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A Comparative Analysis on Using Low Earth Orbit and Geosynchronous Orbit Satellite Communication Systems to Support Telemedical Networks in Austere Environments

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Abstract

In remote locations, satellite communication is the only practical option for telemedical backhaul. Enabling telemedical applications over low earth orbit (LEO) and geosynchronous orbit (GEO) satellite communications links requires a detailed analysis of how the characteristics of these links impact telemedical applications. This article investigates the characteristics of Starlink LEO and Viasat GEO satellite communications to assess which is better suited to support telemedicine in remote locations. Through experimentation, the performance of medical application traffic over LEO, GEO, and terrestrial internet service provider links is compared to show how different link characteristics impact network traffic. Terrestrial internet service provider links provide a baseline for comparison since most applications perform optimally on high-speed terrestrial communication links. The analysis uses objective data to show that the non-interactive and near real-time application tested performs better on a GEO link, while the interactive near-real time and interactive telemetry with messaging applications tested perform better on LEO links. While GEO links add latency impacts to interactive communication that cannot be mitigated, this work reveals that the protocol stack for telemedical applications can be selected or designed to optimize performance over LEO satellite communication links.

Keywords: Telemedicine, satellite communication, low latency communication, throughput, networking

1. Introduction

Humanitarian assistance, disaster relief, and military operations often occur in areas with little to no infrastructure, making satellite communication the only viable option to enable telemedicine. The effectiveness of telemedicine solutions depends on addressing the communication challenges in remote locations.

This research aligns with the effort to design the technological infrastructure and applications required to support telemedical expansion to remote locations. Specific satellite constellations studied as exemplars for this research were Starlink, for low earth orbit (LEO), and Viasat, for geosynchronous orbit (GEO), with VSAT terminals, network topology, and constellation specifics described in Buhl (2024). Telemedicine has become a vital lifeline in austere environments, empowering healthcare workers and first responders with instant access to specialist expertise and critical resources during a military operation or humanitarian crisis. This system depends on the reliability and performance of satellite-based communication systems. This article makes several contributions to the field of telemedicine in austere environments. Expanding on previous LEO versus GEO comparisons, we collect additional network performance metrics and compare them to established requirements for telemedical network performance. The study then uses satellite communication internet service provider (ISP) metrics to determine the impact on telemedical applications, aiming to identify the best satellite communication design choice and its implications for supporting telemedicine in austere environments.

The article is organized as follows, beginning in Section 2 with an overview of previous literature. Section 3 outlines and describes experiments to quantify satellite network performance and then test telemedical applications over the networks. The experimental results and analysis are presented in Sections 4 and 5. Finally, Section 6 summarizes the results and implications.

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2. Related Telemedicine and Satellite Communications Research

The availability of high throughput and low latency networks connected by 5G cellular has led to a surge in telemedicine research. Examples of this research include Qureshi et al. (2022), which produced a consolidation of network key performance indicators (KPIs) required to support many telemedical applications. For instance, Qureshi et al. (2022) set the download and upload throughput requirement as high as 4.6 Mbps for high-definition video streams and found that interactive delay KPIs should be below 400 ms to avoid a pronounced negative impact, with 600 ms being the maximum tolerable delay. The same study also put 500 ms as the upper bound for remote physiological sign monitoring (Qureshi et al., 2022). In contrast, the generally accepted end-to-end delay for real-time face-to-face communication is 150 ms (Jansen et al., 2018).

Previous studies have also performed a comparative analysis of GEO and LEO communication systems for specific applications like control of an remotely operated vehicle (ROV) in Hegarty et al. (2023). Garcia et al. (2023) and Tolouei (2023) focused on Starlink LEO performance and conducted a timescale analysis of LEO satellite communication throughput and packet loss respectively, finding a 15-second periodic behavior with short interruption during satellite communication frequency reallocation and beam switching. Pauliks et al. (2015) on the other hand, examined packet loss impact to compression video codecs and found a 0.25% acceptability margin for video streaming with a significant drop in viewer satisfaction at 3% (Pauliks et al., 2015). Pandav et al. (2022) describes limitations, challenges, and requirements for conducting remote robotic surgery over 5G. In McKnight et al. (2022), a system was developed providing two-way audio and one-way video supported by LEO satellite communication to enable real-time clinical support (RTCS) in an austere environment.

This article expands on the methods used in Hegarty et al. (2023) to look at packet inter-arrival time and the application network traffic data rate. We also expand on the satellite communication link performance metrics gathered in Hegarty et al. (2023) by measuring packet loss ratio and performing throughput and latency measurements periodically over an extended period of time. This article complements the work done in McKnight et al. (2022), Qureshi et al. (2022), and Pandav et al. (2022) by using the network traffic from the four categories of telemedicine information described in Section 3 and satellite communication ISP performance characteristics measured to determine the best satellite constellation for supporting the telemedicine information categories. The research done by Pauliks et al. (2015) helped determine the implications of the results.

3. Summary of Experimentation

The experiments in this study were designed to provide objective, as-is data for determining whether LEO or GEO satellite communication is better suited for supporting telemedicine in austere environments. A detailed hardware, software, and network configuration description can be found in Buhl (2024). The methodology involved two groups of experiments:

- Group 1: Satellite communication comparative performance testing.

- Group 2: Telemedical application testing.

Group 1 experiments were designed to measure network performance metrics for LEO and GEO satellite ISPs over an extended period. These metrics, including throughput, round trip time (RTT), and packet loss ratio, are vital for applying satellite communication and telemedicine in austere environments. As would be the case in most situations, the use of commercial satellites without direct control of other traffic or special prioritization is assumed. Representative constellations were Starlink for LEO, with three orbital shells from 340 – 1,110 km, and Viasat for GEO, at 35,000 km.

Group 2 experiments involved testing the performance of four types of telemedicine applications over LEO, GEO, and terrestrial ISPs using relevant exemplar software in use by the Department of Defense (DOD) Military Health System (MHS):

- Video Connect (Type 1): An interactive, near real-time, web-based, two-way video and audio application used for clinician-patient or specialist video sessions.

- Microsoft (MS) Teams Webinar (Type 2): A non-interactive, near real-time, one-way, video broadcast application for information newscasts and medical training videos.

- Vital Sign Monitoring Telemetry (Type 3): An interactive, telemetry application using a simple Transmission Control Protocol (TCP) connection to share data from physiological monitoring devices, minimally changing metrics, and clinical text with or without images.

- Large File Download (Type 4): A non-interactive, web browser-based download of medical manuals, clinical practice guides, or video and imagery using the TCP protocol.

For each application, key metrics, such as data rates and inter-arrival times, were analyzed to assess the impact of the underlying satellite communication characteristics on application performance. The data collected from both experiment groups was processed using Python scripts and visualized using MATLAB. The results from the application testing were compared to the baseline performance over terrestrial ISPs to determine which satellite communication system, LEO or GEO, more closely resembled the ideal performance. Subjective evaluations of application performance by the testers were available to corroborate results.

By combining the insights gained from the satellite communication comparative performance testing and the telemedical application testing, the study aims to provide a comprehensive understanding of the suitability of LEO and GEO satellite links for supporting telemedicine in austere environments. The implications of the findings were used to generate design recommendations for both applications and networks to optimize the performance of telemedicine over satellite communication links.

4. Experiment Group One Results

Comparative satellite communication performance testing in group one experiments was designed to produce network performance metrics that would help identify the root cause of the application network traffic behaviors seen in group two experiments. This section is organized by network performance metric categories: throughput, RTT, and packet loss ratio. For each of the network performance metric categories, the testing results for LEO are compared to the GEO satellite communication test results.

4.1. Comparative Throughput

All the results from the comparative throughput tests were collected from December 14, 2023 to December 31, 2023 at intervals of approximately 15 minutes. The asymmetric upload and download rates shown in Figure 1 and 2 are consistent with the capabilities advertised by Starlink and Viasat.

From Figure 1, we can see that the average download rate for LEO satellite communication was higher than GEO satellite communication at 88.8 Mbps and 20.5 Mbps, respectively. LEO satellite communication had the potential to reach data rates of up to 180 Mbps, while

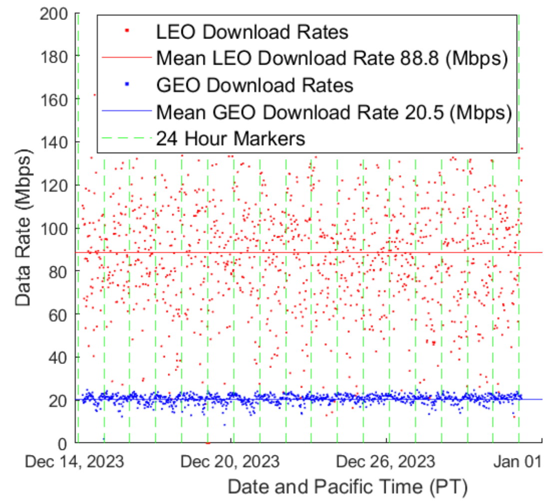

Figure 1. Measured satellite communication download rates plotted with respect to time. LEO rates are in red and GEO rates are in blue.

GEO had a very consistent performance of around 20 Mbps. Average upload rates are shown in Figure 2, and the LEO rate was again higher at 27.9 Mbps compared to 7.6 Mbps for GEO. The spread of possible satellite communication data rates shows most rates for GEO stayed within a 5 Mbps band. In contrast, the range of possible data rates for LEO was much wider. High data rates in telemedicine are highly desirable for both the uplink and downlink, specifically when simultaneously sending and receiving high-definition video. LEO satellite communication is clearly superior with a higher probability of supporting more high-definition video streams, however we confirmed that both constellations exceed the 4.6 Mbps data rate KPIs in Section 2. We note that a higher throughput rate can also mask negative channel performance characteristics such as packet loss, which can have negative impacts to performance as shown in Section 5.

4.2. Round Trip Packet Delay

Data from the RTT tests was collected from December 14, 2023 to December 20, 2023. The testing confirmed that Viasat GEO RTT times were 654 – 676 ms and Starlink LEO times between 78 – 110 ms. The standard deviation for any given test was lower for LEO at 24 ms compared to 33 ms for GEO. As expected, this data confirms that the LEO ISP not only has a lower standard deviation for delay but also outperforms all delay KPIs listed in Section 2 and related to the use cases tested but the GEO ISP does not. For comparison, a latency of 10 – 35 ms is expected from a terrestrial ISP (Federal Communications Commission, 2023).

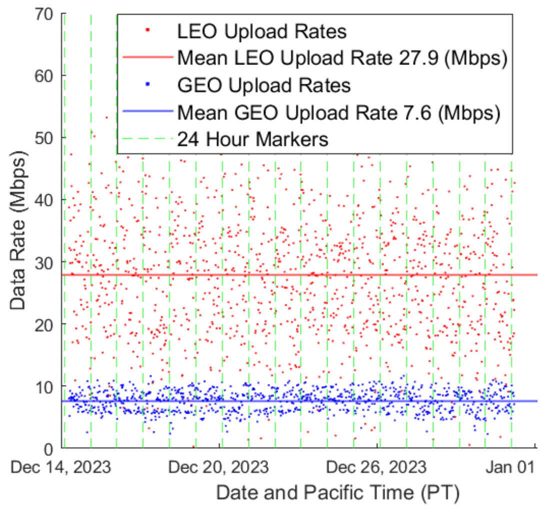

Figure 2. Measured satellite communication upload rates plotted with respect to time. LEO rates are in red and GEO rates are in blue.

4.3. Packet Loss

The figures in this section illustrate the packet loss characteristics of LEO and GEO satellite communication systems, as well as provide a comparison with terrestrial ISPs. The purpose of these figures is to visualize the differences in packet loss performance between the tested systems and to highlight any notable patterns or behaviors. Figure 3 displays the packet loss data for LEO and GEO satellite communication systems over the time tested.

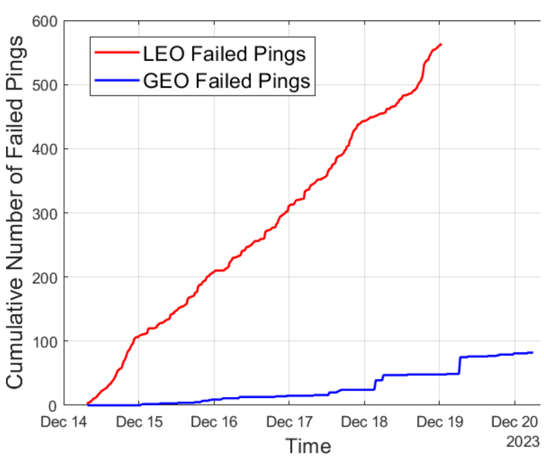

Figure 3. Total failed pings by satellite communication ISP over time.

Figure 3 shows a packet loss ratio of 0.32% and 0.047% for LEO and GEO satellite communication, respectively. Most of the time, terrestrial ISPs have less than 0.004% packet loss (Federal Communications Commission, 2023). This is significant because GEO satellite communication has more than 10 times the packet loss of a traditional terrestrial ISP, and LEO satellite communication has around 100 times the packet loss of a terrestrial ISP. In addition, Michel et al. (2022) found a concerning periodic characteristic of LEO ISP packet loss. His data shows a spike in packet loss that occurs every 15 seconds. This means that not only is LEO packet loss 100 times what we would expect from a terrestrial ISP, but most of that packet loss occurs during a small time window every 15 seconds (Michel et al., 2022). High packet loss during a short window diverges from the normal behavior expected from a terrestrial ISP, and can cause unwanted behavior in applications as discussed in Section 5. Most traffic congestion avoidance algorithms assume an increase in packet loss is primarily due to congestion. The impact is that congestion control algorithms can have sub-optimal performance due to abnormal packet loss. For the two satellite communication ISPs tested, GEO has far better packet loss characteristics.

5. Experiment Group Two Results

Application testing provides objective data to determine whether LEO or GEO satellite communication systems are better suited for the telemedicine applications tested. We analyze the performance of various applications over satellite communication links and compare their network traffic behaviors to those observed over terrestrial ISP links to assess which satellite communication system more closely resembles ideal performance.

5.1. Video Connect (Type One)

Video Connect is a type one, web-based, near real-time, two-way, video and audio application. In this section, we analyze the performance of Video Connect over terrestrial, LEO, and GEO ISPs by examining data rates of traffic streams. By comparing the differences in traffic behaviors across these ISPs, we can infer how the underlying congestion avoidance algorithm responds to the distinct communication channel characteristics of each ISP. This analysis provides insights into which satellite communication ISP is better suited for running type one applications like Video Connect and helps identify potential areas for improvement in application performance.

5.1.1. Data Rates Figure 4 shows the upload and download data rates for Video Connect (type one application) traffic streams over terrestrial, LEO, and

GEO ISPs. The terrestrial ISP is also provided as a baseline for ideal behavior. LEO download rates are stable at the ideal 1 Mbps, but upload rates fluctuate between 50% and 100% of the terrestrial rate, impacting video resolution. GEO download rates match the terrestrial baseline, but upload rates quickly decline to about 10% of the ideal rate, resulting in low-resolution video.

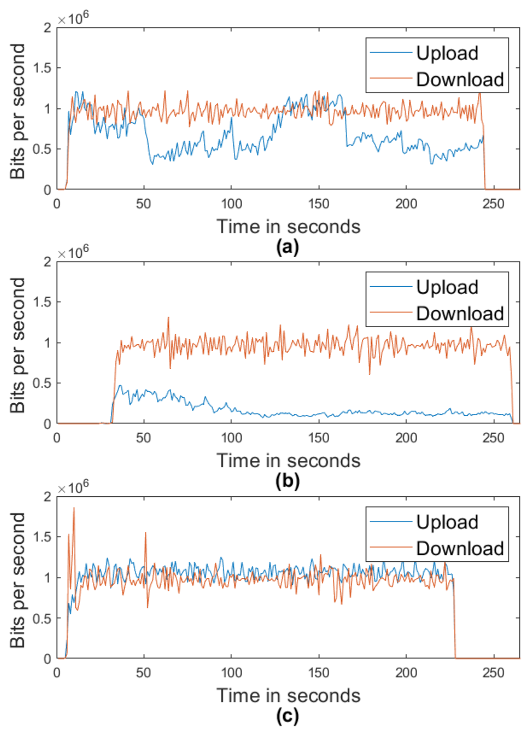

Figure 4. Network traffic rates for Video Connect by ISP during upload (blue) and download (red) for (a) LEO ISP, (b) GEO ISP, and (c) Terrestrial ISP.

5.1.2. Analysis of Terrestrial Versus GEO Rates

We analyze the performance of Video Connect (type one application) over terrestrial and GEO ISPs by examining the data rates and identifying the factors that contribute to any observed differences. This analysis helps us understand how the unique characteristics of GEO satellite communication affect application performance. As seen in Figure 4, the GEO download rate is the same as the terrestrial baseline. However, the upload rate declines very quickly to about 10% of the ideal data rate. This creates a low-resolution video image. The consistently low upload data rate for GEO can be used to infer that a consistently poor channel characteristic is the root cause. The GEO upload channel capacity is orders of magnitude higher than the observed rate, so it cannot be the root cause. While the GEO packet loss rate is higher than terrestrial packet loss, it is well below the 0.25% acceptability margin for video streaming (Pauliks et al., 2015). In addition, the LEO traffic streams have higher packet loss rates but still sustain higher Video Connect data rates.

The consistent but very high latency of the GEO satellite communication channel is the root cause of the poor upload data rate. Latency does not explicitly play a role in bandwidth estimation, but congestion control algorithms can be unresponsive or under-perform in the presence of a high RTT. The combination of high latency and high bandwidth in the GEO satellite communication link results in a large bandwidth-delay product (BDP). To compensate for the poor performance of general transport protocols in this scenario, network operators often introduce large buffers along the communication path (Grazia et al., 2017). Google Congestion Control (GCC) is an example of an algorithm that estimates delay gradient with the assumption that there is a bottleneck queue in the network path producing delay changes that indicate increasing or decreasing congestion. High buffer bloat could reduce the accuracy of delay gradient estimation. This would reduce overall application performance and could produce the behavior shown in the GEO plots from Figure 4. This data supports the conclusion that the Video Connect congestion control algorithm is not robust enough to estimate bandwidth for all high-latency satellite communication connections.

5.1.3. Analysis of Terrestrial Versus LEO Rates

The performance of Video Connect (type one application) over a terrestrial ISP is compared to the performance over a LEO ISPs by examining the data rates and identifying the factors that contribute to any observed differences.

As shown in the top row of Figure 4, the LEO ISP download rates are stable at 1 Mbps, matching the terrestrial ISP baseline. However, the LEO upload rate is inconsistent, fluctuating between approximately 50% and 100% of the terrestrial rate. These fluctuations in bit rate correspond to changes in video resolution, with the ideal resolution achieved when the bit rate reaches 100% of the terrestrial rate, and lower resolutions occurring during periods of reduced data rate.

Although the LEO communication link latency is consistently 3 to 4 times higher than that of a terrestrial ISP, it remains within the 150 ms acceptable RTT margin for face-to-face communications (Jansen et al., 2018). Despite the large fluctuations in available throughput, the LEO ISP data rate consistently surpasses that of the GEO connection and is well above the 1 Mbps required to support the baseline terrestrial data rate for Video Connect. Recall that the LEO ISP channel experiences packet loss spikes at 15-second intervals, which could trigger rate reductions similar to the GCC loss-based sender rate reductions described in Carlucci et al. (2016). These packet loss spikes appear to be the most likely cause of the drops and fluctuations in the upload data rate for Video Connect over the LEO link.

This analysis leads to two additional conclusions about the Video Connect congestion management algorithm. First, the algorithm assumes that either the increasing rate or high level of packet loss in the LEO satellite communication link indicates high congestion. Second, the algorithm is not designed to account for packet loss occurring at regular intervals due to satellite communication frequency reallocation and beam switching. While these assumptions would be valid for a terrestrial ISP, they do not hold for the LEO satellite communication scenario.

5.1.4. Dominant Satellite Communication Characteristics Impacting Video Type One Applications When isolating the type one application User Datagram Protocol (UDP) streams over GEO and LEO ISP paths and comparing data rates to the terrestrial ISP case, it becomes evident that Video Connect (type one) performs better over the LEO than the GEO ISP. The packet loss from the LEO ISP and the latency from the GEO ISP are outside the range of design behavior accommodated by the Video Connect congestion avoidance algorithm, which prevents utilization of the full channel capacity. However, the latency has a far greater impact than the packet loss for Video Connect. Due to the consistently lower resolution over the GEO ISP my hypothesis is that GEO latency is the dominant characteristic impacting the upload video resolution when using GEO satellite communication.

5.2. MS Teams Webinar (Type Two)

In the context of this article, MS Teams Webinar was used as a type two application, focusing on its one-way, real-time broadcast functionality. By analyzing the performance of MS Teams Webinar in this specific use case over different ISPs, we aim to identify the dominant satellite communication characteristics that impact application performance and user experience. This subsection examines metrics such as data rates and inter-arrival times to assess how MS Teams Webinar performs over LEO, GEO, and terrestrial ISPs, providing valuable insights into the suitability of each communication system for supporting one-way, real-time broadcasts in telemedicine applications.

5.2.1. Terrestrial Versus Satellite Communication Data Rates The download data rates for MS Teams Webinar (type two application) are shown in Figure 5 with the LEO, GEO, and terrestrial ISP experiments from top to bottom respectively. The download bit rate pattern is very similar for all of the experiments. The near-ideal data rate performance in all cases indicates the near-ideal performance of the congestion control algorithm. The upload bit rate is very small but is shown because it contains important RTP Control Protocol (RTCP) messages. The most dominant characteristic of the data rate plots is the low data rate at the start of the transmission, followed by the higher data rate at close to 1 Mbps. The video sent for the experiment shows a blank screen with a countdown during the low data rate portion of the transmission, followed by much more dynamic content with moving people and backgrounds during the high data rate section. This indicates that the codec compresses the video before it is transmitted.

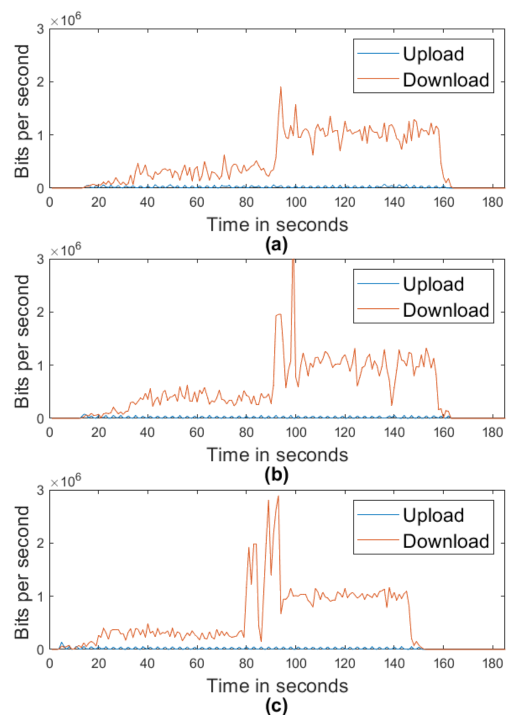

Figure 5. Network traffic rates for MS Teams Webinar (type two application) by ISP during upload (blue) and download (red) for (a) LEO ISP, (b) GEO ISP, and (c) Terrestrial ISP.

5.2.2. Terrestrial Versus Satellite Communication Distribution of UDP Inter-arrival Times The inter-arrival time of UDP datagrams for MS Teams Webinar (type two application) is shown in Figure 6, with LEO, GEO, and the terrestrial ISP shown in the rows from top to bottom respectively. Using the inter arrivals time in the bottom terrestrial ISP row as ideal performance examples, we can see that the GEO ISP has the closest to ideal characteristics. The GEO inter-arrival times group up in the 1 – 15 ms range, just like the terrestrial ISP. The LEO ISP inter-arrival times have a higher variance, with pauses more evenly spread from 1 – 100 ms. While scores for the subjective performance of the LEO and GEO tests were the same, the data would suggest that the application over the LEO channel is farther from the ideal performance characteristics. As discussed in Section 4.3, the LEO ISP has much greater packet loss. The data rates for the MS Teams Webinar tests suggest that the codec is performing compression. Since research by Pauliks et al. (2015) has already established that high-compression codecs are more susceptible to packet loss, observing the inter-arrival time behavior supports the conclusion that the application performance degrades faster over the LEO satellite communication path. While most real time communication (RTC) protocols perform error correction and support re-transmission of missing data at the application layer, the higher packet loss of LEO and the vulnerability of the compression codec to that packet loss make it more likely that the user will experience degradation when using the application. Observing the video from the LEO experiments, it appeared that skips were characteristic of an unrecoverable reference frame. It is likely that the users only experienced similar subjective performance degradation for GEO because the high latency of the channel makes any packet loss more difficult to recover from.

5.2.3. Dominant Satellite Communication Characteristics Impacting Type Two Applications After a close analysis of inter-arrival histograms and data rates for the MS Teams Webinar (type two application) over a LEO, GEO, and terrestrial ISP, it is apparent that the application performs better over the GEO channel due to packet loss on the LEO channel. Even though the subjective observations by testers rated the performance of LEO and GEO equally, the observation of video skips indicating a missing reference frame, inter-arrival time data, and measured packet loss over LEO indicate that the application performance was degrading faster over LEO. While the MS Teams Webinar application performed better over the GEO path, research suggests that alternative codecs and congestion management algorithms that detect satellite handovers could be used to improve the performance of type two applications over the LEO ISP (Li & Wang, 2022). Pauliks et al. (2015) showed that packet loss greater than 3% would cause a significant drop in viewer satisfaction when using a high-efficiency compression codec. The packet loss spikes over LEO could easily exceed 3% over a short time window. Congestion avoidance algorithms like GCC would not trigger transmit rate reduction unless packet loss exceeded 10% for a period of time (Jansen et al., 2018). Based on the data rates observed and the video skips, we can confirm the packet loss impact on the video codec. Packet loss was the dominant performance characteristic in this experiment.

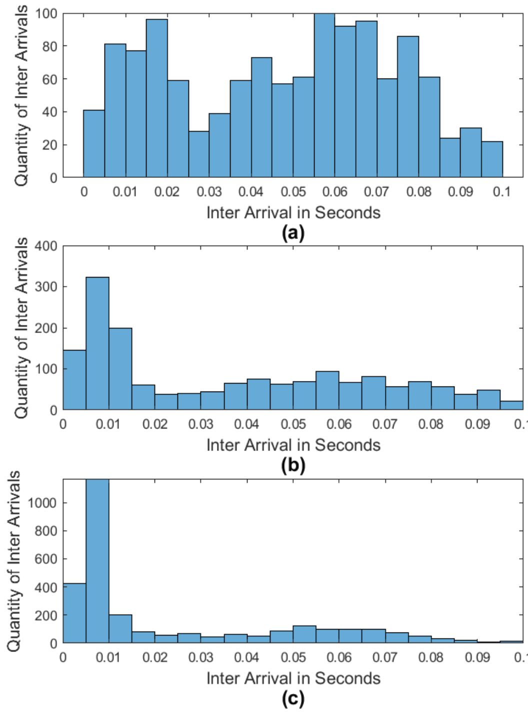

Figure 6. Datagram download inter-arrival time for MS Teams Webinar (type two application) by ISP. (a) LEO MS Teams Webinar, showing the distribution of inter-arrival times. (b) GEO MS Teams Webinar. (c) Terrestrial ISP MS Teams Webinar.

5.3. Vital Sign Monitoring Telemetry Application (Type Three)

In telemedicine, a type three telemetry application plays a crucial role in transmitting real-time patient vital signs data from monitoring devices to remote medical professionals. In this study, the type three telemetry application utilized a simple TCP connection to a server to share data with any distant end application. The test was performed using an Android tablet at the local end of the communication link. Analyzing the performance of the type three telemetry application over different ISPs will provide insights into how the characteristics of each communication system — along with the behavior of the TCP congestion control algorithm — affect the transmission of vital signs data in telemedicine scenarios.

5.3.1. Terrestrial Versus Satellite Communication Data Rates For the TCP applications, the only traffic comparison characteristic used for analysis was the application data rate. The rates for the type three application are shown in Figure 7. The LEO, GEO, and terrestrial ISP experiment data rates are shown in rows from top to bottom, respectively. The middle row differs from the others because of the shortened and flattened data rates. This appears to be much more pronounced for the GEO download data rates than the upload data rates. While TCP congestion control is responsive, it is still reliant on the RTT to determine if a congestion event has occurred when increasing data rate (Liu et al., 2022). The degraded performance shown for GEO in Figure 7 was not detectable by the user but is visible in the data rate.

5.3.2. Dominant Network Communication Metric Impacting Type Three Applications For the type three application test, the LEO ISP clearly outperformed the GEO ISP. The dominant characteristic impacting GEO performance was the high latency of the GEO ISP. It is possible that a better implementation of the performance enhancement proxy (PEP) would improve GEO performance, but latency would still be greater than the 500 ms threshold recommended for remote vital sign monitoring (Qureshi et al., 2022).

5.4. Large File Download (Type Four)

The ability to quickly and reliably download large files, such as high-resolution medical images, patient records, or medical manuals, is essential for effective remote consultation and diagnosis. To assess the performance of different communication systems in this context, we conducted a test involving a web browser-based download of a large file from a DOD file server using the TCP protocol at the transport layer.

The data for this experiment show no degradation of performance using either satellite constellation

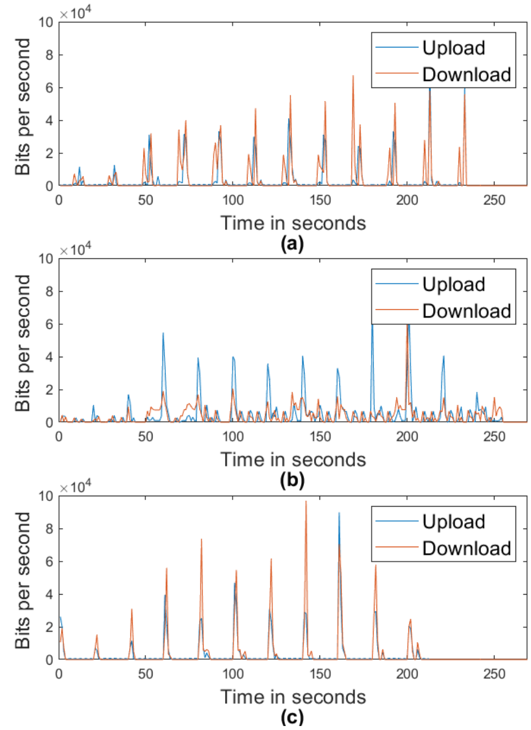

Figure 7. Network traffic rates for vital sign telemetry (type three application) data by ISP. (a) LEO ISP, showing upload (blue) and download (red) rates, (b) GEO ISP, and (c) Terrestrial ISP.

compared to a terrestrial network. The download was completed faster over both the LEO and GEO ISP than the terrestrial ISP. It is unclear why the two satellite communication ISPs with higher latency, packet loss, and lower bandwidth performed so well. The behavior could be related to PEP optimization. While the LEO ISP reached a higher peak data rate, it is unclear that it performed better than the GEO ISP for this test.

6. Conclusion

Telemedicine has emerged as a critical solution for providing healthcare in austere environments, but its success relies on the performance of the underlying communication infrastructure. As military operations, disaster relief, and humanitarian efforts extend into regions with limited terrestrial connectivity, satellite communication has become the backbone for enabling telemedicine. However, the choice between LEO and GEO satellite networks impacts the performance of telemedicine applications. This article makes several contributions to the field of telemedicine in austere environments. First, it objectively demonstrates that LEO satellite communication outperforms GEO for

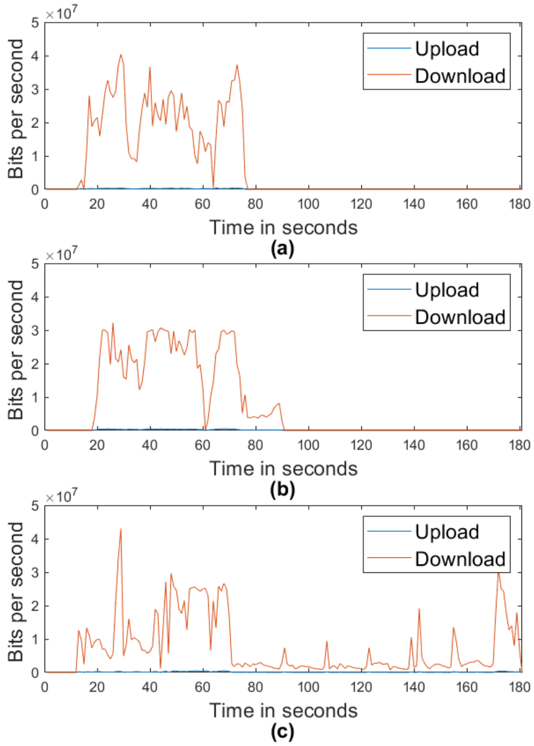

Figure 8. Network traffic rates for large file download (type four application) by ISP. (a) LEO SATCOM large file download, showing upload (blue) and download (red) rates. (b) GEO SATCOM large file download. (c) Terrestrial ISP large file download.

two out of four telemedicine application types tested and has comparable performance for the other two, even with only around half of the planned satellites launched for the Starlink constellation at the time of the tests. This establishes LEO as the superior choice overall. Second, it highlights the higher throughput and lower latency offered by LEO satellite communication compared to GEO over a several week period of time. While this study would benefit from longer testing to determine reliability, testing on a wider range of applications, and cost analysis, the LEO metrics measured are overall more desirable for the telemedicine applications tested. However, it reveals that LEO satellite communication has a higher packet loss ratio than GEO. Based on the unique characteristics of LEO satellite communication systems, the paper offers practical recommendations for application and network design to optimize the performance of telemedicine solutions in austere environments. For application design, this work recommends a combination of these optimizations:

- Use video codecs resilient to packet loss, like those with intra-refresh and sub-frame encoding, for LEO satellite communications (Mody et al., 2014).
- Employ congestion control tailored for LEO characteristics, like outlier detection for handovers (Li & Wang, 2022).
- Consider Quick UDP Internet Connections (QUIC) protocol instead of TCP for more sophisticated congestion control (Iyengar & Swett, 2021).

For network design, this work recommends:

- Be cautious when extending LEO with wireless hops, as added latency and packet loss can compound issues.
- Performance-enhancing proxies can help overcome latency challenges (Liu et al., 2022).
- Use dedicated portable LEO VSATs for critical real-time applications as an alternative to wireless extensions (McKnight et al., 2022).

With such optimizations, LEO satellite communication can provide an effective connectivity backbone to enable high-quality telemedical care in austere environments. These contributions advance our understanding of how different satellite communication systems impact telemedicine applications and provide valuable insights for designing effective and resilient solutions.

References

Buhl, V. J. (2024, June). *A comparative analysis on using low earth orbit and geosynchronous orbit satellite communication systems to support telemedical networks in austere environments* [Master's Thesis]. Naval Postgraduate School. https://hdl.handle.net/10945/73080

Carlucci, G., De Cicco, L., Holmer, S., & Mascolo, S. (2016). Analysis and design of the google congestion control for web real-time communication (WebRTC). *Proceedings of the 7th International Conference on Multimedia Systems*. https://doi.org/10.1145/2910017.2910605

Federal Communications Commission. (2023, January). Measuring Fixed Broadband - Twelfth Report. Retrieved February 29, 2024, from https://www.fcc.gov/reports-research/reports/measuring-broadband-america/measuring-fixed-broadband-twelfth-report

Garcia, J., Sundberg, S., Caso, G., & Brunstrom, A. (2023). Multi-timescale evaluation of Starlink throughput. *Proceedings of the 1st ACM Workshop on LEO Networking and Communication*, 31–36. https://doi.org/10.1145/3614204.3616108

Grazia, C. A., Patriciello, N., Klapez, M., & Casoni, M. (2017). Mitigating congestion and bufferbloat on satellite networks through a rate-based AQM [ISSN: 1938-1883]. *2017 IEEE International Conference on Communications (ICC)*. https://doi.org/10.1109/ICC.2017.7996776

Hegarty, A., Omerdic, E., Trslić, P., Tormey, D., Dooly, G., & Toal, D. (2023). A practical comparison of geo and leo satellite communication systems for remote presence control of an ROV. *OCEANS 2023 - Limerick*, 1–10. https://doi.org/10.1109/OCEANSLimerick52467.2023.10244445

Iyengar, J., & Swett, I. (2021, May). *QUIC loss detection and congestion control* (Request for Comments No. RFC 9002). Internet Engineering Task Force. https://doi.org/10.17487/RFC9002

Jansen, B., Goodwin, T., Gupta, V., Kuipers, F., & Zussman, G. (2018). Performance evaluation of WebRTC-based video conferencing. *ACM SIGMETRICS Performance Evaluation Review*, *45*(3), 56–68. https://doi.org/10.1145/3199524.3199534

Li, X., & Wang, G. (2022). Handover detection and fast recovery over satellite networks for WebRTC. *2022 IEEE 8th International Conference on Computer and Communications (ICCC)*, 599–603. https://doi.org/10.1109/ICCC56324.2022.10065763

Liu, M., Liu, Y., Ma, Z., Porter, Z., Chung, J., Claypool, S., Li, F., Tutlis, J., & Claypool, M. (2022). The effects of a performance enhancing proxy on tcp congestion control over a satellite network [ISSN: 2374-9628]. *2022 IEEE International Performance, Computing, and Communications Conference (IPCCC)*, 325–331. https://doi.org/10.1109/IPCCC55026.2022.9894351

McKnight, G., O'Reilly, D., Guthrie, H., Maung, N. A., Bull, J., Bartels, O., & Baxter, D. (2022). Lessons from the use of telemedicine in the austere military environment and the implications for deployed surgical teams. *BMJ Military Health*. https://doi.org/10.1136/bmjmilitary-2021-002060

Michel, F., Trevisan, M., Giordano, D., & Bonaventure, O. (2022). A first look at starlink performance. *Proceedings of the 22nd ACM Internet Measurement Conference*, 130–136. https://doi.org/10.1145/3517745.3561416

Mody, M., Swami, P., & Shastry, P. (2014). Ultra-low latency video codec for video conferencing. *2014 IEEE International Conference on Electronics, Computing and Communication Technologies (CONECCT)*. https://doi.org/10.1109/CONECCT.2014.6740280

Pandav, K., Te, A. G., Tomer, N., Nair, S. S., & Tewari, A. K. (2022). Leveraging 5G technology for robotic surgery and cancer care. *Cancer Reports (Hoboken, N.J.)*, *5*(8). https://doi.org/10.1002/cnr2.1595

Pauliks, R., Slaidins, I., Tretjaks, K., & Krauze, A. (2015). Assessment of IP packet loss influence on perceptual quality of streaming video. *2015 Asia Pacific Conference on Multimedia and Broadcasting*, 1–6. https://doi.org/10.1109/APMediaCast.2015.7210275

Qureshi, H. N., Manalastas, M., Ijaz, A., Imran, A., Liu, Y., & Al Kalaa, M. O. (2022). Communication requirements in 5g-enabled healthcare applications: Review and considerations. *Healthcare*, *10*(2). https://doi.org/10.3390/healthcare10020293

Tolouei, P. (2023). Analysing the performance of cloud gaming over a low-earth orbit satellite network. https://dspace.library.uvic.ca/items/932cb4c6-0527-4e3a-8bb4-a8cae7c32293/full