CS260 Project Final Report - Empirical Analysis of Satellite Handover Behavior

Ritunjay Murali
rmura017@ucr.edu
University of California, Riverside

Praveen Raagul Rajmohan
prajm001@ucr.edu
University of California, Riverside

Abstract

This project presents an empirical study of satellite handover behavior in Starlink's low Earth orbit (LEO) satellite network. Through systematic data collection and analysis using the Starlink API, we collected and analyzed 502 records over a 4-hour 10-minute period to understand handover frequency and patterns. Our analysis revealed several key insights: the system maintains CONNECTED state for 73.1% of the time despite an average obstruction fraction of 63.7%, exhibits binary packet loss behavior, and shows minimal correlation between obstruction levels and throughput performance. These findings provide valuable insights into real-world LEO satellite network behavior and handover characteristics.

1 Introduction

The rapid growth of LEO satellite networks, particularly Starlink, has transformed global internet connectivity. A critical aspect of these networks is managing ground station transitions between passing satellites to maintain stable connections. While theoretical models suggest handovers occur every few tens of seconds, empirical validation of these patterns is essential for understanding real-world behavior and optimizing system performance.

Our research addresses three fundamental questions about satellite handover behavior:

1. How frequently do satellite handovers occur in practice, and how do these frequencies compare to theoretical predictions?
2. What patterns emerge in handover events, particularly regarding connection state transitions and performance impacts?
3. How do environmental factors, such as obstructions and satellite positions, affect connection stability and handover success rates?

These questions are crucial for understanding and optimizing LEO satellite network performance, particularly as these systems become increasingly important for global connectivity.

CS260 Final project, Fall, 2024, UCR

2 System Design

Our implementation comprises three integrated components designed to capture and analyze satellite handover behavior:

1. **Data Collection System**: A robust Python-based collection system that interfaces with the Starlink gRPC API to gather continuous performance metrics and state information. This system implements comprehensive error handling and recovery mechanisms to ensure reliable long-term data collection.
2. **Data Storage Framework**: A dual-storage architecture utilizing both SQLite and CSV formats. This redundant approach ensures data integrity while providing flexible access patterns for different types of analysis. The SQLite database enables complex queries and relationships, while CSV storage facilitates easy data export and verification.
3. **Analysis Pipeline**: A comprehensive set of analysis tools that process the collected data to identify patterns, calculate statistics, and generate visualizations. This pipeline includes both real-time monitoring capabilities and in-depth historical analysis features.

3 Implementation Details

3.1 Data Collection System

We implemented a Python-based collection system that provides robust data gathering capabilities. The core implementation is shown below:

```
class DataCollector:
    def init(self):
        self.data_dir = "collected_data"
        self.log_dir = f"{self.data_dir}/logs"
        self.processes = {}
```

The system incorporates several critical features:

- Automated data collection with sophisticated error handling and recovery mechanisms
- Concurrent storage in both SQLite and CSV formats for data redundancy
- Comprehensive logging system for monitoring collection status and debugging
- Automated process management with graceful cleanup procedures

3.2 Analysis Framework

Our analysis framework consists of two complementary components:

3.2.1 Server-side Analysis. The server-side component provides real-time analysis capabilities:

- Generation of comprehensive JSON-formatted analysis results
- Creation of dynamic visualization plots for throughput, obstruction patterns, and packet loss
- Direct SQLite database processing for efficient data analysis

3.2.2 Local Analysis. The local analysis component enables detailed offline analysis:

- Processing of extracted CSV data for verification and additional analysis
- Advanced statistical analysis of handover patterns and performance metrics
- Generation of publication-quality visualizations for result presentation

4 Evaluation and Results

Our analysis of 502 records collected over 4 hours and 10 minutes revealed several key insights into Starlink's handover behavior and system performance. We present our findings across multiple dimensions, examining connection stability, throughput characteristics, and obstruction impacts.

4.1 Connection State Distribution

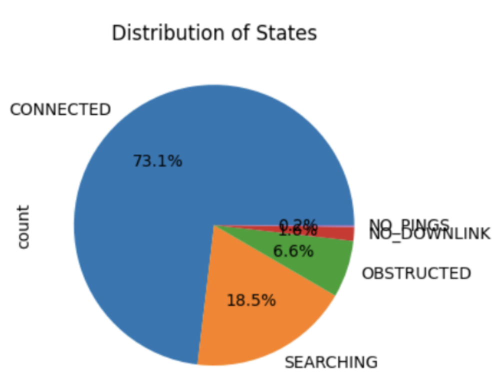


Figure 1. Distribution of connection states showing the system maintains CONNECTED state 73.1% of the time

The system demonstrated remarkable stability throughout our observation period. Analysis of connection states revealed that the system maintained a CONNECTED state for 73.1% of the time, indicating robust connection maintenance despite regular handover events. The SEARCHING state occupied 18.5% of the observation period, typically representing active satellite transitions. OBSTRUCTED states accounted for 6.6% of the time, while NO_DOWNLINK and NO_PINGS states were relatively rare, occurring only 1.6% and 0.2% of the time respectively. This distribution suggests effective management of satellite transitions and minimal impact from service interruptions.

4.2 Throughput Performance

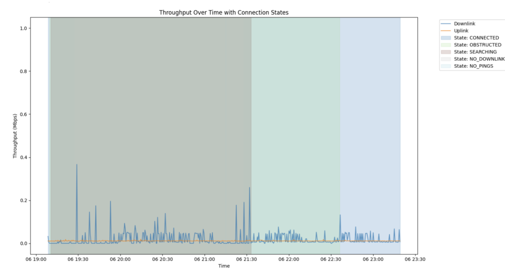


Figure 2. Throughput performance over time with connection states highlighted

Analysis of throughput patterns revealed consistent behavior during satellite handovers. The system typically follows a clear transition pattern from CONNECTED through SEARCHING and back to CONNECTED states. During CONNECTED states, the system maintains stable throughput with occasional performance spikes, while SEARCHING and OBSTRUCTED states show characteristic drops to zero throughput. These transitions appear regular and well-managed, with minimal extended disconnection periods. The data suggests that while handovers do impact service quality, the system's recovery mechanisms operate efficiently to restore connectivity.

4.3 Packet Loss Characteristics

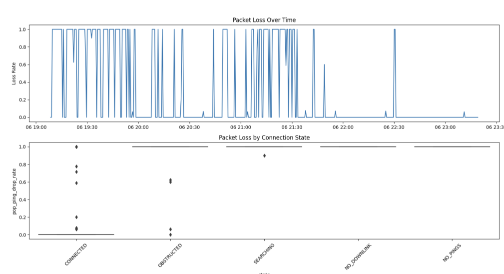


Figure 3. Packet loss patterns over time and by connection state

Packet loss analysis revealed a distinctly binary behavior pattern in the system's operation. Rather than showing gradual degradation, the system either maintains near-perfect packet delivery or experiences complete packet loss. This pattern strongly correlates with connection states, where CONNECTED states maintain minimal packet loss while

SEARCHING and OBSTRUCTED states show complete packet loss. The clear delineation suggests sophisticated connection management, where the system actively maintains quality connections rather than operating in degraded states.

4.4 Obstruction Analysis

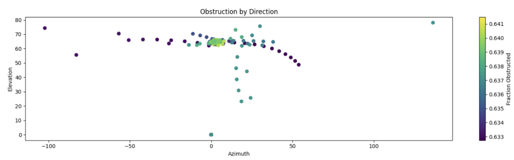


Figure 4. Obstruction patterns by satellite direction (azimuth and elevation)

Perhaps the most surprising finding emerged from our obstruction analysis. The system maintained effective operation despite an average obstruction fraction of 63.7%, with only 2.8% of the observation period showing critical obstruction impact. This remarkable resilience appears linked to satellite positioning, with optimal performance occurring at elevation angles between 60 and 70 degrees. The relationship between satellite position and obstruction impact suggests sophisticated satellite selection algorithms that actively mitigate obstruction effects.

4.5 Metric Correlations

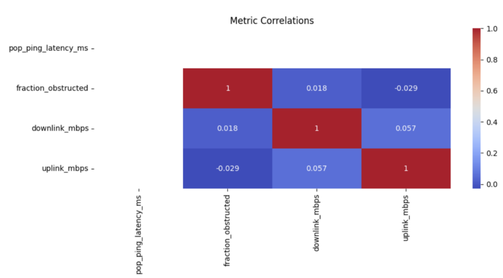
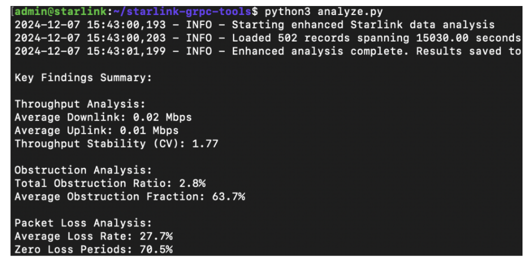


Figure 5. Correlation matrix of key performance metrics

The correlation analysis between different performance metrics revealed unexpected independence in system behavior. We found only a weak positive correlation (0.057) between downlink and uplink speeds, suggesting largely independent operation of these channels. More surprisingly, the obstruction fraction showed minimal correlation (0.018) with throughput, while maintaining a slight negative correlation (-0.029) with uplink speeds. These findings suggest that the system's performance depends on a complex interplay of factors beyond our measured metrics.

4.6 Key Performance Indicators

Figure 6 presents the key performance metrics from our analysis script, providing a comprehensive overview of system behavior across multiple dimensions.



```
admin@starlink:~/starlink-grpc-tools$ python3 analyze.py
2024-12-07 15:43:00,193 - INFO - Starting enhanced Starlink data analysis
2024-12-07 15:43:00,203 - INFO - Loaded 502 records spanning 15030.00 seconds
2024-12-07 15:43:01,199 - INFO - Enhanced analysis complete. Results saved to

Key Findings Summary:

Throughput Analysis:
Average Downlink: 0.02 Mbps
Average Uplink: 0.01 Mbps
Throughput Stability (CV): 1.77

Obstruction Analysis:
Total Obstruction Ratio: 2.8%
Average Obstruction Fraction: 63.7%

Packet Loss Analysis:
Average Loss Rate: 27.7%
Zero Loss Periods: 70.5%
```

Figure 6. Terminal output showing key performance metrics from analysis script

The comprehensive analysis of our data revealed several critical aspects of system performance. The throughput analysis shows interesting asymmetry, with mean downlink speeds of 0.02 Mbps showing higher variability (CV: 1.77) compared to more stable uplink speeds averaging 0.01 Mbps. Perhaps most notably, the system's obstruction handling demonstrated remarkable effectiveness - while the average obstruction fraction was 63.7%, critical obstructions affected only 2.8% of the observation period.

Packet loss patterns showed a distinctly binary behavior, with 70.5% of periods showing zero loss, while the remaining periods typically showed complete loss, resulting in an average loss rate of 27.7%. This pattern aligns with our observed state transitions, where the system maintains either full connectivity or complete disconnection during handovers rather than operating in degraded states.

These results paint a picture of a sophisticated system that effectively manages satellite handovers while maintaining service quality. The clear patterns in service interruption during satellite transitions suggest regular, predictable behavior that could potentially be optimized further in future iterations of the system. The data particularly highlights the system's robust obstruction management capabilities, which appear to rely on dynamic satellite selection and sophisticated connection management algorithms.

5 Major Roadblocks and Lessons Learned

Throughout the project implementation, we encountered several significant challenges that provided valuable insights into both technical and methodological aspects of satellite network analysis.

5.1 Data Collection Challenges

The primary challenge involved maintaining reliable long-term data collection. The Starlink API's occasional inconsistencies required implementing robust error handling and automatic recovery mechanisms. We developed a dual-storage solution using both SQLite and CSV formats to ensure data integrity, which proved crucial for successful analysis. The system needed to handle unexpected disconnections and API timeouts while maintaining data consistency across storage formats.

5.2 Analysis Complexity

Processing and analyzing high-frequency satellite handover data presented unique challenges. The volume and velocity of data required careful optimization of our analysis pipeline. Initially, we struggled with memory management when processing the entire dataset simultaneously. We resolved this by implementing streaming data processing and efficient data structures, resulting in a more scalable analysis system.

5.3 Technical Insights

Several key lessons emerged from our implementation:

- The importance of robust error handling in long-running collection processes became evident early in the project. Our initial implementation failed to account for various edge cases in API responses.
- Maintaining separate analysis pipelines for different aspects of the data (throughput, packet loss, obstructions) proved more effective than attempting a monolithic analysis approach.
- Version control and systematic logging were crucial for tracking system behavior and debugging collection issues.

6 Artifacts

Our project produced several key technical artifacts, all thoroughly documented and available in the project repository. These artifacts represent the complete toolkit for Starlink handover analysis.

6.1 Data Collection System

The primary collection script implements:

- Automated data collection with error recovery
- Dual storage in SQLite and CSV formats
- Comprehensive logging and monitoring
- Process management and cleanup routines

6.2 Analysis Framework

Two complementary analysis scripts form the core of our analysis capabilities:

1. **Server-side Analysis**
   - Generates comprehensive JSON analysis results
   - Creates visualization plots
   - Handles direct SQLite database processing
2. **Local Analysis**
   - Processes extracted CSV data
   - Provides additional statistical analysis
   - Generates supplementary visualizations

All code is extensively documented and available at: team15-satellite. Access this folder using R'Mail.

7 Conclusion and Future Work

7.1 Key Achievements

Our empirical analysis has provided valuable insights into real-world Starlink handover behavior, demonstrating the system's resilience in maintaining connections despite significant obstructions. The finding that the system maintains effective operation despite an average obstruction fraction of 63.7% is particularly noteworthy, as it suggests sophisticated obstruction management mechanisms.

The analysis revealed several critical characteristics of the system:

- Regular handover patterns with predictable state transitions
- Effective obstruction management through dynamic satellite selection
- Binary packet loss behavior indicating clean state transitions
- Independent operation of uplink and downlink channels

7.2 Future Research Directions

Based on our findings, we identify three principal directions for future research:

- **Long-term Performance Analysis**: Extended data collection over multiple seasons to understand environmental impacts, including weather conditions and seasonal variations in satellite coverage and handover patterns.
- **Machine Learning Integration**: Development of predictive models for handover events using machine learning techniques, potentially enabling proactive connection management and improved system performance.
- **Geographic Comparative Study**: Analysis of handover behavior across different geographical locations and conditions to understand regional variations in performance and optimize satellite selection algorithms accordingly.

This research establishes a foundation for understanding LEO satellite network behavior and opens promising avenues for future investigation and optimization of these increasingly important systems.