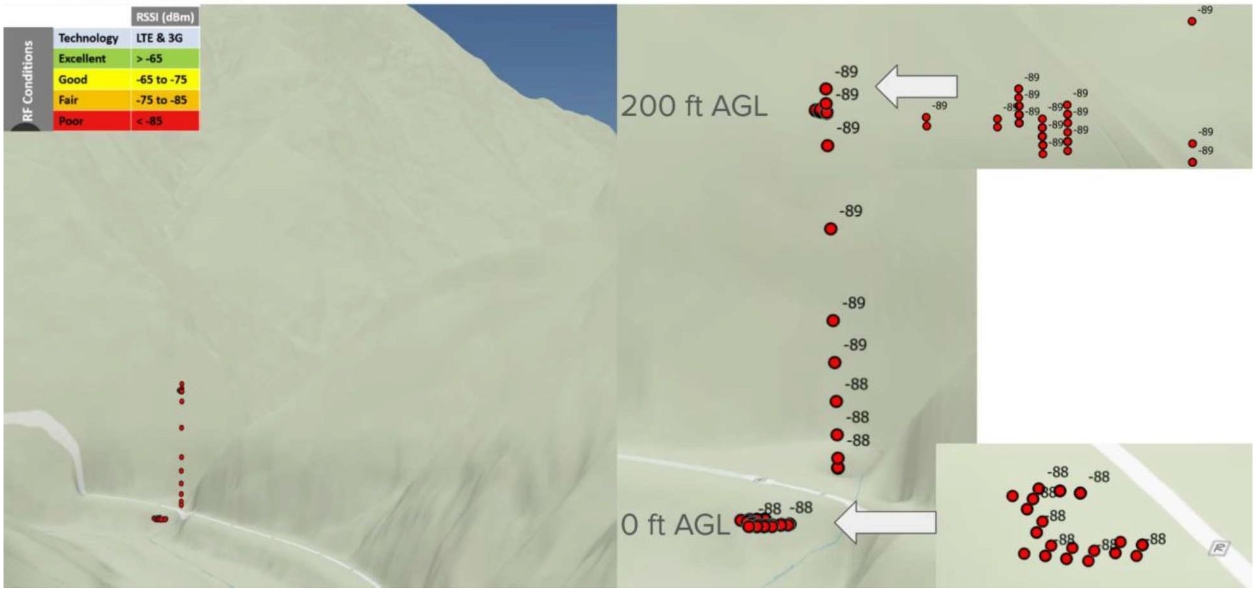

Figure 5.21: LTE signal performance using the UAS system with Proxicast antenna at Location 11. Map generated using ArcGIS software by Esri.

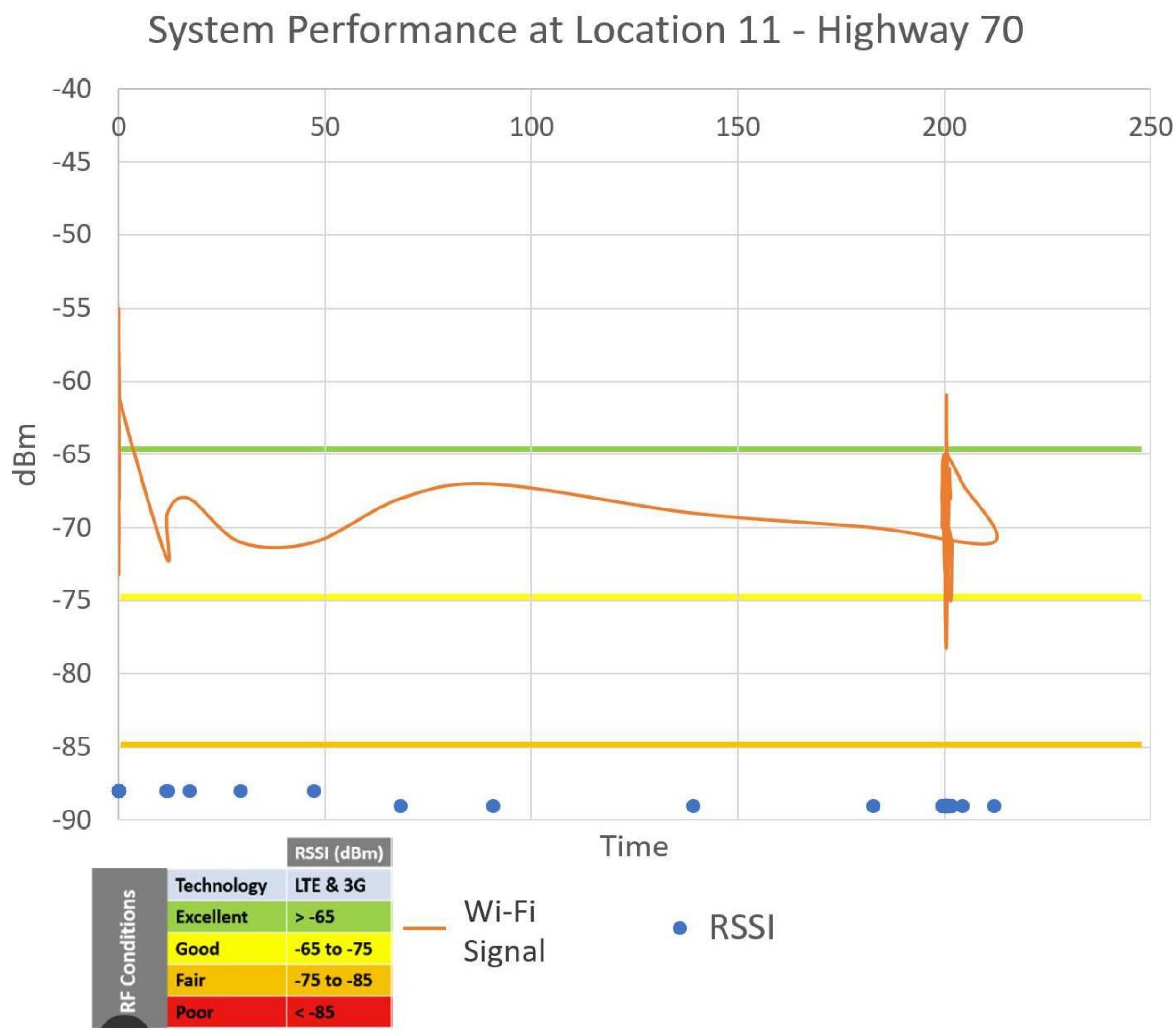

Figure 5.22: UAS system performance using Proxicast antenna at Location 11. RSSI data represents the LTE signal performance at various AGLs. Wi-Fi signal data represents the Wi-Fi connection performance from the modem to the Wi-Fi client.

Observation from Figures 5.21 and 5.22:

- LTE signal before using the UAS system: -89 dBm at 0 AGL.
- LTE signal after using the UAS system: -89 dBm at 200 feet AGL (best recorded value).
- Testing was interrupted due to a helicopter drill occurring in the area. Hence, the AHMCT team was unable to determine whether the LTE signal would improve over time, as the test duration was less than five (5) minutes.

Overall Result on Highway 70

Table 5.4 provides a summary of the data results for Highway 70.

Table 5.4: Summary of the data results for Highway 70

Location	Original Internet Quality (based on Verizon service)	AGL (feet)	LTE Signal RSSI Reading (dBm)	Internet Connection Download Speed (Mb/s)	Internet Connection Upload Speed (Mb/s)	Latency (millisecond)	Retransmission (%)	Email latency or possibility (in second or Y/N)	VoIP (Yes or No)
6	1 bar, slow internet	0	-70	14.97	2.41	59	0.22	5.31	Yes
		200	-58	5.30	2.76	59	0	2.46	Yes
		350	-58	9.45	5.12	105	0.04	8.44	Yes
7	1 bar, un-usable internet	0	-78	3.17	0.28	69	0	5.31	Yes
		200	-78	2.16	0.15	65	0.06	2.46	Yes
		350	-72	1.04	0.60	64	0	8.44	Yes
8	1 bar, un-usable internet	0	-76	2.10	0.83	71	0	9.14	Yes
		200	-76	6.24	1.62	61	1.47	9.82	Yes
		350	-70	3.90	1.87	62	0	9.66	Yes
9	1 bar, un-usable internet	0	-82	6.05	0.08	65	1.40	5.46	Yes
		200	-78	4.59	2.60	65	0	6.98	Yes
		350	-72	3.15	1.89	59	0	13.33	Yes

Location	Original Internet Quality (based on Verizon service)	AGL (feet)	LTE Signal RSSI Reading (dBm)	Internet Connection Download Speed (Mb/s)	Internet Connection Upload Speed (Mb/s)	Latency (millisecond)	Retransmission (%)	Email latency or possibility (in second or Y/N)	VoIP (Yes or No)
10	No service	0	-125	Took too long to respond					No
		200	-90	1.42	0.01	84	0	17.16	Yes
		350	-90	Took too long to respond					No
11	No service	0	-89	Helicopter drill, had to stop testing					No
		200	-89						No

Notes: 1) The original internet quality was assessed using an iPhone with Verizon service. 2) The LTE signal strength was obtained from the RSSI reading collected from the modem. 3) Internet download and upload speeds, latency, and retransmissions were measured using the internet speed test application on an iPhone 16 browser while connected to the UAS system network, with no SIM card installed. 4) Email latency was recorded using a timer. The sender notified the receiver when the "send" button was pressed, and the receiver stopped the timer upon receiving the email. 5) VOIP performance was tested by having the caller place a call while using the UAS system network. The SIM card was removed or the service was disabled to ensure that the call connection relied solely on the UAS system.