Evaluation of Starlink Satellite Broadband Communications for Caltrans ITS Field Elements

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Introduction: Problem and Objectives

- Caltrans rural ITS needs reliable high-bandwidth communications.
- Pending Caltrans fiber-optic broadband:
  - Years away,
  - Won't be installed on every rural highway,
  - Exposed to wildfire, flood and landslides.
- ITS elements fail when comm systems fail.
- ITS elements are deployed to mitigate the effects of snow, fire, floods, and other major incidents.

Introduction: Problem and Objectives

- ITS elements include infrastructure for:
  - Traffic Signals
  - Changeable Message Sign (CMS)
  - Closed-Circuit Television (CCTV)
  - Roadside Weather Information System (RWIS)
  - Highway Advisory Radio (HAR)
  - HAR Flashing Beacon
  - Extinguishable Message Sign (EMS) Detection
  - Traffic Census Stations
  - Ramp Metering systems, etc.
- Most rural field sites in this research lack high-bandwidth comms.
- Caltrans requires a high-bandwidth wireless communications option that is reliable and less susceptible to weather-induced incidents
- The research evaluated Starlink low-orbit satellite internet in rural areas for its
  - Reliability
  - Performance
  - Network architecture
  - Environmental effects of extreme heat/cold, heavy precipitation, etc.

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Starlink Evaluation

- The AHMCT Research Center procured and managed six Starlink kits:
  - One High-Performance (HP) kit mounted at the Redding Fiber Hub.
  - Four Flat High-Performance (Flat HP) kits for CCTV field sites in District 2 (D2),
  - One Actuated Standard Rectangular (SR) kit for initial feasibility test.
- AHMCT partnered with D2 for installations, e.g.,
  - Fit the Starlink antenna,
  - Use available adapters from Starlink shop along with off-the-shelf equipment,
  - Created custom mounts for comm towers and CCTV poles.
- Systems were operated by D2 and remotely managed by AHMCT.

Starlink Early Concerns

- If temperature exceeds specifications, Starlink devices will shut down to protect the device from damage.
  - Starlink has operating temperature of -30°C to +50°C (-22°F to +122°F).
  - Mitigation for overheating (to be tested):
    - Provide shade to prevent direct sunlight and possible overheating.
    - Starlink often connects to satellites in the north - vertical shade sail south of the antenna will block sunlight while preserving signal quality.
  - Mitigation for antenna getting frozen or obstructed by snow (to be tested):
    - Starlink has auto-heating capability for melting snow/ice which can be set to "always active" instead of "auto" to preemptively and temporarily preheat the antenna during snowstorms.
    - It is not recommended to leave it at "always active" as it gets warmer.

Starlink Early Concerns

- Starlink is not affected by most clouds. Denser storm clouds containing more moisture can create rain and cause obstruction.
- Light snowfall can be melted away by the heat generated by Starlink antenna, but heavy snow will negatively impact Starlink performance.
- Sleet and ice can resist melting in extreme cold, block Starlink signals, possibly trigger auto-shutdown.
- Starlink antenna must be securely mounted, so it does not sway or move with strong wind. Small movements in the long run are not supposed to disrupt connection.
- Starlink has unconfirmed numbers for wind resistance, especially hurricanes.
- AHMCT designed a custom mounting arm for better wind resistance to be tested in the future.

Starlink Early Concerns

- Data security and risk of exposure to public net (to be further tested).
  - Secure Shell (SSH) protocol is not supported. A private network is needed to create a secure encrypted “tunnel”.
  - Starlink provides end-to-end encryption over public internet to protect data and confidentiality of user traffic through satellites, but the details of how this encryption works in practice are not confirmed.
  - The Starlink Wi-Fi router supports both WPA2 and WPA3 security protocols.
  - Starlink supports TCP or UDP VPNs.
- Public IP (static vs. dynamic) and remote access capability.
  - Starlink router and settings do not directly support Dynamic DNS.
  - Testing with off-the-shelf wired routers and switches allowed the use of Dynamic DNS to remote access camera footage.
  - Starlink provides public IPv6 for all users, but it is highly dynamic.
  - Starlink provides dynamically DHCP assigned public IPv4 for Priority users.
  - Priority users are reserved an IPv4 that is unlikely to change unless user setup or service location changes.

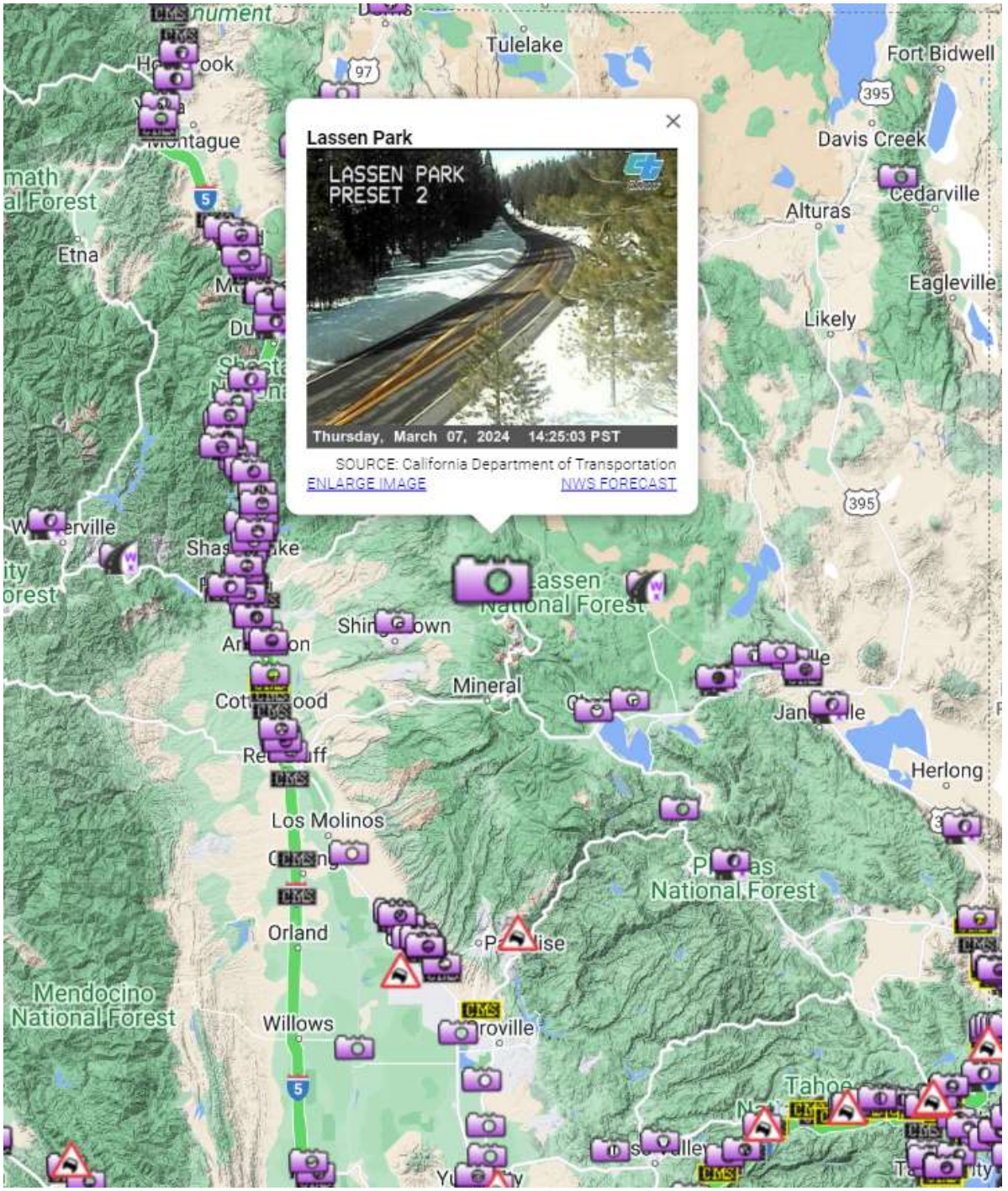
District 2

Focus:

- Improve the quality and consistency of comms between spoke sites and hub, and eventually TMC,
- Support rural areas where high-speed internet is not available,
- Assess impact of extreme weather conditions, snowstorms, power outages, etc.

Goal:

- Evaluate benefits and drawbacks of replacing current low-speed communications with Starlink satellite internet.



Starlink Mounting

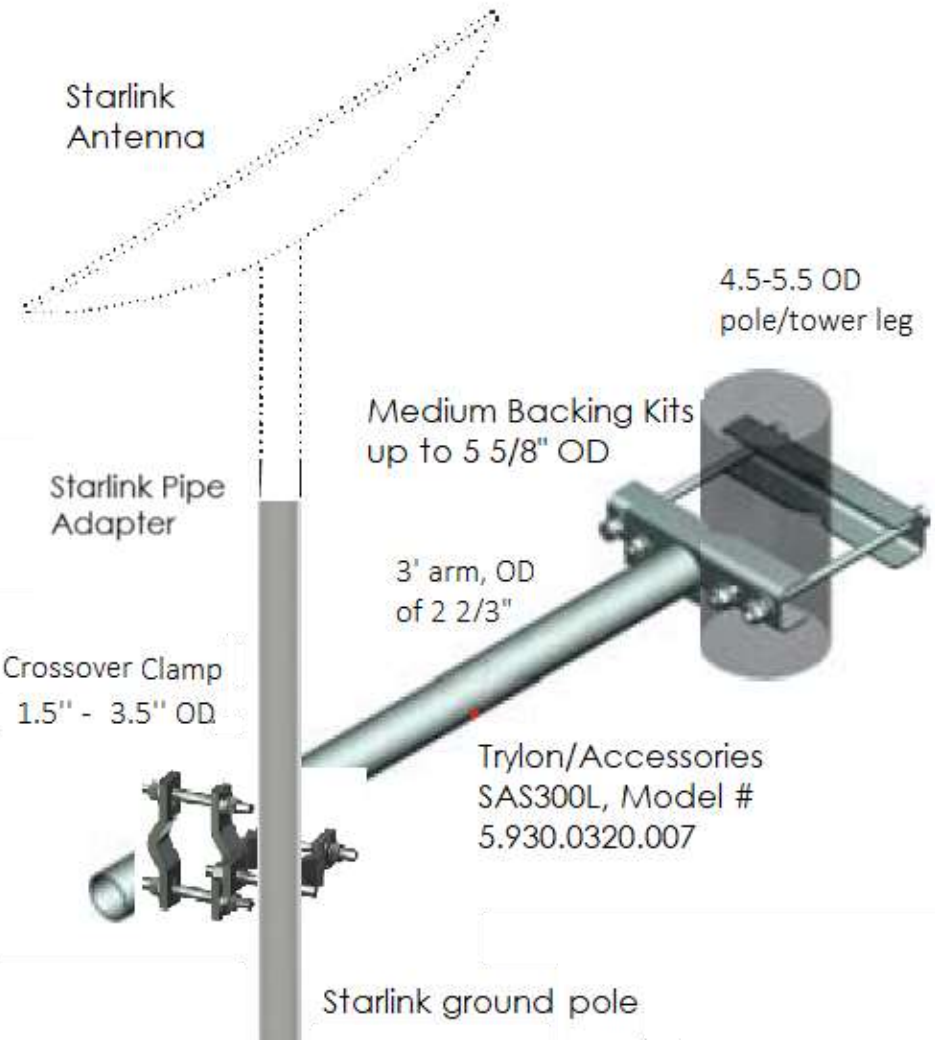
Starlink HP Kit, Redding Fiber Hub

Starlink Flat HP Kit, CCTV Sites

Starlink Mounting:

Temporary Off-the-shelf Mount for Field Testing

- Starlink uses phased array beam steering for all their kits including actuated and non-actuated antennas to transmit and receive electromagnetic waves, oriented towards and from the Starlink satellite positioned 550 kilometers overhead.
- The antenna does not require to be moving to maintain connection with Satellites configured in a hexagonal honeycomb formation.

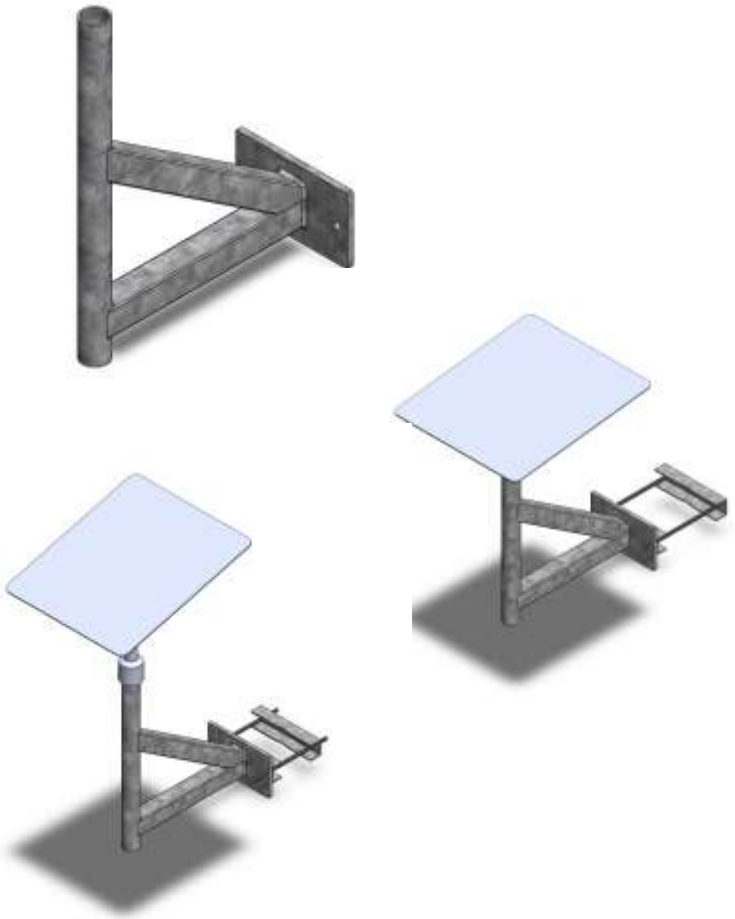


Starlink Mounting: Estimated Cost

Equipment	OD x Length	Qty	Price/Unit	Total
Trylon/accessories SAS300L, medium backing fits	2 3/8" x 3' arm 4 ½ " - 6" clamp	1	$175	$175
SitePro1 Valmont crossover clamp SSCK	1.5" - 3.5" clamp	1	$50	$50
Starlink flat HP pipe adapter	Suitable for pipes up to 2.4" outer diameter (OD)	1	$120	$120
2" x 2' galvanized pipe or Starlink ground pole	1.75-2" x 2'	1	$75	$75
Flat HP 25-m Starlink cable	0.5" x 82'	1	$165	$165
Polyphaser outdoor twisted pair lightning surge protector model IXG-05	N/A	1	$190	$190
Total				**$775**

Starlink Mounting:
AHMCT Design for Permanent Mounting

- 2-beam design with diagonal support,
- Square tubing used due to superior cross section strength for longitudinal loading,
- Round tubing for vertical beam to interface with Starlink kit components,
- Two separate assemblies for both antenna versions,
- Interface with round pole (via clamps) or a wall (via fasteners),
- Wind and lateral/longitudinal loading analyzed and stress results simulated.



Designed by Evan Sim at AHMCT

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Starlink Pilot Test Application

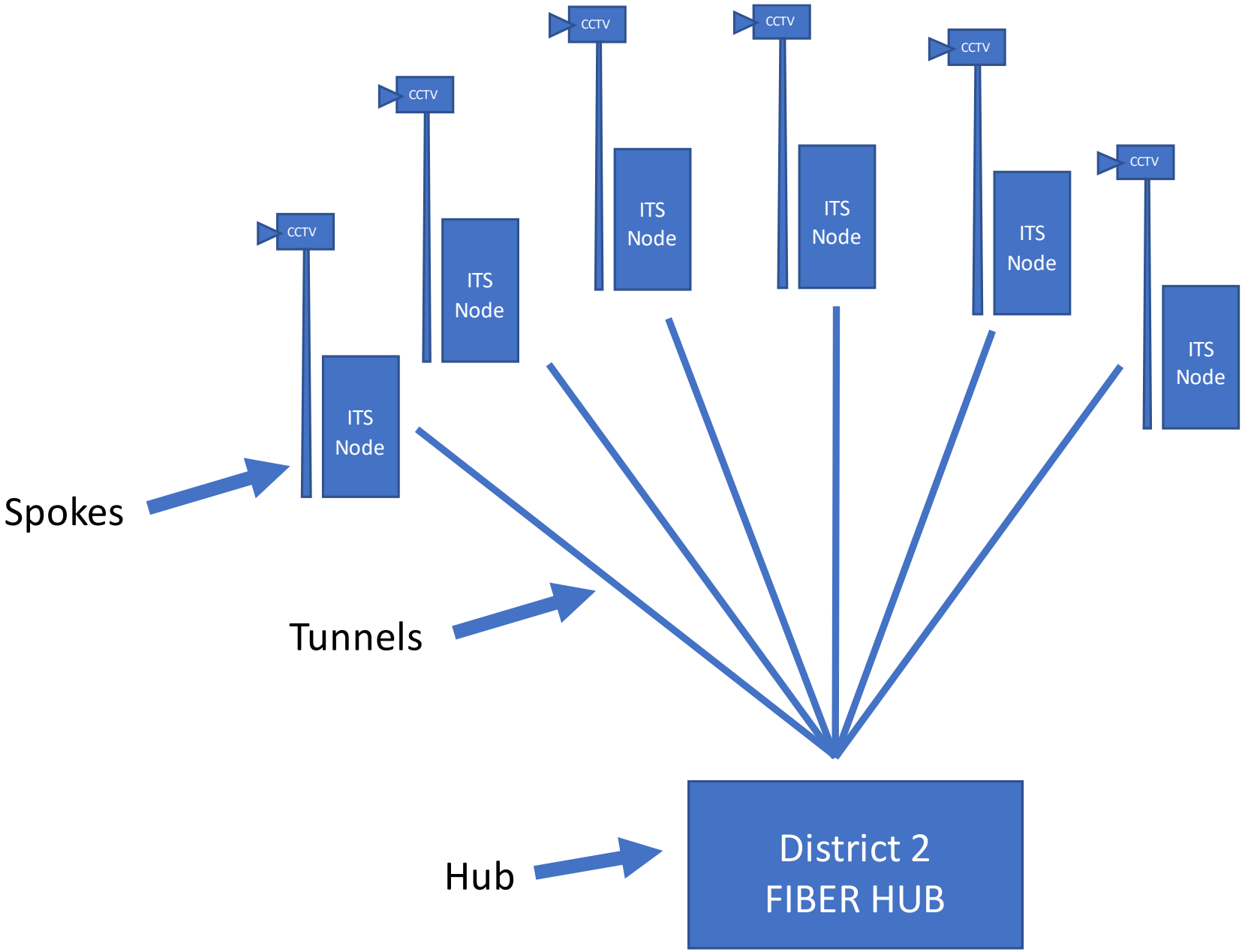
- D2 partnered with AHMCT to equip five sites with Starlink kits:
  - Four CCTV sites as spoke network nodes: Lassen Park, Sims Road, SR70-SR89 intersection, and Cedar Pass.
  - Redding Fiber Hub as the core system which forwards data from CCTV sites to D2 district office.
- D2 is using Starlink satellite communications for two applications:

1. TMC streaming videos to the video wall at Redding D2 district office,
2. Periodic image grabs by the CCTV Information Relay, forwarded to the CWWP for traveler information.

District 2 Application

- TMC video stream defines the required bandwidth.
- All CCTV video encoders set to max 196 Kbps to
  - Prevent network contention at the hub,
  - Reduce data usage at the hub,
  - Mitigate potential latency effects of LEO satellite comms.
- Periodic image grab consists of JPEG at 2CIF (Common Intermediate Format) resolution with frequency of 10 minutes to 1 hour based on the communications type and field element type:
  - Stand-alone CCTV utilizing POTS/ISDN: 1-image/hour,
  - RWIS or CCTV/RWIS site utilizing POTS : 1-image/15-minutes,
  - CCTV on microwave or fiber: 1-image/10-minutes.

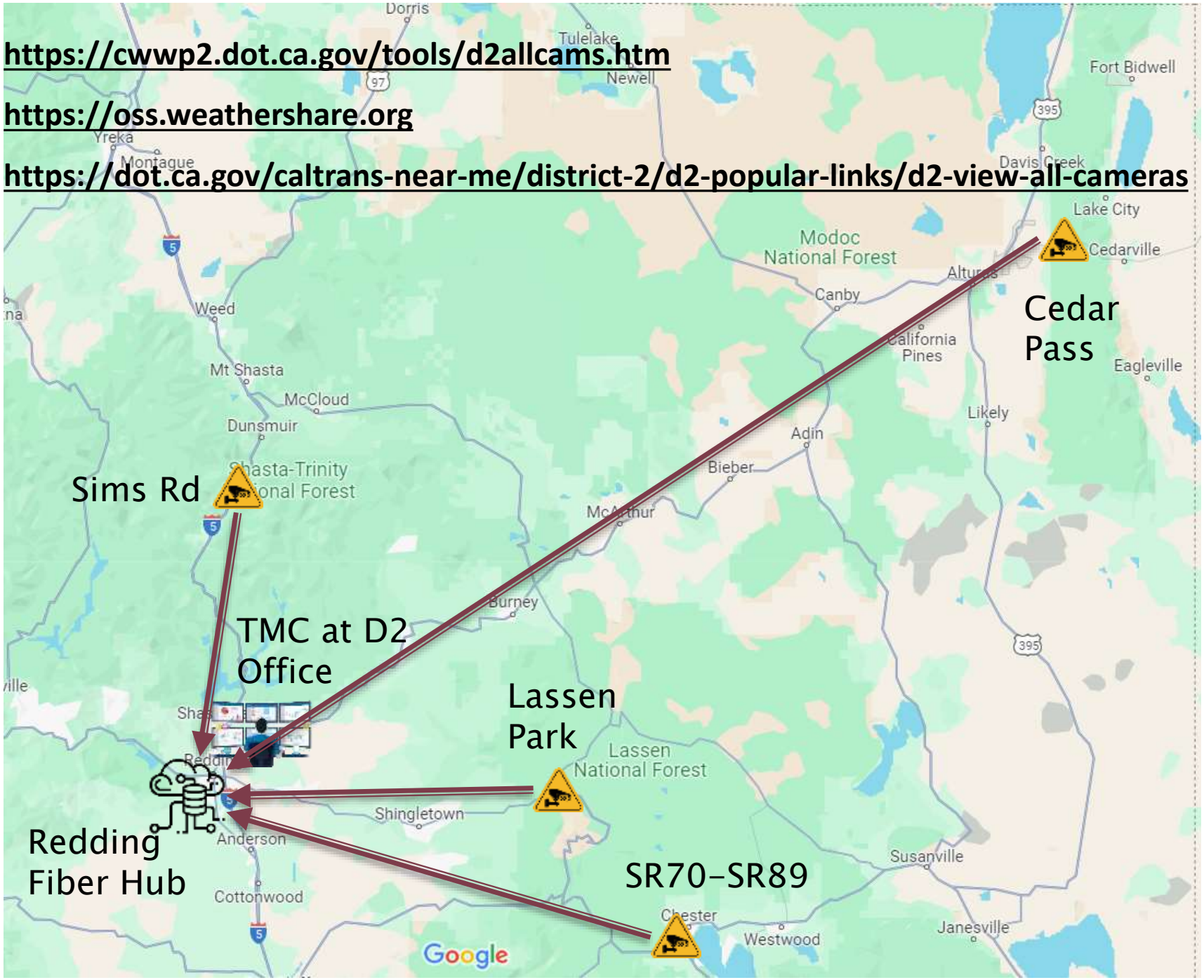
District 2 Network Topology



https://cwwp2.dot.ca.gov/tools/d2allcams.htm

https://oss.weathershare.org

https://dot.ca.gov/caltrans-near-me/district-2/d2-popular-links/d2-view-all-cameras



District 2 Network Topology: Zero-Point Tunnel

- Private network between Starlink devices is not an option. Every kit connects the user to public internet.
- Hub router provides an interconnect point between the Field Element Network and Mobility Networks known as zero-point tunnel.
  - D2 establishes a zero-point tunnel between hub and spoke for secure and reliable connection.
  - Field routers negotiate with HUB router to establish tunnel
  - The service provider would provide a private islanded network restricting outside access.
  - The hub is the only ingress/egress to the network.
  - Helps with overloading and hub failures effecting all carriers at single hub location.

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Evaluated Starlink Systems

Actuated Standard Rectangular (SR)

High Performance (HP)

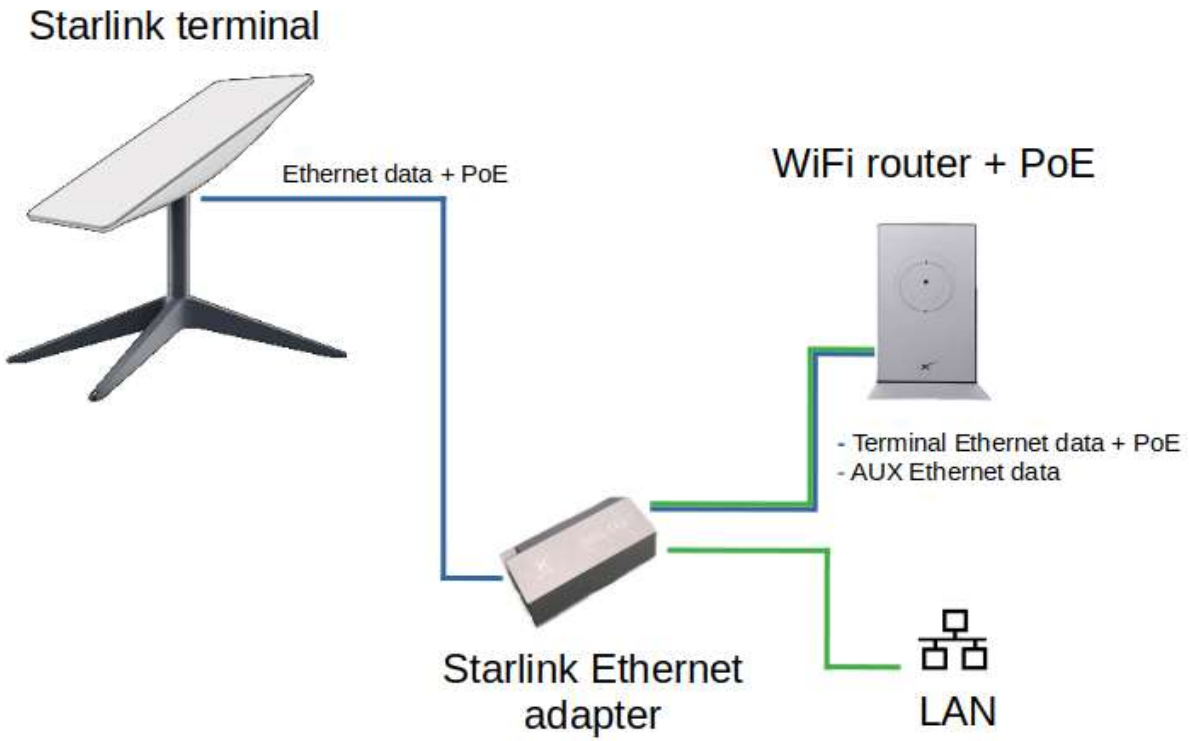
Flat HP

Starlink Systems: SR and HP kits

- Early on, only HP kits with business service provided public IP.
- Since 2023, Starlink allows SR users to upgrade to priority plans to use public IP. This makes use of SR kits viable for Caltrans ITS.
- SR and HP antennas require tilting toward the north using an electric motor/actuator.
- Mechanical parts create a reliability concern. SR and HP kits are less wind resistance compared to Flat HP kit.
- Both SR and HP kits require clear view of sky to the north (northeast to northwest) to establish connection.
- For mounting, SR and HP antennas are more versatile than Flat HP, and compatible with cheaper off-the-shelf solutions.

Starlink Ethernet Adapter:

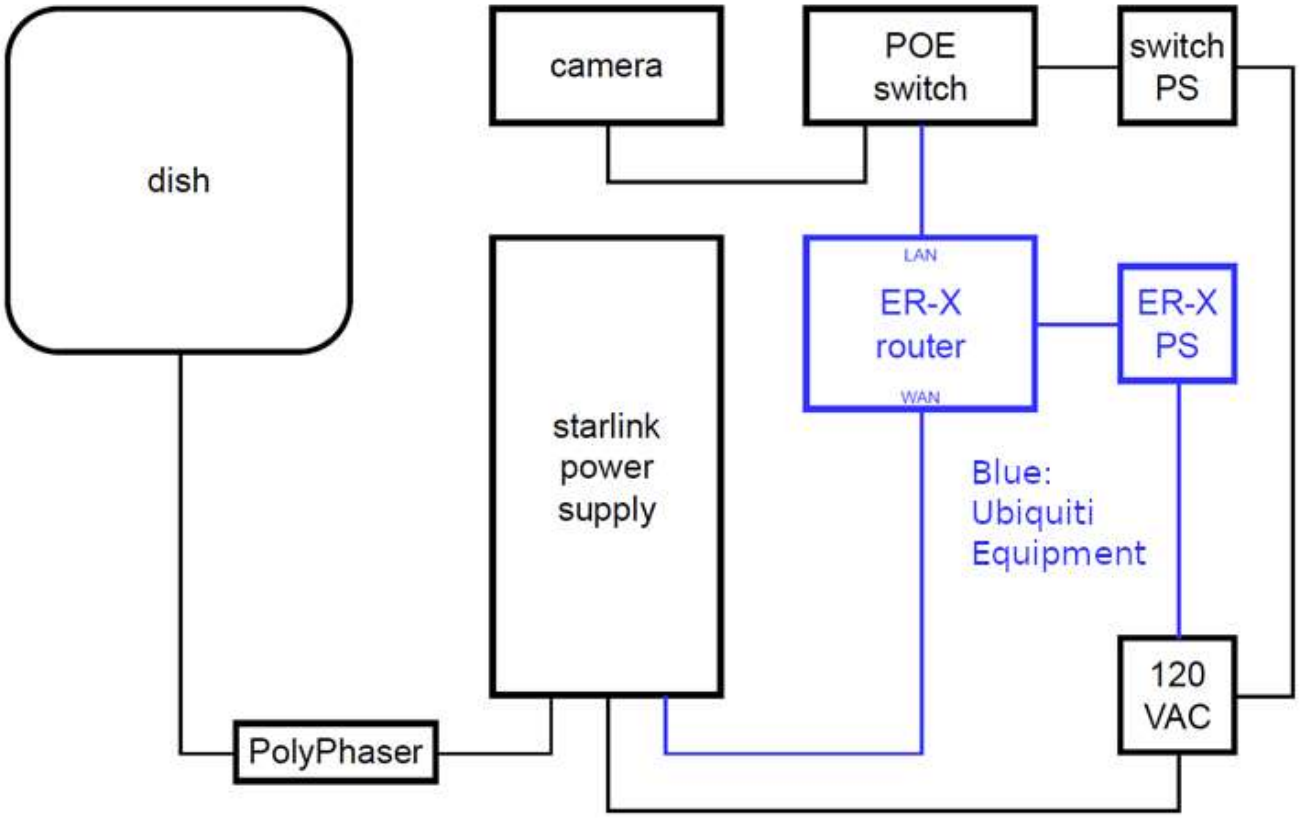
Provides an RJ45 port that can be connected to a third-party wired/wireless router, to a switch, or directly to a computer



(Source: Oleg Kutkov personal blog)

Starlink Public IPv4 Architecture

To test remote access camera footage: Flat HP kit and Ubiquiti EdgeRouter-X wired router and power switch replace Starlink Wi-Fi router



(designed by Travis Swanston at AHMCT)

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Starlink Systems: Surge Suppressor

- Surge suppressor required as communications towers and CCTV poles in rural areas are sporadically hit by lightning.
- Surge suppressors must be installed inline with Starlink antenna cable, potentially impacting the signal strength.
- After six months of testing, either the surge suppressor or the intercepted antenna cable failed, causing periodic interruptions at SR70-SR89.

PolyPhaser surge protector IXG-05

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Starlink Systems: New Flat HP kit

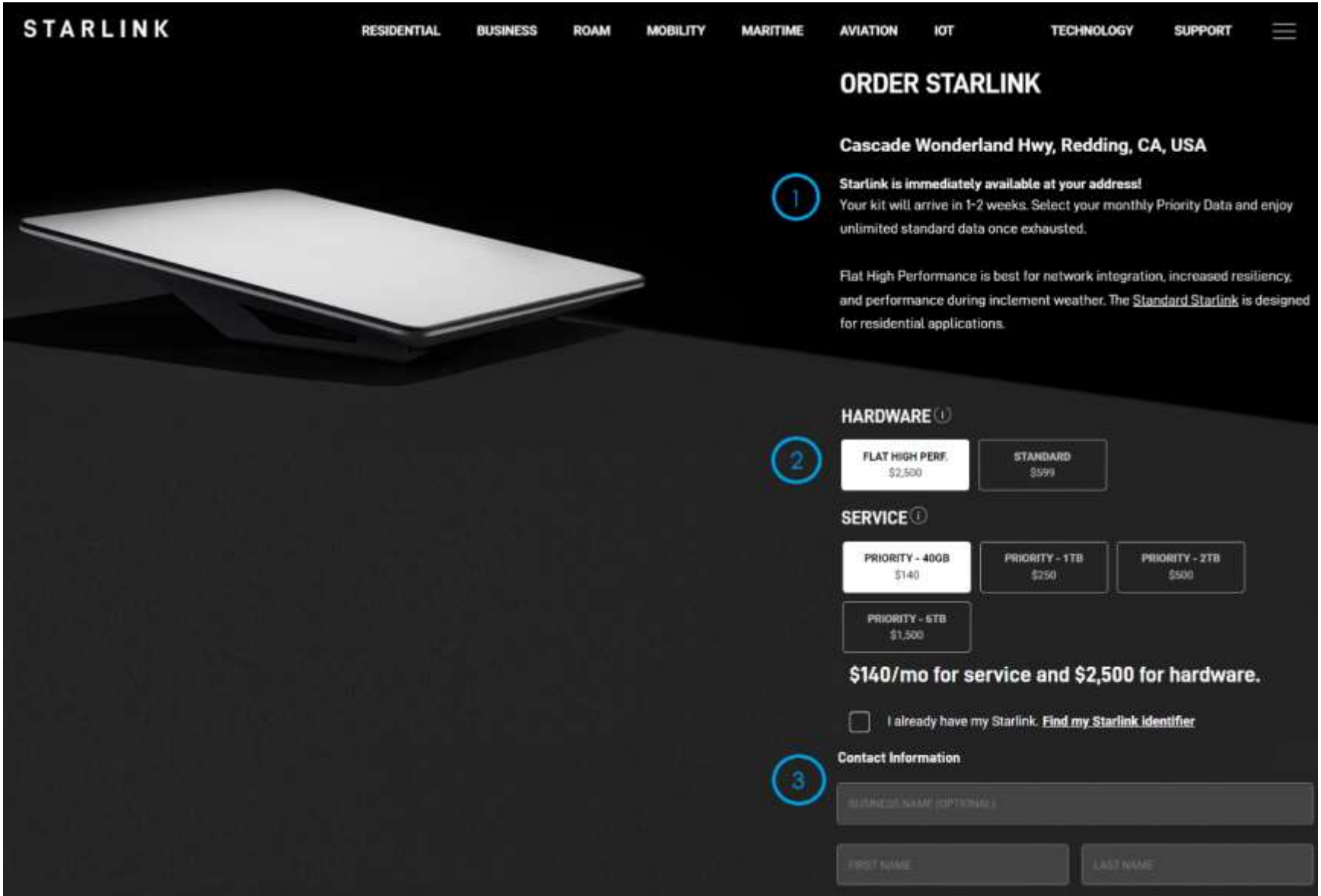
- Flat HP kit introduced in March 2023 as the premium version of HP kit.
- Flat HP is the only system suited for true mobile operation, e.g. a moving vehicle or boat.
- The Flat HP phased-array antenna scans the sky in all directions with 140° field of view.
- Flat HP antenna has fixed orientation, and no moving parts as it does not tilt to scan the sky for satellites.
- Flat HP systems can be more obstructed than HP systems in the same location as the HP antenna scans a wider angle.
- For the Flat HP system, higher obstruction does not necessarily mean lower bandwidth as the hardware can maintain more satellite connections.

Starlink Systems: New Flat HP kit

- According to Starlink.com, the Flat HP antenna survives wind speed of 280 kph+ or 174 mph+ (equivalent of a Cat 5 hurricane). These numbers do not account for the wind resistance of off-the-shelf mounting kits.
- Currently, Starlink only offers a pipe adapter (to attach the antenna to a tailored bracket) for customers who intend to secure the antenna on a pole/pipe (1.75-2.5 inches OD).
- Both HP and Flat HP kits are reported to have operating temperature of -22°F to 122°F and snow melting capability of 3 inches per hour.
- Our evaluation indicates heavy snow with extremely cold temperature can lead to Starlink shutdown to protect the kit.
- At locations where the north view is partially blocked, the Flat HP kit is the only viable system, as SR and HP kits tend to tile towards north (northeast to northwest) to establish stable connection.

Starlink Procurement:

Availability, Hardware paired with Service, Contact Info



Available Starlink Kits and Services to Pair (updated in 2024)

Kit/Antenna	Available Services	Mobility	Public IPv4	Priority Data Cost	Bandwidth
High-performance (Tilts towards North to establish satellite connection)	Priority	Stationary with fixed service address	Yes	Yes (for x price)	No restriction on bandwidth, download/upload speed with priority data. Capped to Standard Residential bandwidth after exceeding prepaid priority data with unlimited standard data until the end of billing period. Current plans include 40-50GB, 1TB, 2TB, and 5-6TB of priority data depending on service. Additional priority data available to purchase in the middle of period either by upgrading the plan or subscribing to $0.50 per GB priority data option.
	Mobile Priority	Stationary without service address available anywhere with capacity	Yes	Yes (for 5x price)	
Flat high-performance (2023 model) (Doesn't tilt, can connect with more limited view of the sky)	Priority	Stationary with fixed service address	Yes	Yes (for x price)	
	Mobile Priority	Mobile, i.e., on the moving vehicle or boat; No service address; Available anywhere with capacity	Yes	Yes (for 5x price)	

Available Starlink Kits and Services to Pair (updated in 2024)

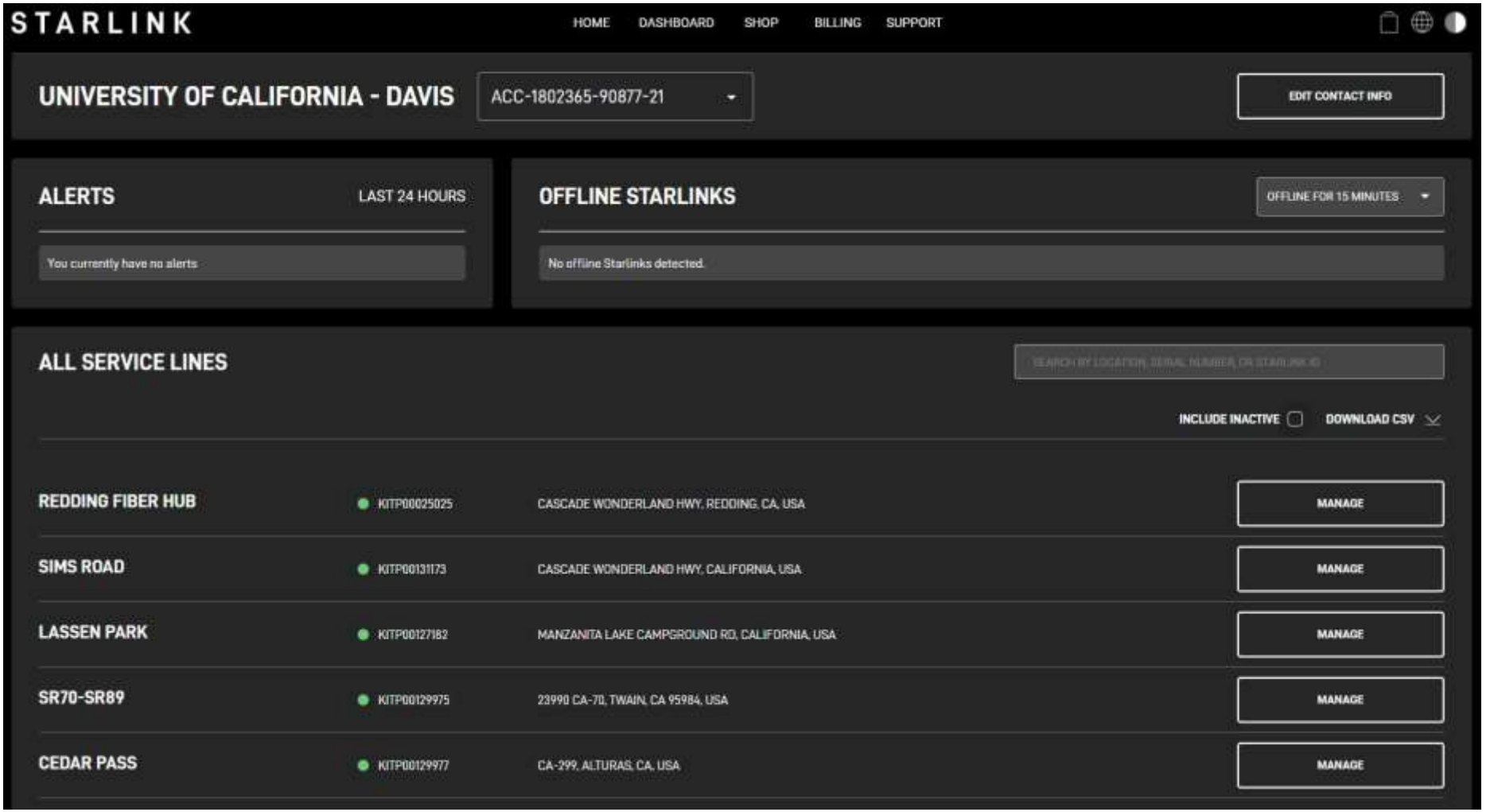
Kit/Antenna	Available Services	Mobility	Public IPv4	Priority Data Additional Cost	Bandwidth
Standard Rectangular (Actuated) (Tilts using equipped electric motor to establish optimal satellite connection)	Residential	Stationary with fixed service address	No	N/A	Limited download and upload speed. Unlimited amount of standard data.
	Roam (Mobile)	Stationary without service address and available anywhere with capacity	No	N/A	
Standard (2024 model) (No actuator, requires manual adjustment)	Priority	Stationary with fixed service address	Yes	Yes (for x price)	Similar to Priority services on HP kits.
	Mobile Priority	Stationary without service address available anywhere with capacity	Yes	Yes (for 5x price)	

Starlink Services: Priority vs Mobile Priority

- The Priority plan guarantees a service address unlike Mobile Priority plan. This is important as the ever-increasing customer pool may exceed capacity.
- Priority is fixed location service that is more suited to applications that do not require any transfer of devices after installation.
- Priority plan offers higher priority data with significantly lower prices compared to the Mobile Priority service.
- There are no technical differences between the two services except for where they are permitted to connect to the internet.
- Both services offer public IPv4 to be used for secure tunneling with Caltrans D2 routers.
- There is no difference in speed or bandwidth between the two priority services.

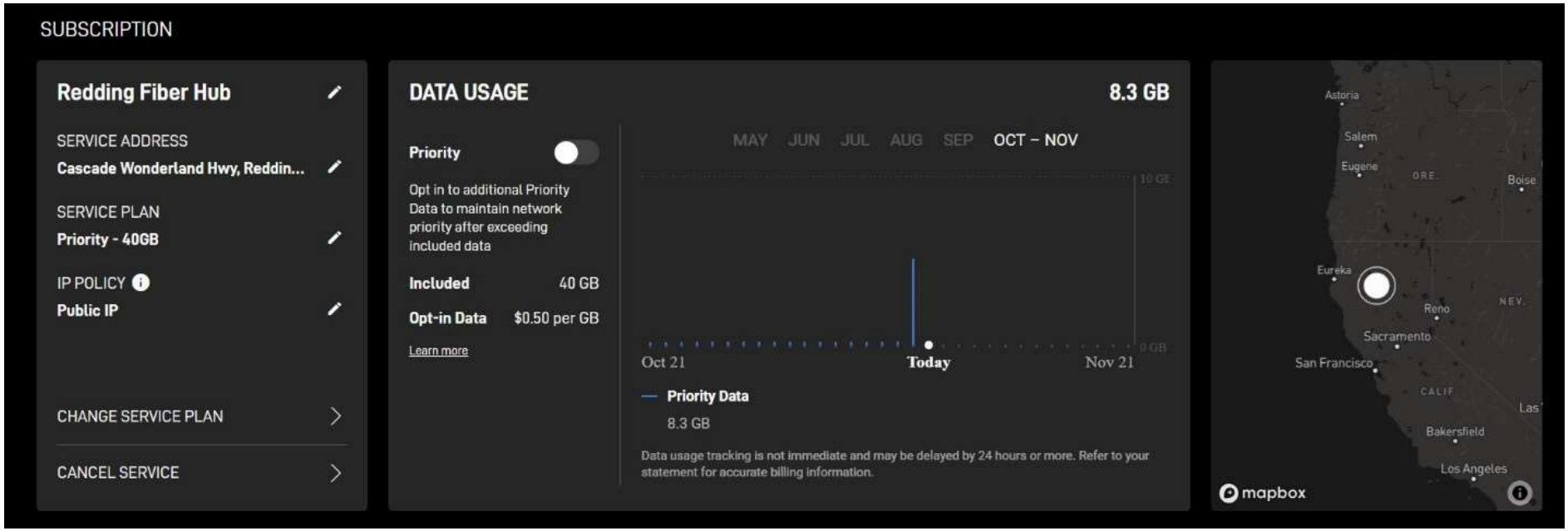
Starlink Management Interface:

Online Dashboard Listing Active Devices



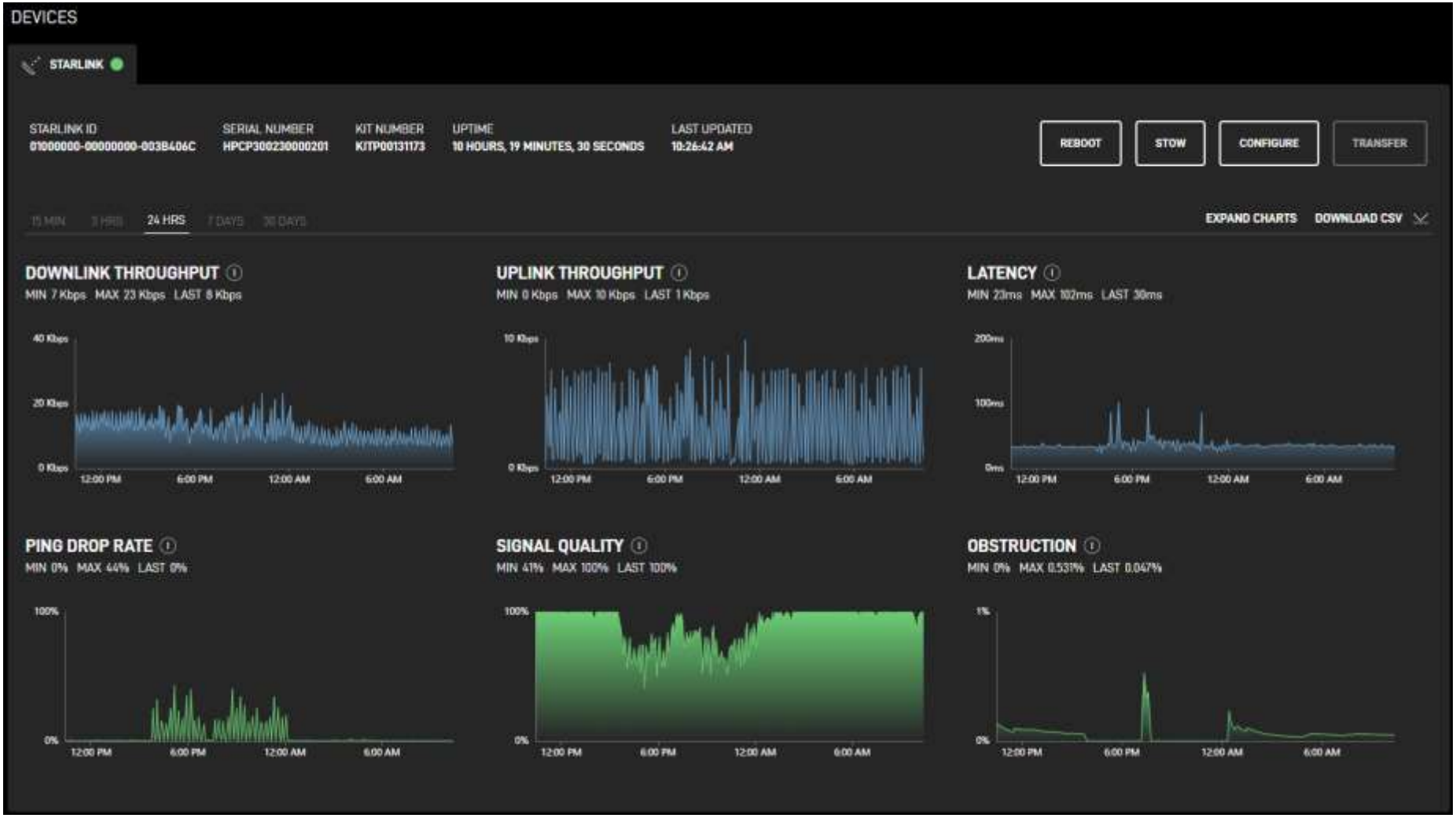
(Source: Starlink Account Dashboard)

Starlink Subscription Management and Data Usage Report



(Source: Starlink Account Dashboard)

Starlink Device Management Toolkit and Data Transfer Report



(Source: Starlink Account Dashboard)

Starlink Performance Evaluation

- Pilot test started October 2023, covered high altitude cold regions with heavy snow, e.g. Lassen Park and Cedar Pass.
- Results to date do not include testing in extended hot temperatures in the summer.
- Starlink provides data for uplink/downlink, latency, obstruction, signal quality, and ping drop rate with resolution as low 15 seconds up to 1 hour.
- Signal quality and ping drop rate depend on several factors, e.g., obstruction (by physical objects, frozen surface, and high humidity), position of satellites, and data traffic in the region.

Starlink Performance Evaluation: Significant Results for SR Kit

- For bandwidth, the SR kit is likely sufficient for applications required by D2 as it provides high down/upload speeds with low latency.
- Initial testing at Sims Rd with the SR system using Starlink Wi-Fi router showed high download and upload speeds with low latency.
- SR antenna is powered directly by the Starlink Wi-Fi router (the same router shipped with HP and Flat HP kits). HP and Flat HP antennas have a separate power supply.
- Starlink Ethernet adapter can be used to connect a third-party router via the provided RJ45 port.
- To disable wireless comm, enable “Bypass mode” in Starlink app settings.

Starlink Performance Stats During Six Week of Testing

Kit	Location	Average Obstruction (%)	Ave Signal Quality (%)	Ave Ping Drop Rate (%)	Average Latency (ms)
HP	Redding Fiber Hub	0.3	99	0.3	32
Flat HP	Sims Rd	7	95	2.5	36
Flat HP	Lassen Pk	30	90	4.5	41
Flat HP	Cedar Pass	1	99	0.3	35
Flat HP	SR70-SR89	1.2	95	1.4	35

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Starlink Performance Stats During Six Week of Testing

Average throughput for four Starlink sites during six weeks of testing in December 2023 and January 2024 (excluding idle times, averaging for five-minute intervals with minimum throughput of 140 kbps)

System	Throughput (kbps)
Redding Fiber Hub (HP, Downlink)	281
Lassen Pk (Flat HP, Uplink)	208
Cedar Pass (Flat HP, Uplink)	210
SR70-SR89 (Flat HP, Uplink)	216

Mean daily uptime change (hours) achieved by Starlink compared to previous ISP at each spoke site a year before

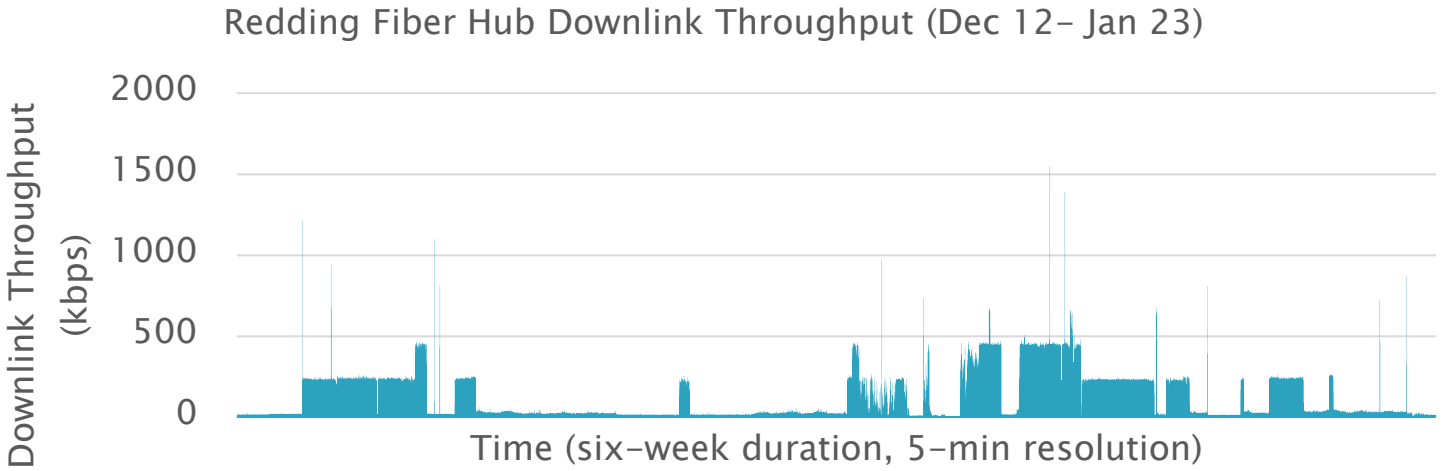
Average daily uptime change (hrs.)	Lassen Pk	Sims Rd	SR70-SR89	Cedar Pass
2nd half of October (2023 minus 2022)	-0.11	-0.11	7.72	-4.6
November (2023 minus 2022)	-0.49	-0.23	17.74	-0.08
December (2023 minus 2022)	-0.4	-0.45	15.16	0.44
January (2024 minus 2023)	-2.88	-1.88	12.36	-2.22
February (2024 minus 2023)	-3.9	-0.5	9.15	-0.25
1st half of March (2024 minus 2023)	7.41	1.3	12.04	5.69
During all 5 months	-0.8	-0.5	13.5	-0.43

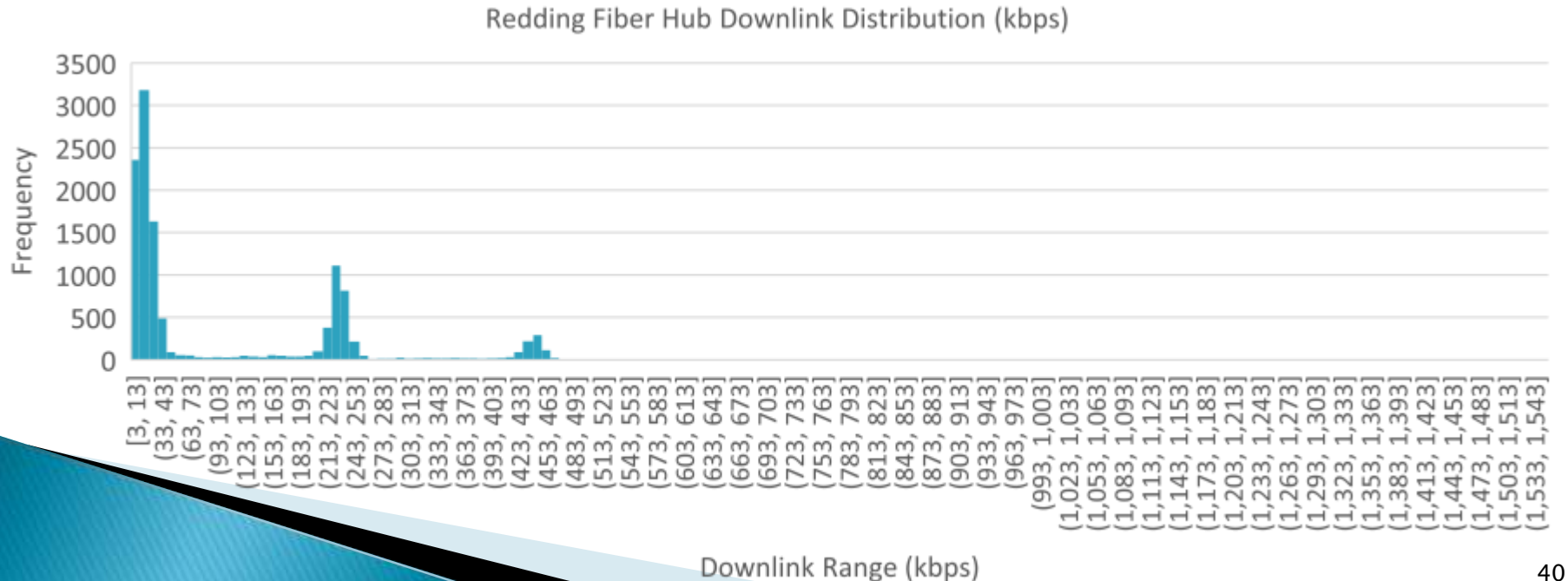
Mean daily uptime change (hours) achieved by Starlink compared to previous ISP at each spoke site a year before

- Stats do not capture the amount of maintenance and support required from D2 to maintain communications between hub and spokes.
- This data only accounts for the first five months of Starlink deployment when D2 was learning about the appropriate configuration and setup of Starlink as a new technology.
- Differences in weather conditions and wildfire occurrence each year impacted results.
- A similar study repeated for hot seasons and multiple years (bigger sample size including wildfire incidents) can shed more light on advantages and disadvantages of shifting from ground-based to satellite-based communications.

Starlink Performance Evaluation:

Redding Fiber Hub



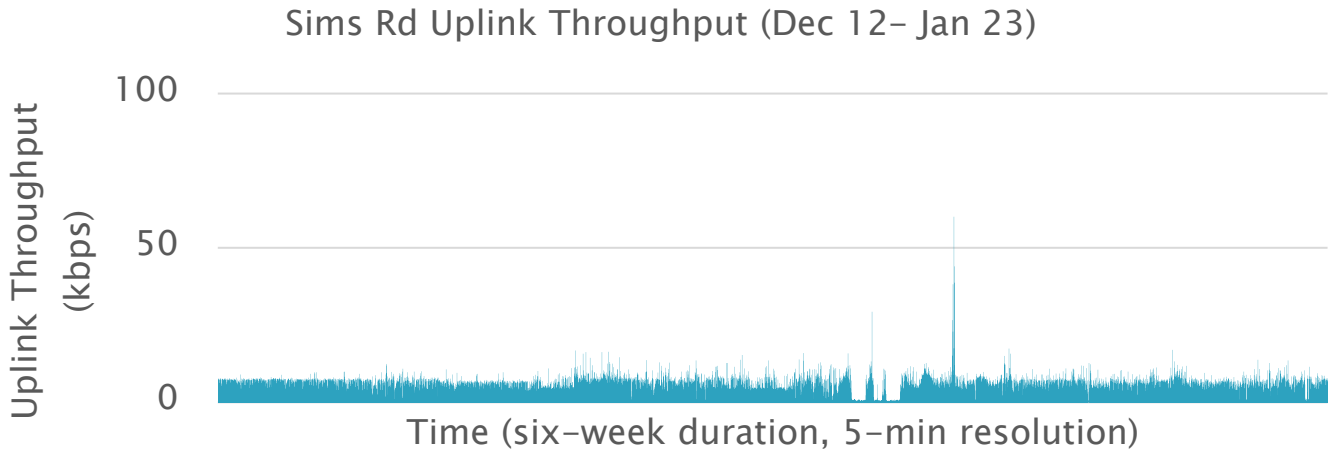


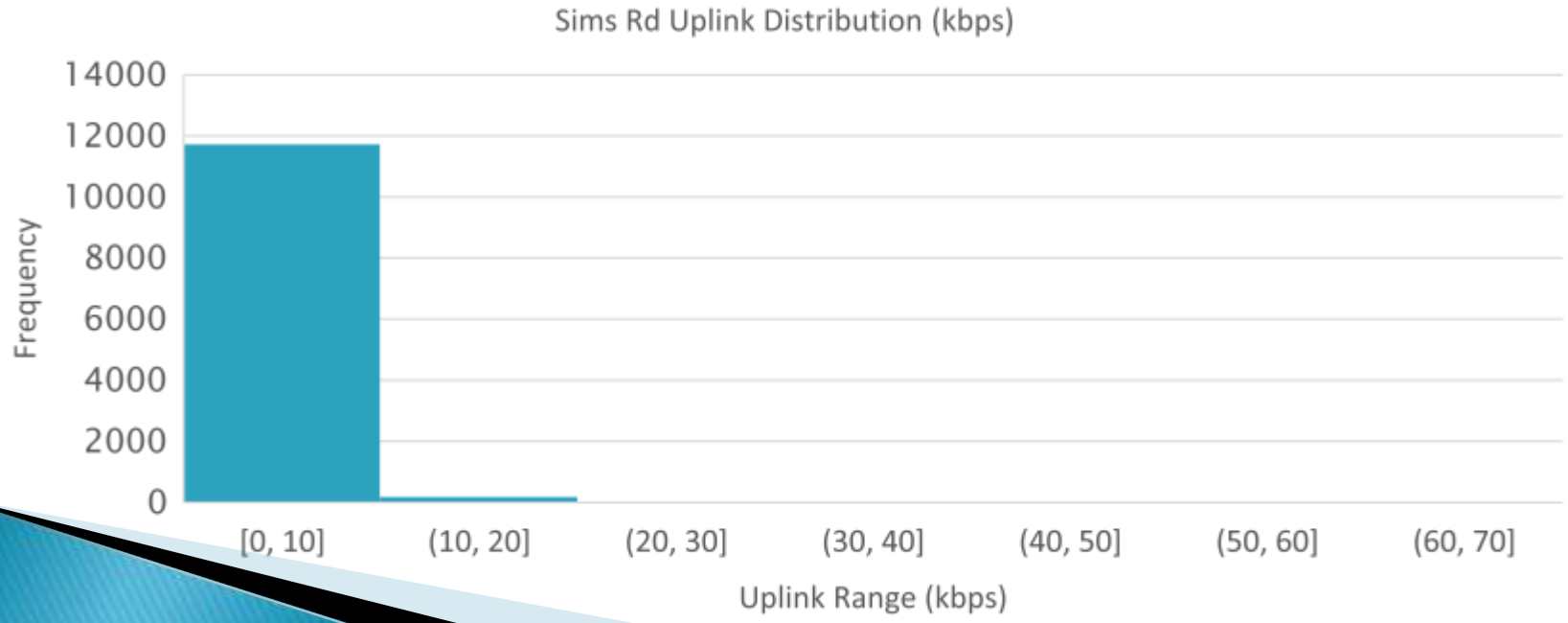
Starlink Performance Evaluation:
Significant Results for HP Kit Mounted at Redding Fiber Hub

- HP antenna does not scan the surrounding sky in all directions and has a smaller field of view vs. Flat kit.
- Starlink dashboard registered less than 0.3% obstruction and ping drop rate and around 99% signal quality on average during six weeks of data collection for HP kit at Redding Fiber Hub.
- One of the highest ping drop rates was recorded on December 28, 2023: ~15% ping drop rate, signal quality 79%, obstruction only 0.26%. This high drop rate followed over an inch of precipitation in the Redding area.
- D2 set the port to force it to negotiate at “100 Mbps/Full” rather than “Auto” following an incident when the interface between the Starlink router and the network switch at the Hub location stopped negotiating.

Starlink Performance Evaluation:

Sims Rd



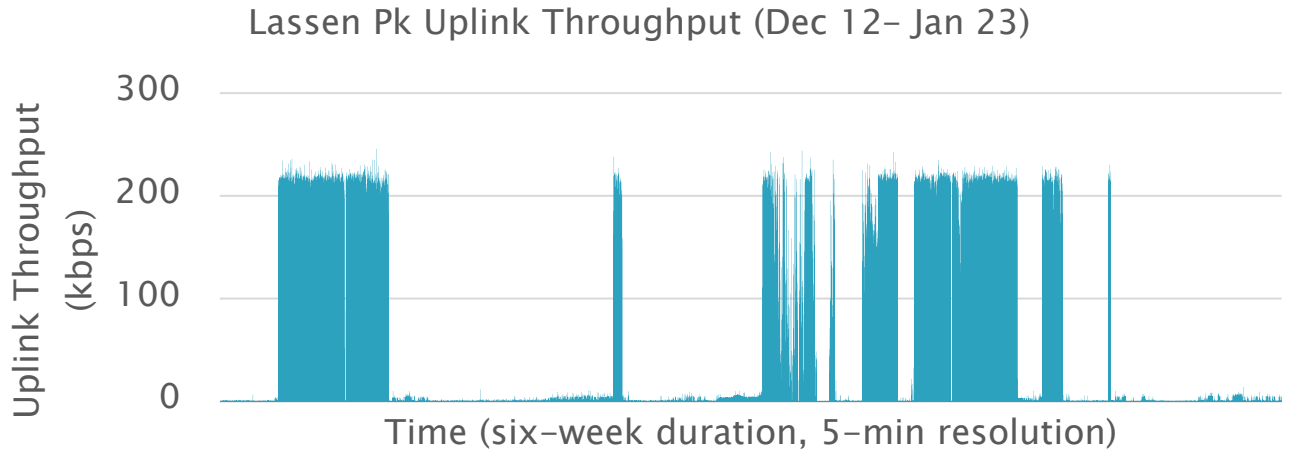


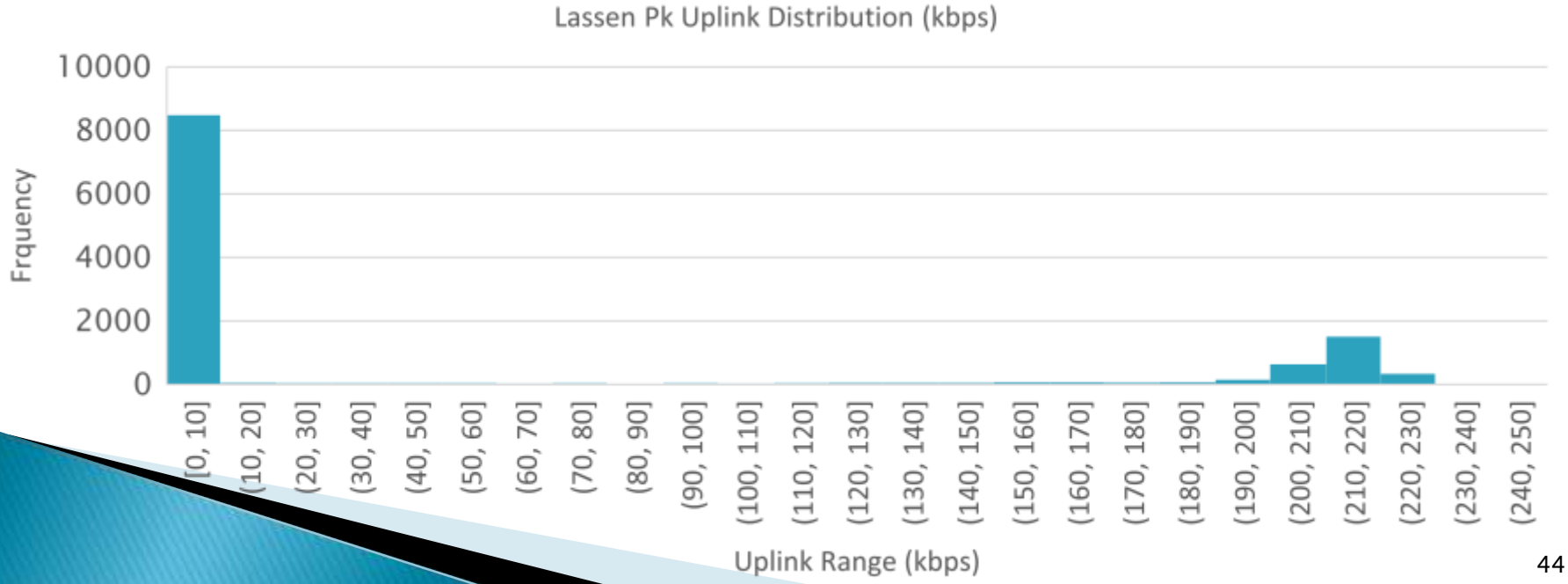
Starlink Performance Evaluation:
Significant Results for Flat HP Kit Mounted at Sims Rd

- Physical obstruction by nearby trees and hills at Sims Rd and Lassen Park sites led to lower signal quality and higher ping drop rates compared to SR70-SR89 and Cedar Pass, even in clear weather.
- Winter storms and precipitation led to higher data loss at Lassen Park, Sims Rd, and to a lesser extent Cedar Pass.
- SR70-SR89 experienced loss of connection due to malfunction in the antenna cable intercepted by the PolyPhaser surge suppressor. Cause of the failure is unknown at this point.
- The Flat HP kit at Sims Rd experienced temporary incidents with loss of connectivity and ping drop rates close to 100% (which usually corresponds to temporary disconnection).
- Between December 18 to 20, 2023, 5 inches of precipitation in the Sims Rd area led to frequent low signal quality with ping drop rates as high as 70%.
- Sims Rd Starlink maintained an average uplink of 3.5 kbps with latency of 40 ms during this time.

Starlink Performance Evaluation:

Lassen Park





Starlink Performance Evaluation:
Significant Results for Flat HP Kit Mounted at Lassen Pk

- Lassen Park had the highest bandwidth demand while dealing with more connectivity issues than other sites due to heavy snowfall, physical obstruction by trees, and one-time incidents such as power outage and loss of negotiation between the router and network switch.
- The Lassen Park system performance data has many missing and outlier values due to connection loss between the system and the Starlink servers.
- Lassen had an average obstruction of 30% during the six-week data collection with maximum of 100% obstruction, which is expected with snowfalls heavier than 3 inches in a short period.
- The ping drop rate and signal quality on average were about 4.5% and 90%, respectively. This drop rate led to downlink and uplink throughputs of 15 and 56 kbps and average latency of 41ms.

Starlink Performance Evaluation:
Significant Results for Flat HP Kit Mounted at Lassen Pk

- Temperatures in the Lassen area dropped below 10°F during December 2023 and January 2024. Heavy snow disrupted the weather station operation in the Manzanita area, leading to lack of weather data except for snow events reported by D2.
- The only confirmed snow event from weather.gov was 5 inches of new snow in the afternoon of December 30, 2023. Ping drop rate reached as high as 98% on this day with latency averaging 51ms.
- The obstruction level on this day is unknown due to significant missing performance data, a bad sign associated with communication loss between Lassen Park system and Starlink servers.
- A power outage occurred on February 3, 2024, causing the Starlink system to remain offline even after the outage ended.
- The system did not power on until a D2 operator manually restarted the system from the cabinet.

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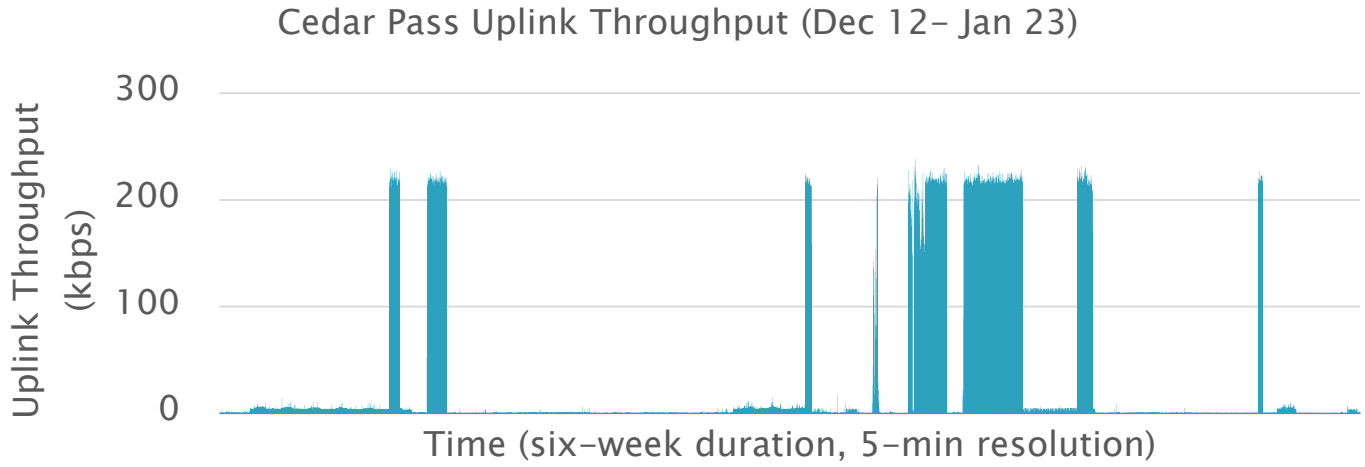
Starlink Performance Evaluation:

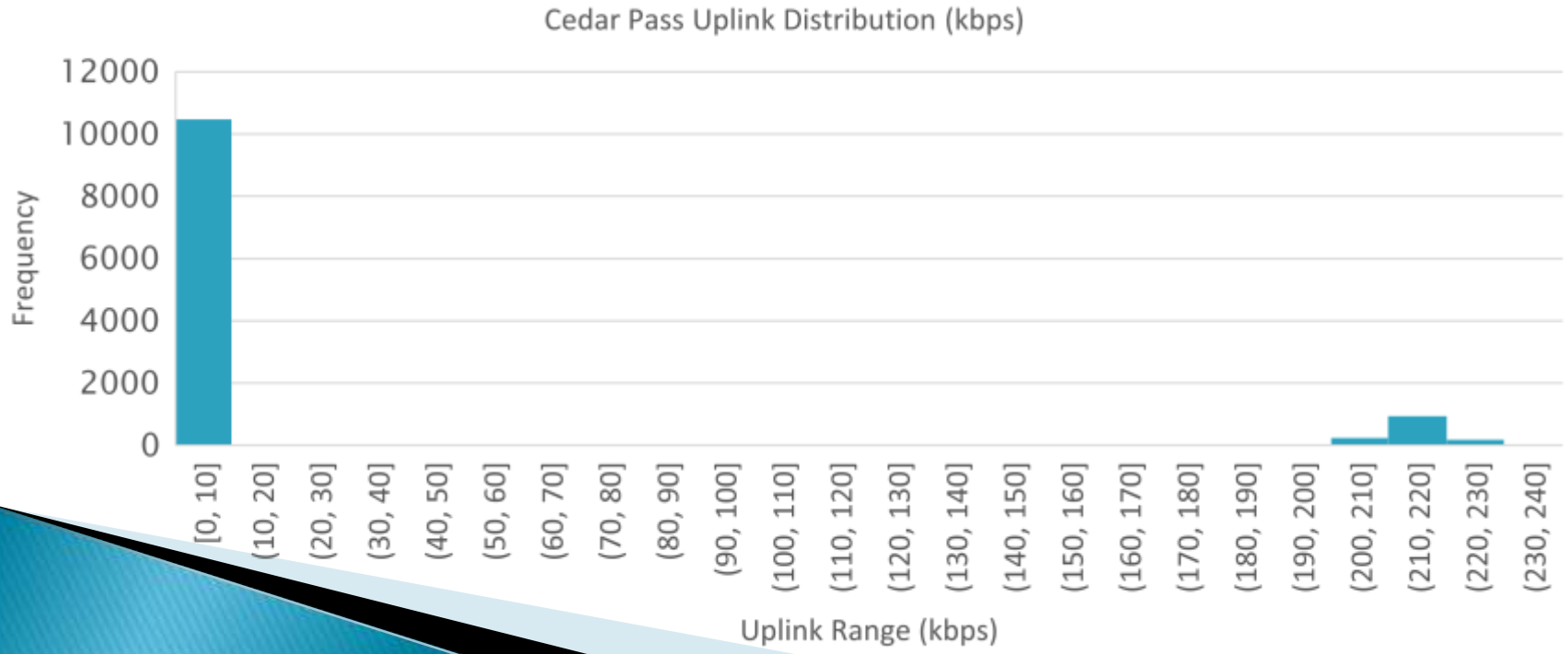
Significant Results for Flat HP Kit Mounted at SR70-SR89 and Cedar Pass

- The Cedar Pass and SR70-SR89 systems had a different situation than the Sims Rd and Lassen Park systems, as they both have a very clear view of the sky from all directions with no physical obstruction when the weather is clear.
- These differences helped to isolate the reason for obstruction periods due to heavy snow and high humidity.
- From the data, sometimes loss of signal or ping drop rates occur when zero obstruction is detected, and the weather is also clear. These events are rare and can be associated with connection of antenna with the Starlink satellite constellation and data traffic in the region.
- In both locations, the number of Starlink users is low, which also helps maintain high quality connections. We do not expect loss of connection due to excess traffic in the area unlike areas near Redding Fiber Hub.

Starlink Performance Evaluation:

Cedar Pass



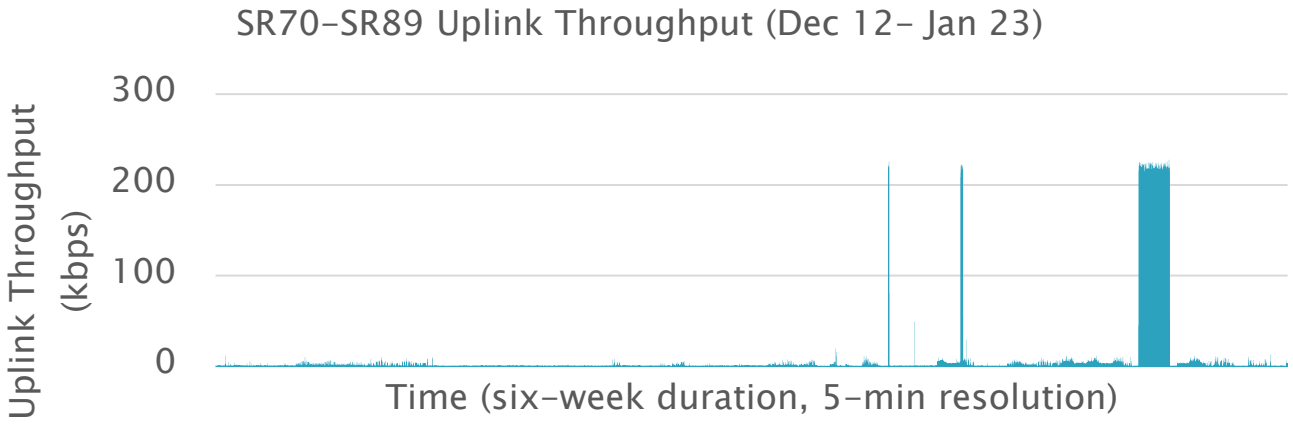


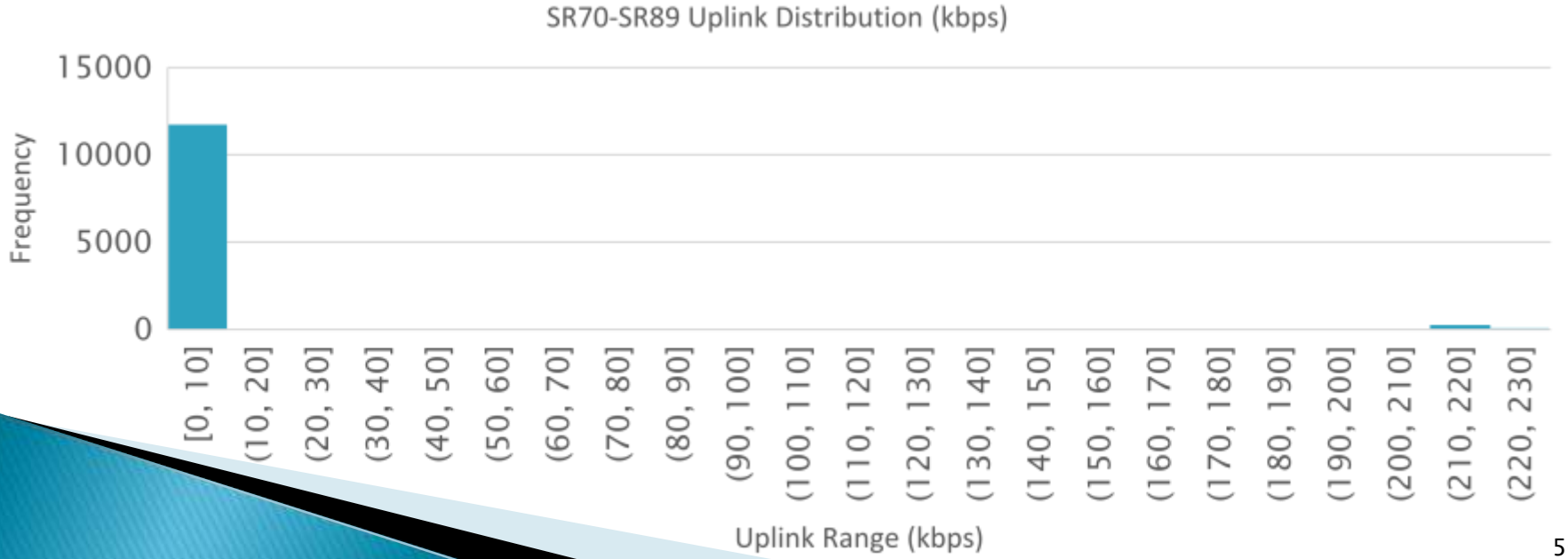
Starlink Performance Evaluation:
Significant Results for Flat HP Kit Mounted at Cedar Pass

- Cedar Pass recorded less than 1% obstruction on average. This resulted in average ping drop rate and signal quality of 0.3% and 99%, respectively. The latency over this period was on average about 35 ms.
- D2 reported a longer than normal disruption at Cedar Pass on November 7, 2023, leading to ping drop rate around 25%, while data uplink was less than 1 kbps. These numbers indicate complete loss of communication for over 24 hours at Cedar Pass, matching the observation made by D2.
- However, the snow accumulation at Cedar Pass was minimal according to D2 data, less than 2 to 3 inches.
- The reason for minimal snow leading to complete disruption over 24 hours may be extremely cold temperatures that creates a layer of ice over the antenna and initiates a shutdown to protect the device.

Starlink Performance Evaluation:

SR70-SR89





Starlink Performance Evaluation:
Significant Results for Flat HP Kit Mounted at SR70-SR89

- For SR70-SR89, the six-week statistics indicate 1.2% of obstruction on average with maximum of 53%, while the average ping drop rate and signal quality were 14% and 95%, respectively. The data uplink throughput at SR70-SR89 was 8 kbps with maximum of 227 kbps and latency of 35 ms.
- SR70-SR89 CCTV experienced a significant downtime over the first two weeks of February 2024 that was periodic and not caused by weather or power outage.
- The system would get back online and then go offline again within minutes while receiving intermittent data from the site.
- Upon investigation, it was discovered that the ethernet interface on the router was going up and down. Changing the configuration to 100 Mbps/Full Duplex similar to Fiber Hub did not resolve the issue.
- D2 electrician replaced the entire antenna cable with its surge protector as the only fix that could resolve the intermittent loss of connection.

Major Results and Conclusion

- The Starlink system appears well-suited for rural communications for Caltrans under ideal conditions but has some drawbacks under heavy snow and extreme cold weather.
- SpaceX Starlink is a young company with a Silicon Valley mindset. Products, services, and policies often change. Usually, these changes are for the better. Users must have the ability to adapt to future changes.
- The Starlink Flat HP Kit is best suited for field installations due to its superior wind specifications, less moving parts, and better satellite coverage especially in positions where the north view is blocked.
- Priority service, which is tied to a location, with 40 GB of high-speed data was deemed sufficient for application in D2.

Major Results and Conclusion

- Starlink account allows changing plans at any time; e.g., user can switch between Mobile Priority and (fixed location) Priority services, allowing user to relocate the system in multiple locations or set a guaranteed service address.
- The mobile service was particularly useful during initial testing which occurred in both AHMCT shop and District 2, but Priority (non-mobile) service was used for all five D2 sites through the field testing.
- Mobile Priority services provide the greatest flexibility. Priority systems provide the most priority data for a given price. Choice between these services depends on the prioritization of mobility vs. data budget; hence, it is left to the user to decide which service is appropriate.
- When the monthly priority data budget is exhausted, there is no added cost, and data communications continues, but at slower standard rate, unless the user subscribes to a $0.5/GB priority data plan.

Major Results and Conclusion

- The field test results showed that additional data are not required as the non-priority data provided by Starlink have sufficient download/upload speeds for the image and video transmission by District 2.
- Obstruction from trees or extreme humidity at some field sites, especially Lassen Pk and Sims Rd, resulted in higher ping drop rates compared to other locations. Overall, these obstructions did not result in extended downtime.
- Extended downtime occurred due power outage and hardware failure, such as antenna cable.
- While Starlink does not guarantee a static IP, users can now activate the public IPv4 option from the Starlink dashboard for any kit while subscribing to any priority plan.

Conclusion and Future Testing

- Flat HP kit with priority plan provides the most reliable commercially available satellite service for ITS rural elements.
- While operational, satellite communications can provide a higher bandwidth than ground communications available at rural sites.
- The additional bandwidth provided by Starlink often remains unused due to other limitations, e.g., network contention at hub locations.
- Satellite communications are as susceptible to weather-induced incidents as ground-based communications.

Future Testing

- The SR antenna is to be tested at District 6 in line with D2's application.
- Extended field testing needed to evaluate:
  - Starlink performance, and the risk of overheating during summer,
  - The effect of other incidents, e.g., wildfire and flooding,
  - The impact of manual adjustment of auto-heating feature,
  - Auto-shutdown and auto-resume capabilities meant to sustain performance and avoid critical damage to the antenna in extremely cold/hot conditions,
  - Long-term sustainability of Starlink as a service provider.

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Live Demonstration of Starlink Application with Flat HP System

- Here onsite, we have a flat HP kit mounted and activated to establish satellite connection in real time.
- The flat HP system is integrated with D2's Cisco wired router and switch simulating a field device (spoke).

Live Demonstration of Starlink Application with Flat HP System

- There is a Starlink HP antenna mounted at the tower in Redding Fiber hub also integrated with a pair of Cisco router and switch.
- Redding Fiber Hub was similarly used in field testing as the core system.
- One system is only uploading while the other is only downloading.

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Live Demonstration of Starlink Application with Flat HP System

- The Starlink at Redding Fiber Hub is negotiating with the Flat HP system here, which simulates a spoke system in the field connected CCTVs, CMS, etc.
- The routers at spoke and hub are programmed to only negotiate among themselves restricting access to the public net.
- We attempt to transmit a camera feed from the spoke to the hub using an islanded tunnel between two Starlink systems.