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Executive Summary

Transit technology is becoming more ubiquitous and often depends on the ability to receive and transmit data packages. Internet connectivity gaps have been identified as a critical barrier to successful transit technology implementation. The California Integrated Travel Project (Cal-ITP) is working to identify possible solutions to this challenge. While some of the connectivity issues may be resolved by building out the telecom network in the future, critical areas without network connectivity will likely remain given California's geography (e.g., mountainous and heavily forested in some areas). Cal-ITP is investigating one potential solution to the connectivity challenge: satellite systems.

Cal-ITP's research is designed to test the feasibility of satellite antenna connectivity on moving vehicles. It seeks to answer the core question: **Can Starlink satellite antennas offer a viable connectivity solution for rural transit agencies in California?**

Satellite antenna testing began with Trinity Transit in October 2023 and continued for four months. During this testing period, the research team evaluated plain upload and download speed measurements, drip activity (e.g., GTFS-RT position updates), and burst activity (e.g., payment processing). The tests were modeled off the previously cellular network connectivity tests.

The research empirically showed that satellite antenna connectivity outperformed traditional cellular connectivity in two ways:

1. **Lack of Dead Zones -** The satellite antenna provided a level of connectivity which resulted in no visible dead zones in the mapping software, as compared to the cellular network, which offered approximately 50% route coverage.
2. **High Transmission Success Rate -** The satellite antenna had a transmission success rate of 99.5% and experienced only one major outage due to extenuating circumstances.

Acknowledgements

The Cal-ITP research team would like to acknowledge several key partners who made this work possible.

Thank you to Sean Campbell and his team at the Caltrans Department of Transportation Division of Research, Innovation and System Information. DRISI graciously allowed the Cal-ITP team to utilize a Starlink satellite antenna to conduct this research. Without this collaboration, our research would have ended before it began.

Thank you to Sarah Saad and her team at Trinity Transit, who jumped head first into this testing and trusted in the process. Sarah's patience, commitment, and flexibility is the true reason the Cal-ITP team was able to gather data to support the findings of this report. We hope our work can help Trinity Transit be that much closer to finding a connectivity solution to support all their transit technology goals.

Introduction

As the world becomes more digitized, transit agencies throughout the state of California are looking to leverage new technologies to improve the rider experience. The large majority of these transit technologies depend on the ability to receive and transmit data packages. Internet connectivity gaps have been identified as a critical barrier to successful transit technology implementation. While some of the connectivity issues may be resolved by building out the telecom network in the future, critical areas without network connectivity will likely remain given California's geography (e.g., mountainous and heavily forested in some areas). The California Integrated Travel Project (Cal-ITP) is investigating one potential solution to the connectivity challenge: satellite systems.

As a result of advances in innovative technological solutions, satellite systems have become an increasingly affordable solution to provide consistent, high-frequency telecommunications access (Burleigh et al., 2019). These systems typically use antennas to tap into the satellite network and can provide real-time information (e.g., vehicle location) and support tasks like data transfers, which are necessary for some transit technologies (e.g., open-loop payment acceptance) (UtilitiesOne, 2023). Exploratory studies have found that satellite antennas can be mounted on mobile infrastructure, like public transit buses, providing connectivity over larger, more geographically challenging areas (Boyle, 2019; Battle Memorial Institute, 2019). This research builds upon preliminary satellite system connectivity findings from other researchers by testing the connectivity results of a Starlink satellite antenna mounted on a fixed route transit vehicle in Trinity County, California. This report is broken into four sections:

1. **Background:** Review of the project goals and objects
2. **Methodology:** Summary of the research phases and methods employed to complete it
3. **Findings:** List of research findings
4. **Next Steps:** Outline of potential next steps based on findings

Background

In California, research is currently underway to understand the potential for Starlink satellite antennas to fill connectivity gaps for transit operators. This work is being completed by the Advanced Highway Maintenance and Construction Technology Research Center at the University of California, Davis (UC Davis) and California Department of Transportation Division of

Research, Innovation and System Information (Caltrans DRISI). The researchers are focusing on stationary Starlink satellite antenna applications, largely regarding real-time signage alerts. Their research scope has not included "in motion" applications (i.e., mounting Starlink satellite antennas on vehicles).

Cal-ITP's research is designed to fill this gap and test the feasibility of satellite antenna connectivity on moving vehicles. It seeks to answer the core question: **Can Starlink satellite antennas offer a viable connectivity solution for rural transit agencies in California?** Prior to the field testing, a preliminary feasibility report confirmed the hypothetically feasibility of the transit application.

UC Davis, Caltrans DRISI, and Cal-ITP chose to test Starlink over other satellite providers and systems because of Starlink's satellite system capacity. Starlink satellites are located much closer to the Earth's orbit than other satellite systems (550 kilometers compared to 2,000 to 36,000 kilometers) (Aerospace Security, 2022). This relative proximity results in improved connectivity latency, the time it takes for data to be transmitted between a sender and receiver (25 to 50 milliseconds [MS] compared to 500+ ms) (Kan, 2024; Starlink, n.d.). The improved connectivity latency is critical for supporting new transit technologies.

Methodology

Answering the research question involved three steps: pre-installation testing, installation, and operation and data collection. Further information on the research steps and findings from hardware testing can be found in the subsections below.

The testing was made possible through collaboration with Caltrans DRISI, who provided the Cal-ITP team with one Flat High Performance Starlink satellite antenna to use for this research. The antenna was loaned to Cal-ITP from October 2023 through February 2024, at which point DRISI planned to recommence testing stationary application.

Pre-Installation Testing

Upon receiving the Starlink satellite antenna, the Cal-ITP research team began bench testing to verify basic functionality. These preliminary tests ran for several days to establish a control baseline. During these tests, the research team encountered minor challenges with initial account credential and antenna placement, all of which were resolved. The control tests demonstrated that the Starlink satellite antenna connectivity and throughput were solid.

As the control tests were run, the research team was simultaneously beginning to identify potential field testing partners. The research team sought a transit agency partner that had a pre-existing relationship with Cal-ITP, operated in a rural service area, and had a history of connectivity challenges. Trinity Transit, a transit agency in Trinity County, emerged as an ideal partner. Additionally, baseline connectivity data was already available for Trinity Transit, from a collection process that occurred during a different series of hardware testing in 2021.

The 2021 testing showed a lack of connectivity on any cellular network for more than 50% of Trinity Transit's routes, making it one of the least internet connected areas in the state. Initial conversations with other Caltrans staff and Trinity Transit personnel confirmed this assessment remained the case in 2023. Additionally, Weaverville - the main town serviced by Trinity Transit - has a history of extreme heat during the summer and significant precipitation during the winter. These weather patterns provided the added benefit of testing the equipment under more extreme conditions.

Trinity Transit Overview

Trinity Transit is a public transit agency in Northern California, operating 10 revenue vehicles which service ~6,100 annual passenger trips on its local and regional bus service (National Transit Database, 2022). The service area extends across Trinity County, a rural area with an average density of 5.1 people per square mile and a rugged, mountainous, heavily forested terrain (United States Census Bureau, 2020).

Trinity Transit confirmed their desire to partner on this field testing as the agency has a vested interest in obtaining GTFS-Realtime capabilities.

Installation

The Flat High Performance Starlink satellite antenna was installed and used in this research, as it is currently the only Starlink satellite antenna which can support in motion connectivity above 10 mph. A satellite antenna, roof mount, AC 120/240V power supply, and WiFi router were all included in the box. However, an inverter was not included in the satellite antenna purchase. This additional component was necessary to connect the satellite antenna to the 12 volts of direct current (VDC) power supply of most transit vehicles. An eight meter long cable was included and longer cables could be purchased separately, as needed.

It is important to note that the satellite antenna installation process requires cables to be punched through the roof. The Starlink satellite antenna kit included a plastic and rubber cuff that was used during installation to provide a seal around the cable hole. Protective plates were used to seal the hole upon hardware deinstallation. Using the protective plates to cover the hole, rather than completely sealing it, allowed for the potential future installation of another satellite antenna. In the transit context, the installation can be seen as no different from other mounted technology that requires internal-external connection.

In total, the installation infrastructure used and their associated costs are listed in the table below.

Table 2. Starlink Antenna Installation Capex Costs (per vehicle)

Hardware	Functionality	Cost*
Flat High Performance Starlink Antenna	Connect to the Starlink Network	$2,500.00
Inverter	Connect antenna to a power supply	$65.95
Protective Plates	Protect the mounting joint from element penetration	$10
Sealer	Protect the mounting joint from element penetration	Already stocked by the maintenance dept.
Total		**$2,575.95**

*Costs are calculated pre-taxes and for market-value purchases made in March 2024.

The research team installed the satellite antenna onto a pre-selected vehicle, and confirmed the soundness of the installation work with Trinity Transit staff prior to operation. The vehicle chosen was an older model with a non-step, composite (fiberglass and metal) roof, no utility closet, and non-standard access to vehicle power. This represented a more challenging installation scenario, allowing the research team to better understand the system's full capabilities.

The receiver was installed on the roof of an agency vehicle on October 30, 2023, where it remained until February 27, 2024 while tests were run.

To allow for independent assessment of system availability, throughput, and network coverage, the research team also installed two test devices alongside the antenna unit: a ruggedized router produced by a major transit technology brand and Raspberry Pi unit. Both additional devices had been used for the 2021 connectivity testing, allowing for comparable results. The research team set up these two devices to send data packages to a test server at predetermined intervals and to record the time for round trip transmission.

Operation and Data Testing

Satellite antenna testing began following the completion of installation and included evaluations of plain upload and download speed measurements, drip activity (e.g., GTFS-RT position updates), and burst activity (e.g., payment processing). The tests were modeled off the previous cellular network connectivity tests. The satellite antenna tests, specifically for the GTFS-RT measurements, were beneficial as they represented real-world use cases and allowed for a comparison between previously created real-time cellular connectivity-based maps with satellite connectivity. Tests were automatically run each day and generated cloud computing platform accessible logs.

There were a couple of testing phases.

1. In the first phase, the research team generated a data package request every five minutes and recorded the time for round trip transmission. Once it was established that the connection link functioned as expected, a GPS transmitter was added to the test devices.
2. Entering the second phase, the data package requests expanded to include latitude/longitude information to allow for map visualization.

3. In the final phase, the frequency of requests was shortened to every 30 seconds for increased test granularity.

Findings

The research empirically showed the satellite antenna connectivity outperforming traditional cellular connectivity in two ways:

1. **Lack of Dead Zones -** The satellite antenna provided a level of connectivity which resulted in no visible dead zones in the mapping software, as compared to the cellular network which offered approximately 50% route coverage.
2. **High Transmission Success Rate -** The satellite antenna had a transmission success rate of 99.5% and experienced only one major outage due to extenuating circumstances.

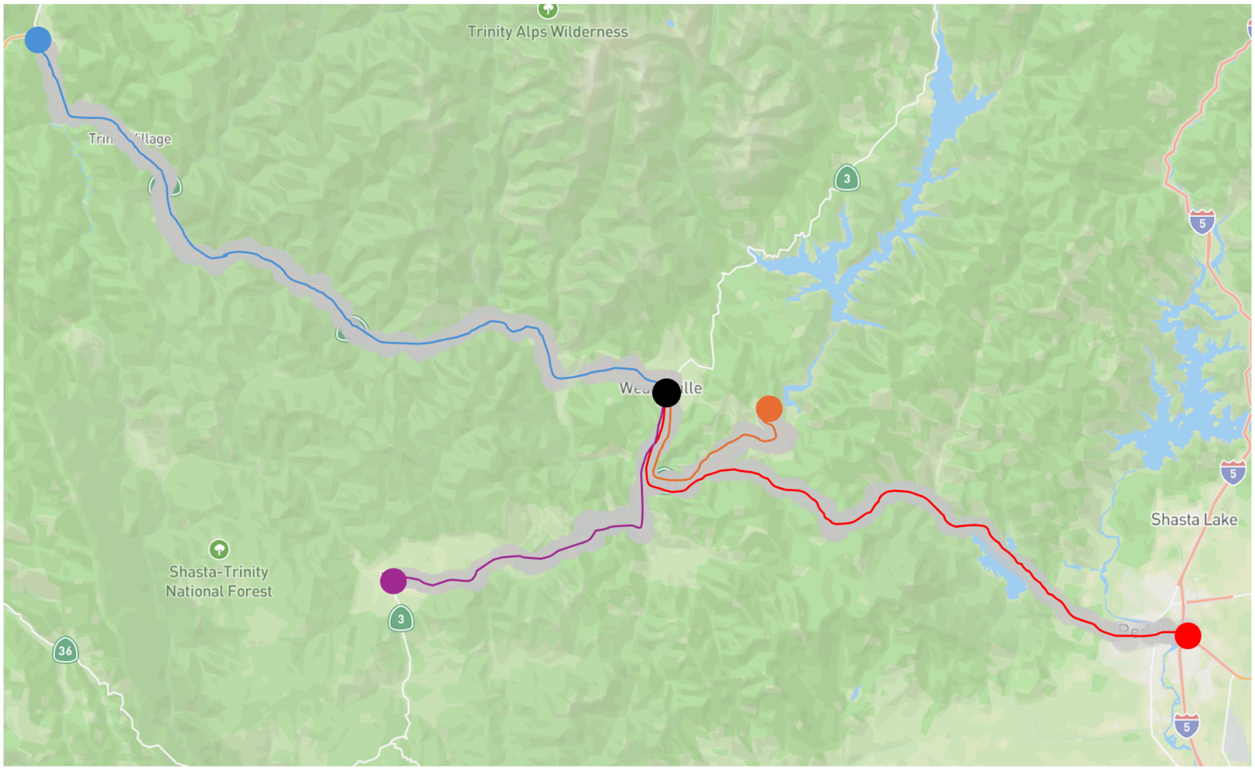
Connectivity Testing Results

As previously stated, multiple testing phases were conducted. The findings from each of these phases are summarized below.

Baseline Testing - Cellular Connectivity

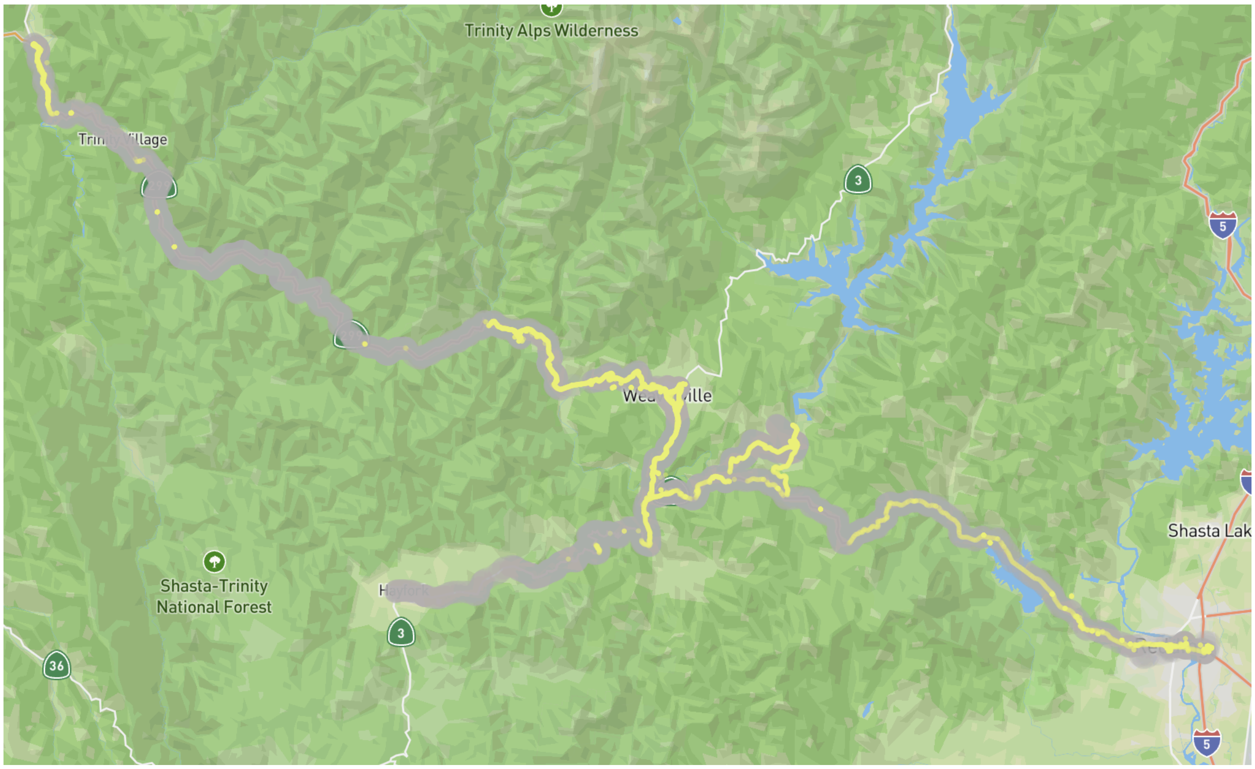
As depicted in Map 1, Trinity Transit runs four routes, all of which begin/end in Weaverville. From Weaverville, these routes go to Willow Creek (blue), Hayfork (purple), Lewiston (orange), and Redding (red).

Map 1. Trinity Transit Scheduled Routes



In 2021, the research team used the same test devices to map the connectivity of two major cellular networks: AT&T’s FirstNet and Verizon. Data packages containing latitude/longitude were requested every 30 seconds. This same methodology was replicated in Phase 2 of Starlink satellite antenna testing. The initial cellular network testing occurred over a two week period in June/July. The results are depicted in Map 2, with the gray signifying the scheduled routes and the yellow dots indicating a cellular network ping.

Map 2. Cellular Network Testing Results (2021)



This testing identified significant connectivity gaps in the Willow Creek and Hayfork routes. These dead zones were attributed to the rocky terrain of the areas, wherein the road is often partially or fully obscured by rock outcroppings and deep valleys.

Phase 1 Testing - Satellite Antenna Baseline

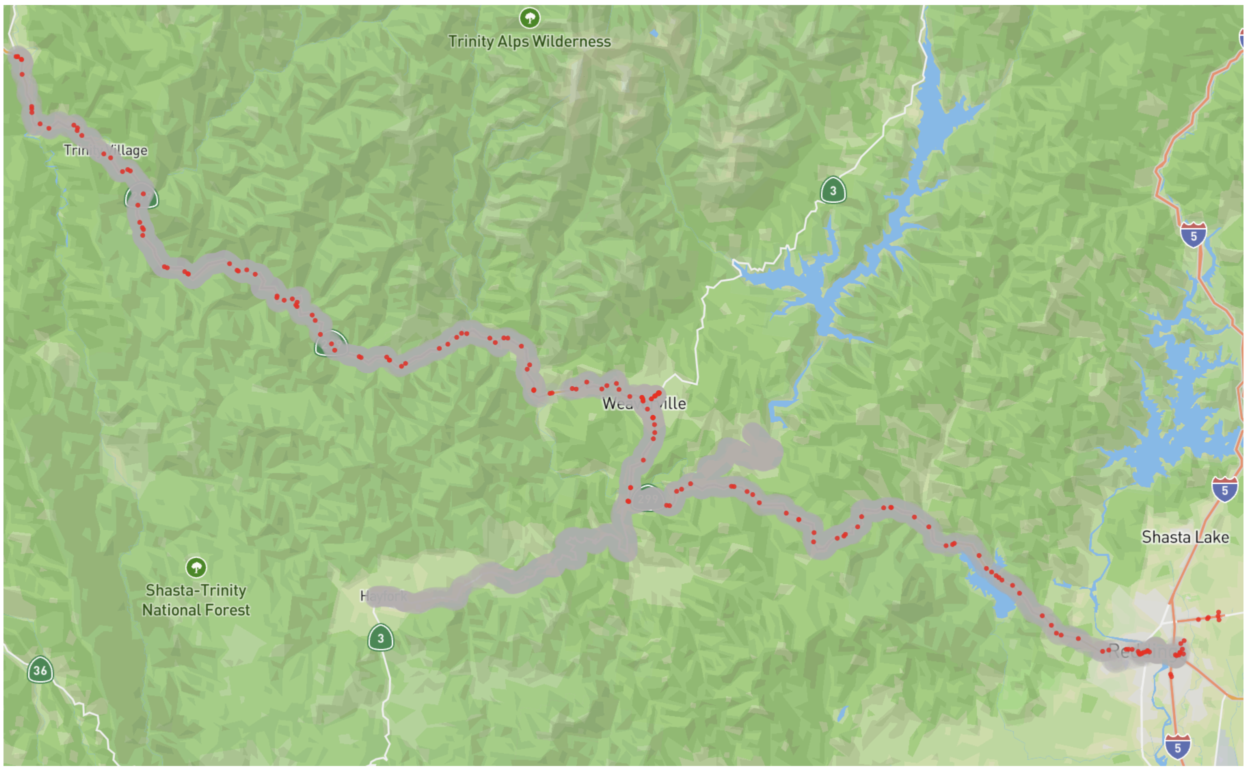
Testing for Phase 1 occurred over several weeks and focused on confirming that the satellite antenna was consistently connecting to the internet. Data package requests were sent every five minutes.

Once the baseline was confirmed, the research team added a GPS antenna in order to map the location of the pings into a visualization software.

Phase 2 Testing - Satellite Antenna & GPS at 5 Minute Pings

Phase 2 combined the five minute data package requests with the GPS coordinates. Map 3 depicts one week of testing with five minute pings, with the gray signifying the scheduled routes and the red dots indicating a satellite network ping. Note that neither the Hayfork nor the Lewiston route were tested due to driver schedules.

Map 3. Phase 2 Testing Results (5-minute requests)



The red satellite network pings appeared roughly at regular intervals, which seemed to correspond with the five-minute request parameter. To confirm this, the research team entered Phase 3.

Phase 3 Testing - Satellite Antenna & GPS at 30 Second Pings

In Phase 3, the research team increased the request frequency from five minutes to 30 seconds. Map 4 depicts two weeks of testing with 30 second pings, with the gray signifying the scheduled routes and the red dots indicating a satellite network ping.

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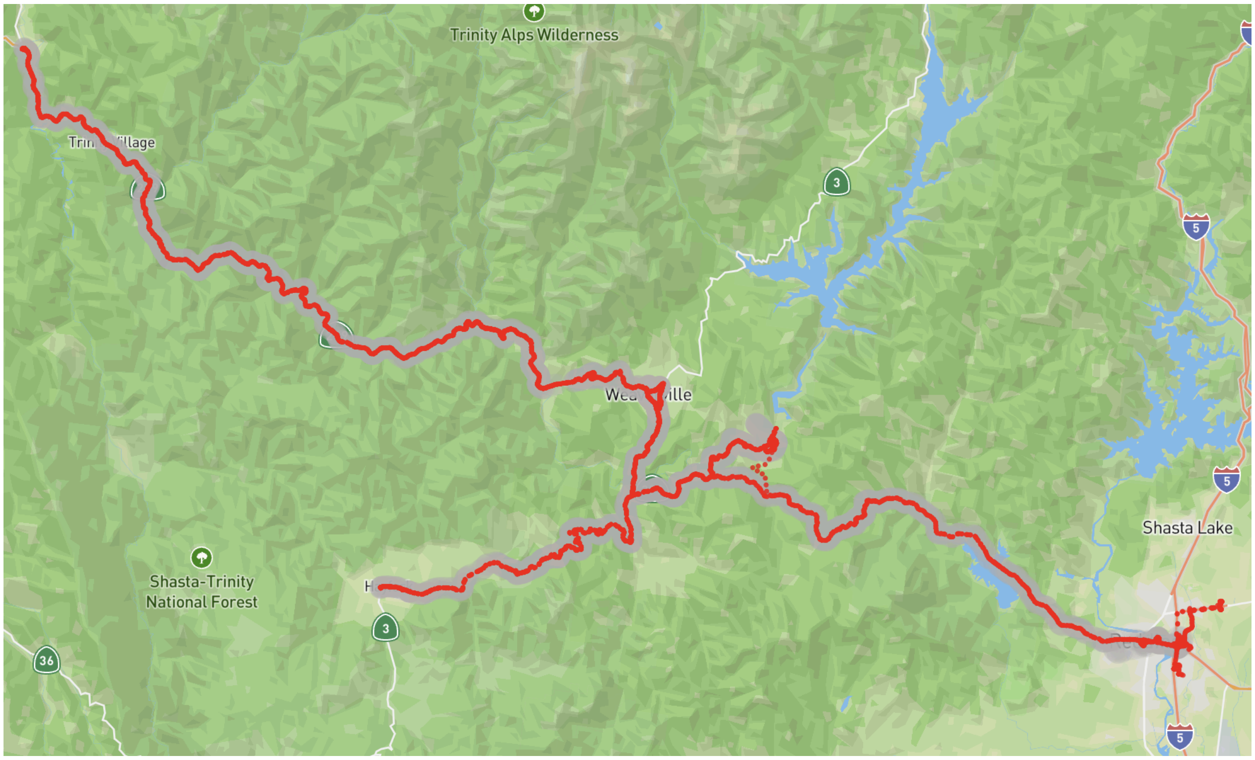
Map 4. Phase 3 Testing Results (30-second requests)



As the research team expected, the gaps seen in Phase 2 were filled by increased data request frequency. This illustrates that the gap was due to a lack of a request, not a connectivity dead zone. Overall, the results show a solid line, with the exception of a single, small break on the Hayfork route.

Satellite Antenna Evaluation

The research team overlaid the 2021 cellular connectivity results (in yellow) with the Phase 3 satellite antenna results to create a network comparison. As visually depicted in Map 5, the satellite connectivity successfully filled all identified cellular network dead zones and provided a transmission success rate of 99.5%.

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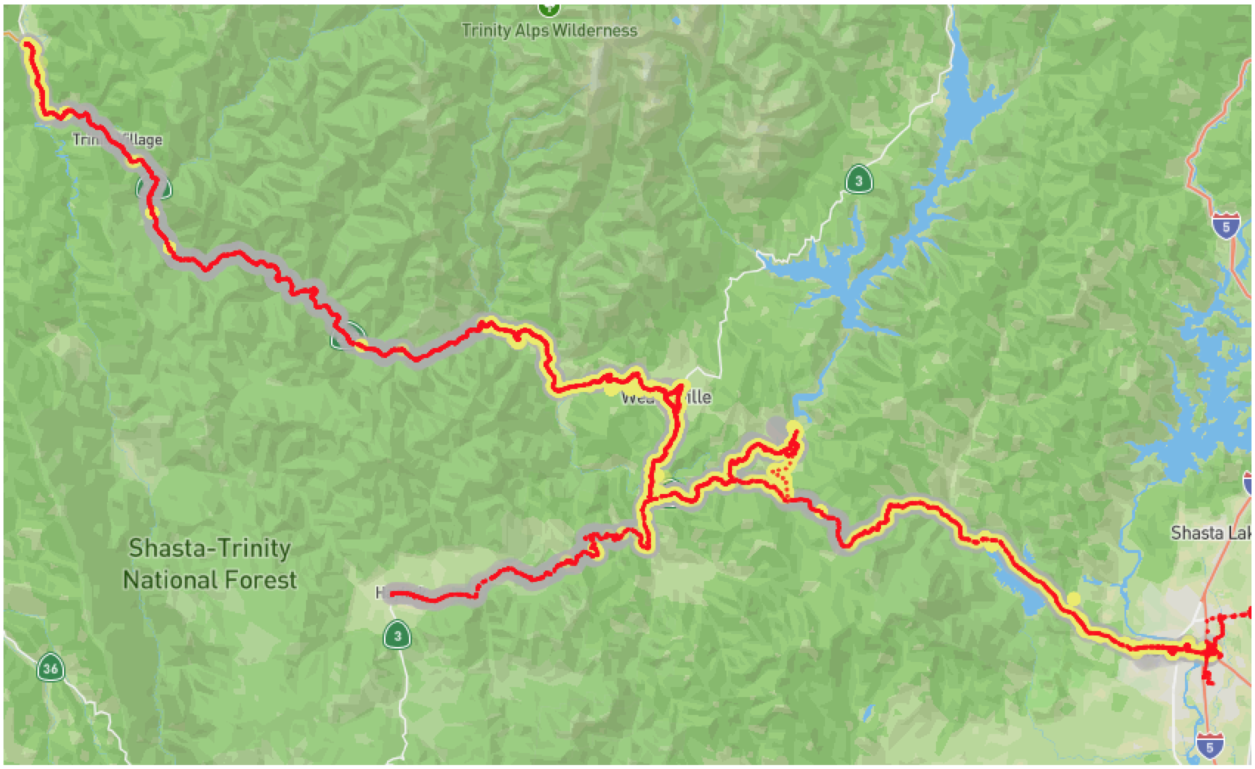
Map 5. Comparative Results (Cellular vs. Satellite Antenna Connectivity)



Satellite Antenna Performance
During the testing period, the satellite antennas performed well with high data transmission success rates and only one outage. Between October 30, 2023 and February 27, 2024, the tested satellite antenna attempted to transmit 13,939 data packets, each between two and five kilobytes, mimicking traffic that would be seen with location pings and payment verification. Of the nearly 14,000 attempts to transmit pings, 65 failed, yielding a success rate of 99.5%.

The mean nominal throughput for packages was 36 kilobit per second (kbps), but this number does not fully represent the results observed. As described in the data testing methodology, the research team measured round trip times for packet submission, from first initiating transmission until confirmation that transmission completed. This means the measurements included items such as waking networking components from sleep states, both on the antenna and the test devices. Initial tests performed after installing the antenna saw download throughput in the double-digit megabit per second (Mbps) range, as measured using commercially available mobile applications.

Only one major outage was observed, although it lasted for a few days. Remote troubleshooting eventually identified the root cause as an inadvertent factory reset of the Starlink satellite antenna unit, triggered by agency trainees jiggling the ignition key repeatedly. The reset led to the test devices being unable to connect to the satellite antenna WiFi. The research team was able to reconfigure the unit remotely and resume testing.

Lessons Learned

The research team documented the following lessons learned throughout the course of this trial. It is important to note that several of these items would have likely gone undetected with a less hands-on approach:

- **Factory Reset Considerations:** The factory reset procedure for a Starlink satellite antenna unit is initiated by power-cycling seven times, with a period of at most a couple of seconds between cycles. This approach seems less than ideal for vehicles that are used for personnel training or may have trouble starting due to inclement weather or mechanical issues.
- **Dependability:** The few observed satellite antenna system outages were traceable to external circumstances (e.g., factory reset, driver parked in hangar, etc.).
- **Ease of Maintenance and Monitoring:** The Starlink online interface allowed the research team to interface with the system and conduct routine maintenance without the need for any additional site visits. The few outages were all resolved remotely. By comparison, the ruggedized router, used as a test device and to which code was pushed, required an order of magnitude more effort to maintain.
- **Necessary Installation Training:** The installation procedure may be beyond the skills of agency personnel who are not trained for bus maintenance and repair.

Research Limitations

While this research is designed to complement other research efforts and supply initial testing findings, there are limitations that are important to note. At the time of testing (Late 2023-Early 2024), Starlink was the leading satellite connectivity system in terms of capacity and connectivity latency. As the market evolves and expands, other satellite systems may be equally viable solutions and need to be similarly tested. Additionally, this testing was conducted in the later months of the year in Trinity County. While the satellite withstood the climatic and terrain conditions of the four month testing period, the same performance may not be witnessed in other climatic time periods or regions (e.g., those with extreme heat). The short testing period also limited the insight on the maintenance costs and challenges associated with Starlink antennas. Future research may need to work to close these gaps.

Next Steps

The research findings from field testing can help inform next steps for future work to resolve ongoing connectivity barriers. This work largely revolves around addressing the costs of Starlink satellite antennas and data plans and identifying other agencies with which to trial Starlink. Specifically, these next steps include:

- **Add Starlink Satellite Antenna to Government Contracts:** There is not a contract vehicle in place to purchase Starlink satellite antennas and data plans. This is a challenge as the costs may exceed a transit agency's competitive procurement threshold. As such, the team recommends that the Starlink satellite antenna and its data plan be added to government contracting vehicles. This could be accomplished by adding Starlink as a vendor to the California Multiple Award Schedules. This will help lower acquisition administrative costs, create procurement efficiencies, and secure predictable pricing for the foreseeable future.
- **Find Grants to Support Starlink Satellite Antenna Purchases:** The cost of the Starlink satellite antenna is high and may be inaccessible to public transit agencies. This is especially true of the small, rural agencies who would likely need and benefit the most from Starlink connectivity. Starlink satellite antenna costs can be addressed through grant funding. These grants may be unconventional and broadly designed to support transit technology initiatives. The team recommends that further work be done to identify which grants are potentially options and to summarize their eligibility requirements.
- **Identify Public Transit Agencies for Partnerships:** Trinity Transit represents one rural California transit agency who struggles with connectivity and may benefit from Starlink connectivity. It is important that other agencies, especially those who are looking to implement transit technology initiatives and need this connectivity, are also supported. To help with this, the Cal-ITP team can begin developing

criteria or metrics that generally characterize transit agencies that struggle with connectivity. These characteristics can help narrow down potential partner agency options and help efficiently distribute Cal-ITP resources and support to agencies who can benefit the most from it.