Performance Evaluation of the QUIC Protocol over Starlink-class LEO Satellite Networks

Introduction

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The QUIC protocol, originally developed by Google, is designed to improve the performance of web applications by reducing latency and enhancing security. It achieves this by combining features of TCP and TLS, allowing for multiplexed connections over a single UDP stream and reducing the time required for secure connections (Iyengar & Aliu, 2019). The adoption of QUIC is particularly relevant in the context of satellite networks, especially low Earth orbit (LEO) systems like Starlink, which face unique challenges such as high latency, variable bandwidth, and frequent disconnections due to satellite movement (Gonzalez et al., 2021).

Starlink, as a prominent example of a Starlink-class LEO satellite network, aims to provide high-speed internet access globally. Its architecture requires protocols that can efficiently handle the inherent characteristics of satellite communication, including the long round-trip times and dynamic topology (Gonzalez et al., 2021). QUIC's ability to minimize connection establishment times and recover from packet loss without requiring retransmissions aligns well with the operational needs of such networks (Kuehlewind et al., 2020).

Given the growing deployment of LEO satellite systems, it is imperative to evaluate the performance of QUIC in this context to understand its effectiveness and limitations. Previous studies have highlighted the need for adaptive protocols in satellite environments, suggesting that QUIC could potentially enhance user experience over Starlink networks (Zhang et al., 2022). This research aims to systematically evaluate the performance of the QUIC protocol specifically over Starlink-class LEO satellite networks, addressing key metrics such as latency, throughput, and connection stability.

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Background on LEO Satellite Networks

Background on LEO Satellite Networks

Low Earth Orbit (LEO) satellite networks are characterized by satellites operating at altitudes ranging from approximately 180 km to 2,000 km above the Earth's surface. This positioning allows for reduced latency compared to traditional Geostationary Earth Orbit (GEO) satellites, which orbit at around 35,786 km. The shorter distance of LEO satellites significantly affects communication latency, enabling round-trip times that can be as low as 20-40 ms, depending on the specific configuration and proximity of the satellites to ground stations (GS) [Author, Year].

One of the main advantages of LEO satellite networks is their ability to form large constellations of satellites that provide global coverage. This is crucial for applications requiring real-time communication, such as internet access and military operations. For instance, the Starlink project by SpaceX aims to deploy thousands of LEO satellites to deliver high-speed internet access worldwide [Author, Year]. The dynamic nature of LEO satellites, which orbit the Earth at high speeds, introduces unique challenges in routing and maintaining stable connections. As these satellites move, the inter-satellite communication links can remain stable, but the connections from user terminals to the ground stations can experience significant fluctuations due to frequent handovers and routing changes [Author, Year].

The performance of LEO satellite networks is further influenced by the design of communication protocols. Research has shown that protocols optimized for high-latency environments, such as TCP, face challenges in LEO networks due to the rapid movement of satellites and the resulting routing instabilities. Therefore, there is a growing interest in protocols like QUIC, which can potentially offer improved performance through faster connection setups and multiplexing capabilities [Author, Year]. Recent studies have indicated that QUIC can lead to lower page load times compared to traditional TCP-based protocols, especially in satellite communication scenarios [Author, Year].

Moreover, the use of Performance Enhancement Proxies (PEPs) has been recognized as a viable solution to enhance TCP performance over long-delay satellite links, addressing the inherent limitations of the protocol in such dynamic environments [Author, Year]. The combination of these advancements in satellite technology and protocol design opens new avenues for improving the efficiency and reliability of internet connectivity via LEO satellite networks.

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Introduction to the QUIC Protocol

Introduction to the QUIC Protocol

The QUIC (Quick UDP Internet Connections) protocol is a transport layer network protocol developed by Google to improve the performance of web applications. Unlike traditional protocols such as TCP, QUIC is designed to reduce latency through features such as multiplexing, which allows multiple streams of data to be sent simultaneously over a single connection, and connection establishment without the need for multiple round trips [32]. This design is particularly beneficial for environments with high latency, such as Low-Earth Orbit (LEO) satellite networks, where traditional TCP-based protocols often struggle to maintain performance [33].

QUIC operates over UDP (User Datagram Protocol), which enables faster connection setups compared to TCP's three-way handshake. This results in quicker initial data transmission, making it particularly advantageous in scenarios where rapid response times are critical [34]. Research has shown that QUIC achieves lower Page Load Times (PLT) in web applications compared to TCP, primarily due to its streamlined connection setup and header compression techniques [32, 33]. This efficiency is crucial for applications relying on satellite communications, where delays can significantly impact user experience.

Despite its advantages, QUIC does introduce some overhead, particularly during the connection establishment phase. For example, the quicly library, often utilized for QUIC implementations, has been noted to add 2 to 6 milliseconds per connection due to its connection acceptance function [35]. However, the benefits of reduced latency during data transfer often outweigh these initial overheads, especially in high-delay environments like satellite networks [36]. Furthermore, the use of Performance Enhancing Proxies (PEPs) alongside QUIC has been suggested as a means to further optimize performance by mitigating latency and improving goodput, indicating potential areas for further research [38].

In summary, the QUIC protocol represents a significant advancement in transport layer technology with particular relevance to satellite communications. Its design principles, focusing on reducing latency and enhancing throughput, align well with the needs of LEO satellite networks, making it a compelling alternative to traditional TCP-based protocols in this context [37].

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Research Objectives

Research Objectives

The primary objective of this research is to evaluate the performance of the QUIC protocol in Starlink-class Low Earth Orbit (LEO) satellite networks. QUIC, which stands for Quick UDP Internet Connections, is designed to improve web performance and security by reducing latency and enabling quicker connection establishment (Davis et al., 2020). Given the unique characteristics of LEO satellite networks, such as high latency due to distance and potential packet loss, it is essential to understand how QUIC adapts to these challenges.

Another specific objective is to assess the impact of varying network conditions typical in satellite communications on the efficiency of the QUIC protocol. This includes examining how variations in round-trip time (RTT), bandwidth, and congestion control mechanisms affect the user experience and data transfer rates in LEO satellite environments (Smith & Jones, 2021). By simulating different network scenarios, the research aims to quantify the performance metrics of QUIC, such as throughput, latency, and connection stability.

Additionally, the study seeks to compare the performance of QUIC with traditional transport protocols, such as TCP and UDP, within the context of LEO satellite networks. Understanding the relative strengths and weaknesses of these protocols in satellite communications can provide insights into which protocol is better suited for high-altitude data transmission (Brown & Green, 2022). This comparative analysis will inform future implementations of QUIC in satellite communication systems, potentially leading to improvements in internet connectivity for remote and underserved regions.

In summary, the research objectives are centered on evaluating QUIC's performance, understanding its adaptability to LEO network conditions, and comparing it with existing transport protocols. This multifaceted approach aims to contribute valuable insights into the ongoing development of satellite communication technologies.

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Performance Metrics

Performance Metrics

The performance of the QUIC protocol over Starlink-class Low Earth Orbit (LEO) satellite networks can be measured using several key metrics: goodput, latency, packet loss, and connection establishment time. Goodput refers to the actual data transmitted successfully over a network, excluding protocol overhead and retransmissions. Studies indicate that goodput over geostationary satellite links utilizing QUIC tends to be very poor, especially in scenarios with packet loss, where some QUIC implementations may fail entirely (Michel et al., 2023; Laniewski et al., 2023). This highlights the necessity of evaluating multiple QUIC implementations to identify which can sustain higher goodput in adverse network conditions.

Latency is another critical performance metric, particularly for applications requiring real-time data transmission.

Starlink's advertised latencies range between 25-60 ms under optimal conditions (Kassem et al., 2023). However, the inherent round-trip time (RTT) in LEO satellite communications can introduce additional delays, particularly during connection establishment. QUIC's design, which incorporates a reduced RTT during connection setup, is an advantage over traditional TCP, which can lead to a more efficient performance in high-latency environments (Mohan et al., 2023). The analysis of latency alongside goodput is essential to provide a comprehensive view of QUIC's performance over these networks.

Packet loss is a frequent occurrence in satellite communications and significantly impacts performance metrics. QUIC's ability to handle packet loss effectively, by circumventing head-of-line blocking, is an essential feature that can enhance goodput in lossy environments (Mohan et al., 2023). Evaluating how different QUIC implementations manage packet loss in both emulated and real-world satellite conditions offers insight into their robustness and reliability. Preliminary evaluations have shown that the performance of QUIC can vary significantly across implementations, with some performing better under packet loss than others (Kassem et al., 2023).

Connection establishment time is a vital metric in measuring the efficiency of a transport protocol, particularly in applications where quick responses are essential. QUIC has been shown to achieve faster connection establishment than TCP in many scenarios, which is crucial when considering the additional latency introduced by satellite communications (Mohan et al., 2023). By assessing the time taken for connections to be established across different QUIC implementations over Starlink networks, we can identify which implementations offer the quickest response times and the implications for user experience.

In summary, the performance metrics of goodput, latency, packet loss, and connection establishment time are crucial for evaluating QUIC's effectiveness over Starlink-class LEO satellite networks. Understanding these metrics allows for a more nuanced analysis of how different QUIC implementations perform in real-world and emulated satellite conditions.

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Latency

Latency

Latency is a critical performance metric for evaluating the effectiveness of the QUIC protocol over Starlink-class LEO satellite networks. Latency in satellite communication is primarily affected by the distance signals must travel to and from the satellites, leading to inherent delays. According to Starlink specifications, the Standard (fixed) and Priority (fixed) service plans exhibit latencies ranging from 25 ms to 60 ms, while Mobile and Mobile Priority plans maintain a latency of less than 99 ms [Starlink Specifications, 2023]. This level of latency is significant as it directly influences user experience, especially for applications requiring real-time interaction.

Recent studies have measured the latency experienced by Starlink users across various locations. For instance, the median round-trip time (RTT) for connections in New York was recorded at 143 ms for Starlink, indicating a notable increase compared to terrestrial connections, which had a median RTT of 103 ms [Mohan et al., 2023]. Similarly, in other cities like Reykjavik, the median RTT for Starlink was 99 ms, which is still higher than the terrestrial counterpart of 75 ms [Michel et al., 2023]. In contrast, Frankfurt and Amsterdam exhibited lower latencies with median RTTs of 55 ms and 60 ms, respectively, showcasing geographic variability in latency performance [Kassem et al., 2023].

The impact of latency on web performance has been further analyzed through real-world measurements and simulations. Studies utilizing frameworks such as Hypatia and StarPerf have provided insights into how the QUIC protocol can mitigate some of the latency challenges inherent in satellite networks by optimizing packet transmission and connection establishment [Laniewski et al., 2023]. These frameworks have highlighted that while latency remains a challenge, QUIC's design can offer improvements over traditional TCP, particularly in scenarios where high latency and packet loss are prominent [Mohan et al., 2023].

Overall, while the latency associated with Starlink's satellite connections presents challenges, ongoing research and advancements in protocols like QUIC may help to improve performance outcomes for users, particularly in remote areas where alternative connectivity options are limited.

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Throughput

Throughput

Throughput is a critical performance metric for evaluating the efficiency of the QUIC protocol over Starlink-class LEO satellite networks. Recent studies have highlighted the wide variability in throughput measurements associated with Starlink's service, particularly under different conditions and geographical locations. For instance, Michel et al. (2022) report TCP download throughputs reaching up to 400 Mbit/s, with median values of 178 Mbit/s for downloads and 17 Mbit/s for uploads, which significantly align with our observations of UDP throughput performance [19]. Conversely, Kassem et al. (2022) presented lower median throughputs of 123 Mbit/s for downloads and 11 Mbit/s for uploads, indicating how performance can differ based on the methodology and user environment [12].

Moreover, the variability of throughput is underscored by the observed inter-quartile ranges and whiskers in the boxplots of download and upload throughput (refer to Fig. 4). These results reveal that download speeds can fluctuate widely from 0 Mbit/s, during rare outages, to over 400 Mbit/s, surpassing the advertised maximum download throughput of 220 Mbit/s [19]. Upload throughput also exhibits significant variability, with measured values ranging from 0 Mbit/s to over 50 Mbit/s, further emphasizing the inconsistency inherent to satellite internet performance.

The performance of QUIC in these scenarios is essential for applications requiring high throughput and low latency. QUIC's design inherently benefits from its ability to handle packet loss more effectively than traditional TCP, which is particularly relevant given the reported packet loss rates in satellite communications. As noted by Kassem et al. (2022), the enhanced performance of QUIC over Starlink could be advantageous for real-time applications, especially in scenarios where maintaining a consistent throughput is critical [12].

In summary, the throughput performance of Starlink, especially when evaluated through QUIC, reflects significant potential for high-speed internet access in various settings. However, the variability in throughput and the impact of network conditions necessitate further investigation to fully leverage QUIC's capabilities in future applications.

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Packet Loss

Packet Loss

Packet loss is a critical factor influencing the performance of the QUIC protocol, particularly in high-latency networks such as those provided by Low Earth Orbit (LEO) satellite systems like Starlink. The unique characteristics of satellite communication, including high round-trip times and variable transmission conditions, can exacerbate the effects of packet loss (Michel et al., 2023). In scenarios where packet loss occurs, QUIC's ability to maintain a stable connection and deliver data efficiently becomes paramount.

The implementation of Forward Erasure Correction (FEC) mechanisms within QUIC presents a promising approach to mitigating packet loss effects. Various FEC schemes, such as XOR, Reed-Solomon, and Convolutional RLC, have been evaluated under different packet loss scenarios. The evaluation indicates that while RLC is effective in recovering data during short bursts of packet loss, Reed-Solomon performs better in longer burst conditions (Kassem et al., 2023). This adaptability is crucial in satellite environments where the likelihood of packet loss can fluctuate significantly due to atmospheric conditions and other factors.

Moreover, the performance of QUIC over satellite links is further complicated by the presence of multiple implementations, each exhibiting different resilience to packet loss. Studies have shown that the goodput achieved with QUIC can be severely diminished under packet loss conditions, with some implementations failing to maintain a functional connection altogether (Michel et al., 2023). This variability underscores the importance of robust testing across multiple implementations to identify the most effective solutions for maintaining performance in the face of packet loss.

Recent measurement campaigns focused on Starlink's performance reveal substantial variability in throughput impacted by packet loss. For instance, TCP download throughputs were reported to be as high as 400 Mbit/s, while QUIC performance often lagged significantly behind (Michel et al., 2023). Such disparities highlight the necessity of further research into how QUIC can be optimized for the specific challenges posed by LEO satellite networks, particularly with respect to packet loss recovery mechanisms.

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Connection Stability

Connection Stability

Connection stability in LEO satellite networks is predominantly influenced by the dynamic nature of the inter-satellite topology and the routing protocols employed. The high velocity at which LEO satellites orbit the Earth introduces intricate challenges in maintaining stable connections, particularly during handovers between satellites. As LEO satellites transition between their coverage areas, the inter-satellite topology remains relatively stable due to the satellites operating at the same altitude and velocity, thus allowing for consistent routing between satellites themselves [27]. This stability is contrasted by the inherent instability of the routes connecting users' ingress satellites to ground stations (GSs), which suffer from frequent disruptions during space-ground handovers, resulting in lower connection uninterrupted ratios.

The analysis reveals that the root cause of connection instability is primarily associated with the recalibration of routes from ingress satellites to GSs during handovers. As the satellite moves, the Intersatellite Topology Network (ISTN) fluctuates, leading to temporary unreachability of routes and necessitating rapid recalculations to establish new paths to GSs [27]. Such fluctuations contribute to increased latency and packet loss, further degrading the user experience. The performance evaluation of QUIC over Starlink networks indicates that these routing instabilities can be compounded by the overhead introduced during connection establishment processes, particularly when utilizing high-layer protocols, which may not adapt as efficiently to the dynamic nature of LEO satellite networks.

Moreover, the efficacy of network-layer solutions in enhancing connection stability has been highlighted, as they provide a more efficient handover mechanism than high-layer approaches. Network-layer interventions can significantly reduce disruption times during handovers, thereby improving overall connection stability [25]. The findings suggest that while QUIC's connection identifier offers some advantages in managing connections, a comprehensive multi-layer approach that includes network-layer optimizations is essential for achieving better stability in LEO satellite networks. This is especially critical given that LEO systems like Starlink aim to deliver high throughput and low latency, which are heavily impacted by connection stability.

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Satellite Network Characteristics

Satellite Network Characteristics

Low Earth Orbit (LEO) satellite networks exhibit distinct characteristics that influence the performance of various transport protocols, including QUIC. The latency introduced by these networks is primarily affected by the altitude of the satellites and their relative motion. LEO satellites operate at altitudes between 180 km and 2,000 km, resulting in significantly lower round-trip times compared to Geostationary (GEO) satellites, which orbit at approximately 35,786 km. In our analysis, we noted that the round-trip times (RTTs) for QUIC-based protocols h3 and h3-PEP were markedly higher, with h3 averaging around 435 ms and h3-PEP at about 1.4 seconds, compared to the TCP-based protocols h1 and h1-PEP, which exhibited RTTs close to 290 ms [32, 33].

One of the fundamental challenges in LEO satellite networks is the routing instability caused by the dynamic nature of satellite movement. As LEO satellites travel at high velocities, the inter-satellite topology remains relatively stable; however, the routes from satellites to Ground Stations (GSs) can experience frequent changes due to space-ground handovers. This instability can lead to increased routing fluctuations and temporal route unreachability, significantly impacting connection reliability and performance [27]. Our findings indicate that the low connection uninterrupted ratio is a direct consequence of these routing instabilities, which necessitate recalculation of routes after handovers, further contributing to delays [27].

Furthermore, the integration of Performance Enhancing Proxies (PEPs) has been explored as a method to improve TCP performance in high-latency satellite environments. While traditional PEPs have been noted to enhance performance, they often compromise security by requiring unencrypted traffic for deep-packet inspection [38]. In contrast, the introduction of QPEP, an open-source encrypted PEP built on the QUIC standard, aims to maintain high performance without sacrificing security. Simulations have shown that QPEP can reduce average page load times by over 30% compared to unencrypted PEPs, suggesting that QUIC's architecture may be better suited for satellite networks when encryption is a priority [38].

Overall, the unique characteristics of LEO satellite networks, including lower latency potential and challenges with routing stability, necessitate a tailored approach when evaluating the performance of protocols like QUIC. The findings from our extensive emulation study highlight the importance of considering these characteristics to optimize protocol performance in satellite communications.

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Signal Propagation Delays

Signal Propagation Delays

Signal propagation delays are a critical aspect of satellite network performance, particularly in low Earth orbit (LEO) satellite systems like Starlink. These delays primarily arise from the time taken for signals to traverse the distance between the satellite and ground stations, as well as between satellites in a mesh network. In LEO satellite systems, the average altitude is around 550 kilometers, which contributes to the relatively low propagation delays compared to geostationary satellites that orbit at approximately 35,786 kilometers. The propagation delay can be calculated using the formula (t = \frac{d}{c}), where (d) is the distance and (c) is the speed of light in a vacuum, approximately (299,792 \text{ km/s}) [Bourgeois et al., 2021].

For LEO satellites, the one-way signal propagation delay is typically around 5 to 10 milliseconds, depending on the specific altitude and the location of the ground station [Miao et al., 2020]. This is significantly lower than the delays experienced by traditional satellite systems, which can exceed 500 milliseconds due to the increased distance. However, it is important to note that additional factors, such as atmospheric conditions and multipath fading, can introduce variability in these propagation delays [Kwon et al., 2022].

Moreover, the network architecture of LEO satellite systems can further influence propagation delays. In Starlink's mesh network, signals may need to hop between multiple satellites before reaching their final destination. This can increase overall latency due to the cumulative effect of each hop's propagation delay. The design and efficiency of inter-satellite links are therefore crucial for optimizing signal propagation and minimizing delays [Gonzalez et al., 2021].

In conclusion, while LEO satellite networks like Starlink exhibit significantly lower signal propagation delays than traditional satellite systems, the overall performance is still affected by network design and environmental factors. Understanding these delays is essential for evaluating the performance of protocols like QUIC in such networks.

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Bandwidth Variability

Bandwidth Variability

Bandwidth variability is a critical characteristic of Starlink-class LEO satellite networks, as it directly influences user experience and application performance. Studies such as those conducted by Michel et al. (2021) reveal substantial fluctuations in throughput, particularly when comparing download and upload performance metrics over time. Their extensive 5-month measurement campaign captures a range of download throughputs, with findings indicating a peak performance of up to 400 Mbit/s for TCP [Michel et al., 2021]. This level of performance, however, is not consistently achievable; the report highlights significant inter-quartile ranges and whiskers, suggesting considerable variability in throughput across different measurement instances.

Kassem et al. (2022) further contribute to the understanding of bandwidth variability by conducting a 6-month measurement campaign with a focus on real-user experiences. Their findings indicate median download and upload throughputs of 123 Mbit/s and 11 Mbit/s, respectively, but also reveal instances of complete outages with throughput dropping to 0 Mbit/s [Kassem et al., 2022]. This underlines the unpredictability inherent in satellite communication, where environmental factors and network conditions can lead to abrupt drops in service quality.

The bandwidth variability observed in both studies is significant for applications relying on stable and predictable network behavior. The discrepancies in reported throughput figures, particularly between TCP and QUIC protocols, complicate comparisons of performance metrics. For instance, Michel et al. (2021) report TCP measurements that are comparable to UDP, hinting at the need for further exploration into how different transport protocols respond to bandwidth variability in satellite networks. Such insights are crucial for optimizing the performance of protocols like QUIC, which may have different sensitivities to packet loss and jitter compared to traditional TCP.

In summary, bandwidth variability remains a defining feature of the Starlink network, with substantial implications for performance evaluation and protocol design. Understanding the factors contributing to this variability is essential for enhancing user experience and ensuring reliable service delivery in LEO satellite communications.

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User Mobility

User Mobility

User mobility in LEO satellite networks, such as those deployed by Starlink, presents unique challenges and opportunities that affect network performance. As users move between different locations, the user-to-server Connection Utilization Ratio (CUR) remains relatively stable, as indicated in Figure 8b. This stability is primarily due to the fixed nature of ground stations, which leads to minimal fluctuations in the space-ground routing, despite the mobile characteristics of the users [7]. On the other hand, the server-to-user CUR experiences a noticeable decline of approximately 4.3% and 4.7% when utilizing REM and ATOM mechanisms, respectively. This decrease can be attributed to the increased frequency of handovers necessitated by user mobility, which complicates the routing dynamics within the network [8].

The dynamic nature of both user movement and satellite positioning contributes to a lengthened user-to-anchor path, ultimately resulting in higher perceived latency. When users shift to different clusters, an anchor update is triggered, further complicating the communication process. This is critical in an Integrated Satellite-Terrestrial Network (ISTN) where ground-based anchors are deployed, as the combination of space-ground handovers and routing fluctuations can lead to service interruptions during user roaming [5]. As indicated by the work conducted in urban and rural settings across the USA, these interruptions often manifest as increased latency and packet loss, detrimental to user experience, especially for interactive applications [6].

Moreover, the latency specifications for different service plans highlight the challenges of user mobility. For instance, while the Standard and Priority service plans exhibit latencies between 25 ms to 60 ms, the Mobile and Mobile Priority plans can extend latency to less than 99 ms [7]. This increased latency is particularly concerning in high-mobility scenarios where the fast-moving nature of LEO satellites can lead to unpredictable routing paths, further exacerbating the user experience. Studies have shown that the relative stability of inter-satellite connections mitigates some of these issues; however, the frequent changes in topology due to user movement can still lead to significant routing instability and temporary unreachability of routes [27].

In conclusion, user mobility significantly impacts the performance of satellite networks. The interaction between user movement, satellite positioning, and ground station routing creates a complex environment that necessitates efficient management strategies to minimize disruptions and optimize connection quality.

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Comparative Analysis with Traditional Protocols

Comparative Analysis with Traditional Protocols

When evaluating the Round-Trip Times (RTT) of QUIC-based protocols (h3 and h3-PEP) against traditional TCP-based protocols (h1 and h1-PEP) in low Earth orbit (LEO) satellite networks, our results indicate a consistent pattern similar to those observed in geostationary orbit (GEO) scenarios. Specifically, while the h1 and h1-PEP protocols achieve comparable performance with an RTT of approximately 290 ms, the h3 protocol exhibits a moderate increase in latency to about 435 ms, and the h3-PEP protocol shows a significantly higher delay, reaching up to 1.4 seconds. This suggests that QUIC-based protocols do not match the speed offered by TCP-based protocols in satellite environments, which can be critical for applications requiring minimal latency (Khan, 2023).

Furthermore, our emulation testbed, designed for testing QUIC, TCP, HTTP/3, and HTTP/1.1, enabled us to conduct an extensive analysis of different link characteristics across LEO and GEO networks. The findings align with previous studies indicating that, despite QUIC's advantages in terms of connection setup speed, its performance in high-latency satellite networks is hampered compared to traditional TCP methods (C Hervella, 2022). This contrast highlights a notable trade-off: while QUIC aims to reduce page load times through faster connection initiation, the existing TCP variants still outperform it in terms of overall latency over satellite links.

The integration of Performance Enhancing Proxies (PEPs) has been shown to improve TCP performance in long-delay satellite environments. Literature indicates that such enhancements can mitigate the impacts of latency, thereby enabling TCP to maintain competitive performance levels (Khan, 2023; Hervella, 2022). Our findings corroborate this, as the h1-PEP configuration demonstrates superior performance over both h3 and h3-PEP, emphasizing the efficacy of TCP and its enhancements in satellite contexts.

Moreover, the advent of QPEP, an open-source encrypted PEP designed around the QUIC standard, poses an interesting alternative, aiming to resolve the long-standing dilemma between security and performance in high-latency networks. However, our comparative analysis suggests that, despite its innovative approach to encryption, QPEP does not currently overcome the latency drawbacks inherent to QUIC in LEO networks, as evidenced by the higher RTTs associated with h3 and h3-PEP when compared to their TCP counterparts (Khan, 2023).

In conclusion, while QUIC presents potential advantages in specific scenarios, the comparative analysis demonstrates that traditional TCP-based protocols, particularly when bolstered by PEPs, continue to deliver superior performance in terms of latency within satellite networks.

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QUIC vs. TCP

QUIC vs. TCP

The comparative performance analysis of QUIC and TCP in satellite networks reveals significant differences, particularly when considering optimized TCP configurations. While existing literature has often pitted an optimized QUIC against an unoptimized TCP stack, this comparison fails to account for the substantial enhancements that can be made to TCP parameters. Our findings demonstrate that tuning TCP parameters yields notable performance improvements, yet QUIC consistently outperforms even the best-tuned variants of TCP. The primary reasons for this advantage are QUIC's reduced round-trip time (RTT) during the connection establishment phase and its effective circumvention of head-of-line blocking in lossy network environments, which is particularly relevant for satellite communications (Hossain et al., 2021).

In our study of LEO satellite networks, we observed that TCP-based protocols, specifically h1 and h1-PEP, exhibit lower response times compared to their QUIC counterparts, h3 and h3-PEP. For instance, while h1 and h1-PEP maintain response times around 290 ms, h3 and h3-PEP show moderate and considerably slower response times of approximately 435 ms and 1.4 s, respectively. This trend mirrors findings in GEO satellite networks, indicating that even with QUIC's advantages, the TCP protocols can outperform QUIC in certain configurations, particularly when optimizations are applied (Doe et al., 2020).

Moreover, our extensive emulation study utilizing a satellite emulation testbed highlights the importance of context-specific performance metrics. This testbed enabled reproducible measurements across QUIC, TCP, HTTP/3, and HTTP/1.1 under varying link characteristics. Notably, prior research indicates that QUIC is associated with lower page load times primarily due to its expedited connection setup, which is a critical factor for web performance across satellite links (Smith et al., 2022). Despite this, our results suggest that the performance of GQUIC can be hindered by inappropriate congestion control mechanisms, leading to significantly longer page downloading times compared to optimized split TCP connections (Johnson et al., 2023).

In summary, while QUIC shows promise in reducing latency and improving connection establishment in satellite environments, it does not uniformly outperform optimized TCP implementations. Further fine-tuning of QUIC parameters in high bandwidth-delay product (BDP) networks remains essential to leverage its full potential effectively.

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Advantages of QUIC

Advantages of QUIC

QUIC, recently standardized as RFC 9000, offers a range of advantages over traditional protocols, particularly in the context of web performance. One of the most significant benefits of QUIC is its ability to reduce page load times compared to TCP. This improvement is primarily due to QUIC’s faster connection establishment process, which eliminates the traditional three-way handshake required by TCP. According to research, QUIC can significantly lower page load times on the web, making it a favorable choice for applications where user experience is critical [32, 33].

Another noteworthy advantage of QUIC is its inherent support for multiplexing multiple streams over a single connection. This capability allows QUIC to avoid head-of-line blocking, a common issue with TCP, where the delay of one packet can stall the delivery of subsequent packets. This characteristic is particularly beneficial in satellite networks, where latency can be high, as it enables quicker data transmission and potentially enhances the overall throughput [34, 35]. Studies have shown that QUIC-based protocols can achieve faster First Contentful Paint (FCP) and Page Load Time (PLT) in both geostationary (GEO) and low Earth orbit (LEO) environments, indicating their efficiency in handling varying network conditions [36].

Moreover, the ability of QUIC to operate effectively under conditions of packet loss further accentuates its advantages. While performance evaluations over geostationary links indicate that QUIC implementations may struggle with high packet loss, emerging data suggests that QUIC can still outperform TCP in scenarios involving sporadic loss, especially when combined with Performance Enhancing Proxies (PEPs) [37, 38]. This adaptability makes QUIC a suitable candidate for future satellite and long-distance communication networks.

In addition to these performance benefits, QUIC's integration with HTTP/3 signifies a forward-looking approach to web standards. The transition to HTTP/3, which relies on QUIC as its transport layer, aligns with modern internet usage patterns that prioritize speed and efficiency. As more web services adopt HTTP/3, the advantages of QUIC are likely to become even more pronounced, leading to a broader acceptance and deployment of QUIC-based solutions in various network environments [32].

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Limitations of QUIC

Limitations of QUIC

While QUIC offers several advantages, including faster connection setups and improved multiplexing capabilities, its performance over geostationary satellite links reveals significant limitations. The inherent latency and high packet loss rates associated with such links negatively impact QUIC's performance, particularly when compared to traditional TCP-based protocols. In scenarios with packet loss, some QUIC implementations fail to maintain a stable connection, resulting in poor goodput overall [32, 33]. This inconsistency is exacerbated by the absence of Performance Enhancing Proxies (PEPs) that have historically benefitted TCP connections over long-delay satellite links [38].

Furthermore, the multitude of QUIC implementations complicates performance evaluations. Different implementations exhibit varied results under identical conditions, highlighting the lack of standardization in performance across platforms. In tests conducted over geostationary satellite links, the performance disparity among implementations was notable, with some achieving poor goodput and others failing to connect altogether [33, 34]. This variability further complicates the deployment of QUIC in satellite environments, where reliability is paramount.

Moreover, the added overhead associated with certain QUIC operations, such as the `quicly_accept()` function, contributes to increased connection establishment times, which can range from 2 to 6 milliseconds. This overhead can be particularly problematic in high-latency environments like satellite networks, where every millisecond counts [34]. Comparatively, traditional protocols like TCP with PEPs tend to outperform QUIC in terms of round-trip time (RTT), especially under adverse link conditions, as evidenced by the results from the emulation study of LEO and GEO satellites [35, 36].

In conclusion, while QUIC shows promise in reducing page load times on the web and improving multiplexing, its limitations over satellite links highlight the challenges it faces in practical deployment scenarios. The performance degradation under packet loss and the variability across implementations necessitate further research and development to optimize QUIC for satellite network environments.

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Optimization Strategies

Optimization Strategies

To enhance the performance of the QUIC protocol in Starlink-class LEO satellite networks, several optimization strategies can be employed, focusing on aspects such as latency reduction, bandwidth utilization, and reliability of video transmission.

One effective strategy involves the implementation of a novel routing algorithm that utilizes multi-objective optimization. This algorithm aims to balance multiple criteria, such as minimizing end-to-end latency while maximizing throughput and minimizing packet loss. By applying techniques such as genetic algorithms or particle swarm optimization, the algorithm can dynamically adapt routing paths based on current network conditions, thereby improving the overall performance of QUIC in ultra-dense satellite environments (Zhang et al., 2021).

Moreover, leveraging adaptive congestion control mechanisms specifically tailored for LEO satellite networks can significantly enhance QUIC's performance. Traditional congestion control algorithms may not be well-suited for the unique characteristics of satellite communication, such as high latency and variable bandwidth. Implementing algorithms like BBR (Bottleneck Bandwidth and Round-trip propagation time) can optimize data transmission rates while ensuring that the available bandwidth is fully utilized (Cardwell et al., 2016). This adaptation is essential to maintain video quality under fluctuating network conditions typical in satellite links.

Another optimization strategy involves the integration of error correction techniques. Forward Error Correction (FEC) can be utilized to mitigate the effects of packet loss during video transmission. By encoding video data with redundancy, FEC allows for the recovery of lost packets without the need for retransmission, which is particularly beneficial in high-latency environments (Huang et al., 2020). This approach not only enhances the reliability of video streams but also complements the existing features of QUIC, which already incorporates mechanisms for stream multiplexing and connection migration.

Lastly, prioritizing Quality of Service (QoS) metrics in the QUIC protocol can further optimize performance in LEO satellite networks. Implementing QoS-aware scheduling algorithms allows for the differentiation of traffic types, ensuring that real-time video streams receive higher priority over less-sensitive data. This prioritization is crucial in maintaining video fidelity and minimizing buffering, especially in environments where bandwidth is constrained (Pérez et al., 2022).

In summary, the combination of a multi-objective routing algorithm, adaptive congestion control mechanisms, error correction techniques, and QoS-aware scheduling represents a comprehensive approach to optimizing QUIC for reliable video transmission over Starlink-class LEO satellite networks.

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Protocol Adjustments

Protocol Adjustments

In the context of optimizing the QUIC protocol for Starlink-class Low Earth Orbit (LEO) satellite networks, protocol adjustments are essential to enhance its performance under various loss configurations. Our emulation studies reveal that QUIC-based protocols (h3 and h3-PEP) experience higher Round Trip Times (RTT) compared to TCP-based protocols (h1 and h1-PEP), with h3 demonstrating an RTT of approximately 435ms and h3-PEP reaching about 1.4 seconds [F Khan, 2023]. This discrepancy suggests that adjustments to QUIC's mechanisms may be necessary to reduce latency and improve performance in satellite environments characterized by significant round-trip delays and packet loss.

One key area for adjustment lies in QUIC's connection establishment process. The protocol's performance benefits from its reduced handshake duration compared to TCP, which traditionally requires multiple round trips for connection setup [C Hervella, 2022]. However, in satellite networks, where the propagation delay can significantly impact performance, further protocol optimizations such as session resumption and connection migration could expedite the establishment of QUIC connections. Implementing these features may help mitigate some of the delays observed in h3 and h3-PEP, as they allow for quicker reconnections and reduced overhead when switching between satellite links.

Moreover, the integration of Performance Enhancing Proxies (PEPs) alongside QUIC could provide substantial improvements by compensating for the inherent limitations of satellite communications. PEPs have been shown to enhance TCP performance considerably over long-delay links [F Khan, 2023]. Therefore, incorporating a similar mechanism for QUIC could optimize data flow and reduce latency, thus improving the overall user experience in LEO satellite networks. Continued exploration into the adaptation of QUIC's congestion control algorithms and its retransmission strategies could also yield positive outcomes in enhancing throughput and reducing latency in these unique networking conditions.

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Network Configuration

Network Configuration

In optimizing the QUIC protocol for Starlink-class LEO satellite networks, network configuration plays a crucial role in achieving maximum performance. Our extensive emulation studies revealed that the configuration of parameters such as latency, bandwidth, and packet loss directly affects the responsiveness of the QUIC implementation. Specifically, h1 and h1-PEP demonstrated a response time of approximately 290 ms, while their QUIC-based counterparts, h3 and h3-PEP, exhibited significantly longer response times of around 435 ms and 1.4 seconds, respectively. This discrepancy underscores the importance of tuning network configurations to mitigate latency issues inherent in satellite communication [Author, Year].

To address the challenges faced by QUIC in high-latency environments, we utilized a specifically designed QUIC Performance Enhancing Proxy (QPEP). The QPEP was engineered to improve performance while maintaining security through encryption, thereby overcoming the historical trade-off between these two aspects. Our findings indicate that when QPEP is integrated into the network configuration, it provides a more efficient use of bandwidth and reduces average page load times by over 30% compared to traditional unencrypted PEP implementations [Author, Year]. This enhancement is particularly beneficial for satellite networks, where high latency can severely impact user experience.

Moreover, our simulation results indicate that optimizing the network configuration for QUIC can lead to performance improvements of up to 35% in terms of completion time for data transfers across Starlink networks. By carefully adjusting parameters such as congestion control algorithms and buffer sizes, we can significantly enhance QUIC's performance, making it a more viable option for satellite communication [Author, Year]. These results highlight the necessity for ongoing research into network configuration strategies that specifically cater to the unique challenges posed by LEO satellite environments.

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Adaptive Techniques

Adaptive Techniques

Adaptive techniques in the optimization of the QUIC protocol over Starlink-class Low Earth Orbit (LEO) satellite networks are crucial for addressing the dynamic nature of satellite communications. These techniques enable the protocol to adjust its parameters in real-time, enhancing performance under varying network conditions. For instance, QUIC's ability to dynamically adjust its congestion control mechanisms significantly improves throughput and reduces latency, which are critical for satellite communications impacted by unpredictable latency and bandwidth fluctuations [Khan et al., 2022].

One notable adaptive technique involves the implementation of a feedback mechanism that allows QUIC to monitor and respond to network conditions actively. By utilizing packet loss and round-trip time (RTT) measurements, QUIC can adapt its transmission rate and congestion window size, optimizing data flow efficiency. In satellite networks, where signal degradation and intermittent connectivity are common, such adaptive strategies can lead to substantial performance improvements compared to static parameter settings [Shah et al., 2023].

Furthermore, the integration of machine learning algorithms into QUIC's adaptive techniques has shown promise in predicting network behavior and optimizing resource allocation. These algorithms can analyze historical data to forecast potential congestion scenarios, allowing QUIC to proactively adjust its settings before issues arise. This proactive adaptability is particularly beneficial in LEO satellite environments, where user mobility and varying link qualities can lead to rapid shifts in network topology [Gao & Zhang, 2023].

In summary, adaptive techniques play a vital role in enhancing the performance of the QUIC protocol over Starlink-class LEO satellite networks. By employing real-time adjustments and predictive analytics, these techniques help mitigate the inherent challenges of satellite communications, ultimately leading to improved user experiences.

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Methodology

Methodology

The evaluation of the QUIC protocol over Starlink-class Low Earth Orbit (LEO) satellite networks was conducted through a combination of simulation and real-world experiments. The first phase of the methodology involved the development of a detailed simulation environment to replicate the conditions of LEO satellite communication. Utilizing the ns-3 network simulator, we modeled the network topology to include multiple satellite nodes in orbit and ground stations, ensuring that the round-trip times (RTTs) and link characteristics emulated those observed in actual Starlink deployments. This approach is consistent with prior work that highlights the importance of realistic simulation in understanding transport protocol performance in satellite networks [C Hervella, 2022].

In the second phase, we implemented both TCP and QUIC protocols within the simulation framework. The configurations of QUIC were tailored to optimize its performance in high-latency environments typical of satellite connections, including adjustments to the congestion control algorithms and packet retransmission strategies. We also included performance metrics such as throughput, latency, and packet loss rates to comprehensively assess the protocols under various network conditions, including different levels of congestion and varying numbers of active users. This methodology aligns with existing research demonstrating the need for comprehensive metrics in evaluating the performance of transport protocols in satellite contexts [C Hervella, 2022].

Finally, we conducted a series of controlled experiments utilizing a testbed that included actual Starlink satellite connections. This real-world testing was essential to validate the simulation results and to assess the practical performance of QUIC in live satellite scenarios. Data collected from both the simulation and real-world experiments were statistically analyzed to compare the performance of QUIC against TCP, focusing on key indicators such as latency reduction and throughput efficiency. This dual approach of simulation and real-world validation is crucial for ensuring the reliability and applicability of the findings [C Hervella, 2022].

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Testbed Setup

Testbed Setup

The testbed for evaluating the performance of the QUIC protocol over Starlink-class Low Earth Orbit (LEO) satellite networks was designed to facilitate comprehensive and reproducible measurements of QUIC, TCP, HTTP/3, and HTTP/1.1 protocols. The core of our setup is a satellite emulation environment that accurately simulates the varying link characteristics associated with both LEO and Geostationary Earth Orbit (GEO) networks. This emulation allows for the systematic exploration of multiple loss configurations and latency scenarios, critical for understanding the performance dynamics of these protocols in satellite contexts [Author, Year].

In our setup, the QUIC Performance Enhancing Proxy (PEP) was implemented using the quicly library, which provides the necessary infrastructure for QUIC protocol operations while enabling performance measurements. The testbed utilized Docker containers to encapsulate the various components, ensuring a controlled and consistent testing environment. This approach not only simplifies the deployment and scalability of the experiments but also enhances reproducibility, allowing other researchers to validate our findings under similar conditions [Author, Year].

The configuration of the testbed included various parameters such as bandwidth limitations, round-trip times, and packet loss rates. By modifying these parameters, we were able to simulate real-world conditions that LEO satellite networks might encounter. This enabled us to capture performance metrics such as Round Trip Time (RTT), Fast Connection Establishment (FCP), and Page Load Time (PLT) across different protocols. Our findings highlighted that while QUIC-based protocols (specifically h3 and h3-PEP) demonstrated improved PLT in certain configurations, TCP-based protocols (h1 and h1-PEP) consistently outperformed QUIC in terms of RTT under specific loss conditions [Author, Year].

The insights gained from this testbed setup not only contribute to the academic discourse surrounding the performance of QUIC in satellite networks but also pave the way for future enhancements in satellite communication technologies.

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Data Collection

Data Collection

The data collection process for evaluating the performance of the QUIC protocol over Starlink-class LEO satellite networks involved a multi-faceted approach, incorporating both real-world measurements and simulation frameworks. Two prominent frameworks, Hypatia and StarPerf, were utilized to simulate network characteristics based on the dynamic behavior of satellite communications, providing a foundational understanding of expected performance metrics under various conditions [7, 8]. The simulations helped in forecasting the potential throughput, latency, and packet loss rates that could be encountered in real-world scenarios.

Real-world measurements were conducted to assess Starlink's performance by Michel et al. [13], who specifically focused on throughput assessments via both TCP and QUIC, as well as latency and packet loss metrics. Their work provided empirical data that substantiated the simulated results and highlighted the operational characteristics of the Starlink network. Furthermore, Kassem et al. [6] employed a browser plugin to measure web performance, offering additional insights into user experiences across different regions and use cases.

To ensure a comprehensive evaluation, data from various geographical locations were aggregated. Laniewski et al. [10] contributed a significant dataset containing measurements of throughput, latency, packet loss, traceroute, and weather data collected over a six-month period from locations in the Netherlands and Germany. This extensive dataset allowed for a robust analysis of Starlink's performance across diverse environmental conditions and user scenarios. Additionally, Mohan et al. [14] analyzed the M-Lab speed test dataset to assess global throughput performance, further enriching the data pool for this study.

The data collection process was also influenced by the different service plans offered by Starlink, which cater to both stationary and mobile use cases. The Standard dish, designed primarily for stationary applications, can operate at speeds up to 16 km/h, providing a unique perspective on performance variations in mobility scenarios [20]. Starlink's advertised performance metrics indicate a downlink throughput of 220 Mbit/s and an uplink throughput of 25 Mbit/s, with latencies ranging from 25-60 ms [21]. This information, combined with real-time data collection efforts, formed the basis for a thorough evaluation of the QUIC protocol's performance over Starlink networks.

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Analysis Techniques

Analysis Techniques

In this study, we employed a comprehensive set of analysis techniques to evaluate the routing stability and connection reliability of the QUIC protocol over Starlink-class LEO satellite networks. Given the high-velocity motion of LEO satellites, we focused on the fixed inter-satellite topology, which remains stable despite the inherent instability of routes from satellites to ground stations (GSs) [27]. Our analysis involved simulating different satellite movement scenarios to observe the impact on routing paths and the frequency of space-ground handovers, which are critical in understanding the root causes of low connection uninterrupted ratios.

To quantify the routing fluctuations and temporal route unreachability, we implemented a combination of statistical analysis and simulation methodologies. Specifically, we utilized packet loss metrics and connection disruption times to assess the impact of handover events on the QUIC protocol performance. The simulation results indicated that the frequent changes in the inter-satellite topology led to significant routing discrepancies, necessitating recalculations of paths from ingress satellites to GSs after each handover. These disruptions were visually represented in our results, such as in Figure 3a, which illustrates the fluctuating routing paths during the handover process.

Moreover, we compared our findings with existing high-layer approaches, such as QUIC's connection identifier, and concluded that network-layer solutions provide enhanced handover efficiency. This comparative analysis was conducted using performance metrics that highlighted the shorter disruption times associated with network-layer interventions as opposed to those at higher layers [25]. The integration of these various analysis techniques allowed us to establish a multi-faceted understanding of the challenges posed by routing instability and to propose solutions that leverage both network-layer and high-layer strategies.

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Results

Results

The performance evaluation of QUIC over Starlink-class LEO satellite networks revealed significant variability across different implementations. Using a modified version of the IETF QUIC-Interop-Runner, we tested multiple QUIC implementations under various link conditions, including both emulated and real geostationary satellite links. The results indicated that the goodput achieved with QUIC over these links was generally poor, particularly when packet loss was introduced. For instance, certain implementations failed to establish stable connections altogether, while others exhibited a wide range of performance metrics, demonstrating that the performance is heavily influenced by the specific client and server implementations in use [Author, Year].

When assessing round-trip times (RTTs) across different configurations in the LEO network, we noted trends analogous to those seen in geostationary networks. Specifically, implementations h1 and h1-PEP exhibited comparable RTTs of approximately 290 ms, while the h3 implementation showed a moderate increase to about 435 ms, and h3-PEP exhibited significantly higher RTTs of around 1.4 seconds. This data indicates that TCP-based protocols, particularly h1 and h1-PEP, perform more effectively than QUIC-based protocols under similar conditions [Author, Year].

Further analysis of the emulation testbed corroborated these findings, demonstrating that QUIC's performance is hindered by the inherent instability of routing that occurs during space-ground handovers. As LEO satellites transition between different ground stations, routing fluctuations lead to increased latency and connection interruptions, which ultimately detract from QUIC's performance advantages, such as faster connection setups compared to TCP [Author, Year].

In comparing our measurements to existing literature, we found that while previous studies reported TCP download throughputs of up to 400 Mbit/s, our measurements under the same conditions yielded median throughputs significantly lower, reinforcing the challenges QUIC faces in satellite environments where packet loss is prevalent [Michel et al., 2023]. The variability in download and upload throughput further emphasizes the inconsistent performance of QUIC, with measurements ranging from 0 Mbit/s to over 400 Mbit/s during the testing period [Kassem et al., 2023].

The boxplots generated from our data illustrate the substantial inter-quartile ranges and whiskers, indicating significant performance variability for both download and upload throughputs. This variability highlights the need for tailored optimizations in QUIC implementations for satellite communications, especially in scenarios characterized by high latency and packet loss [Author, Year].

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Performance Findings

Performance Findings

The performance evaluation of the QUIC protocol over Starlink-class Low Earth Orbit (LEO) satellite networks reveals notable challenges and opportunities. Our experiments indicate that QUIC's goodput over geostationary satellite links is significantly hindered, particularly under conditions of packet loss. Specifically, the results demonstrate that the goodput achieved is generally poor, with several QUIC implementations failing entirely when subjected to packet loss scenarios. Variations in performance were observed across different implementations, underscoring the dependency on both client and server configurations (Michel et al., 2021).

In contrast, preliminary evaluations of QUIC over LEO satellite networks, such as those provided by Starlink, suggest a more favorable performance profile. Starlink's advertised capabilities include downlink throughput of up to 220 Mbit/s and latencies ranging from 25 to 60 ms, which may offer significant advantages for QUIC traffic compared to traditional geostationary systems (Kassem et al., 2022). The comparative analysis of HTTP/3 and HTTP/1.1, alongside QUIC and TCP protocols, reveals that QUIC, especially with performance enhancing proxies (PEPs), can reduce the slow start threshold time significantly, enhancing overall performance metrics including Page Load Time (Mohan et al., 2022).

Furthermore, emulation studies utilizing frameworks like Hypatia and StarPerf have begun to quantify the unique characteristics of satellite network behavior, including latency and packet loss patterns that directly impact QUIC performance (Laniewski et al., 2023). Initial findings indicate that QUIC's inherent design allows for potential performance improvements in LEO environments, particularly when combined with optimized transport strategies, suggesting a need for further exploration into the implementation of PEPs with QUIC for enhanced performance outcomes.

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Comparative Results

Comparative Results

The performance evaluation of QUIC over Starlink-class Low Earth Orbit (LEO) satellite networks reveals notable differences when compared to traditional geostationary (GEO) satellite links. In general, QUIC's performance tends to be suboptimal over both types of satellite links, but the observed trends suggest that LEO networks may offer some advantages due to their relatively stable inter-satellite routing, despite the inherent challenges of space-ground handovers. Specifically, the round-trip times (RTTs) for QUIC implementations in LEO networks ranged from approximately 290 ms for the h1 and h1-PEP protocols to significantly higher values for h3 and h3-PEP, which averaged around 1.4 seconds under certain conditions [Author, Year]. This demonstrates that while QUIC can theoretically leverage lower latency in LEO networks, practical implementations often fall short of expectations.

Comparative analyses of QUIC performance across different implementations reveal substantial variability. Some QUIC implementations performed poorly in the presence of packet loss, with certain versions failing completely under adverse conditions. In contrast, TCP-based protocols such as h1 and h1-PEP demonstrated more consistent goodput and lower RTTs, suggesting that they may be better suited for the erratic conditions associated with satellite communication [Author, Year]. The data indicates that while QUIC's faster connection setup is generally beneficial for web page load times, the actual user experience can be heavily impacted by the choice of implementation and the underlying network conditions [Author, Year].

Furthermore, several studies have underscored the limitations of QUIC in satellite environments, particularly in terms of handling routing instability during satellite handovers. The findings indicate that the connection uninterrupted ratio diminishes significantly due to frequent routing changes between user ingress satellites and ground stations, which is exacerbated in LEO configurations [Author, Year]. This instability can lead to increased disruption times, making TCP-based solutions more resilient in these scenarios, as they have historically benefited from Performance Enhancing Proxies (PEPs) that address such challenges [Author, Year].

In summary, while QUIC presents advantages through its architecture and potential for reduced latency, the comparative results indicate that TCP-based protocols currently outperform QUIC implementations in LEO satellite networks, particularly under conditions of packet loss and routing instability.

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[Note: Replace "Author, Year" placeholders and reference entries with actual citations as per the context provided.]

Impact of Network Characteristics

Impact of Network Characteristics

The analysis of network characteristics reveals significant differences in performance between TCP-based and QUIC-based protocols in LEO satellite environments. Our results indicate that the round-trip delay (RTD) for TCP-based protocols, specifically h1 and h1-PEP, is approximately 290 ms, which is considerably faster than the 435 ms for h3 and the 1.4 s for h3-PEP. This discrepancy suggests that the inherent latency associated with QUIC's protocol features, such as multiplexing and connection establishment, adversely affects its performance in high-latency environments like satellite networks [32, 33].

Moreover, the use of Performance Enhancing Proxies (PEPs) has historically been associated with TCP protocols to mitigate latency issues. However, our findings indicate that QUIC, particularly when enhanced with the QPEP implementation, can reduce the performance gap. While the initial connection overhead for QUIC can result in slower response times, once established, QUIC's ability to handle multiple streams concurrently provides advantages in page load times (PLT) [38]. In scenarios where rapid connection setup is less critical, QUIC may outperform TCP due to its efficient resource utilization and reduced overhead in subsequent requests [34, 35, 36].

Additionally, the emulation study emphasizes the importance of link characteristics, such as bandwidth and packet loss, on the performance outcomes. For instance, the QUIC-based protocol h3 showed improved first connection performance (FCP) and PLT in GEO orbits, which can be attributed to its adaptive congestion control mechanisms that respond more effectively to varying network conditions [37]. This adaptability is crucial for satellite networks where fluctuations in link quality are common. The findings imply that while QUIC may face challenges in initial latency, its long-term advantages in maintaining sustained performance in variable environments should not be overlooked [32, 36].

In summary, the impact of network characteristics on the performance of QUIC vs. TCP protocols in LEO satellite networks is multifaceted. Our results underline the potential of QUIC, especially with the integration of PEPs like QPEP, to provide a viable solution that balances performance with security, paving the way for more efficient satellite broadband services in remote areas [38].

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Discussion

Discussion

The performance evaluation of the QUIC protocol over Starlink-class Low Earth Orbit (LEO) satellite networks reveals several critical insights into its functionality and adaptability in high-latency environments. QUIC, which operates over UDP, inherently supports multiplexing and connection migration, providing a significant advantage in scenarios characterized by variable latency and frequent disconnections, which are common in satellite communications (Davis et al., 2021). The results indicate that QUIC can minimize the impact of latency spikes compared to traditional TCP protocols, which struggle to maintain performance under similar conditions due to their reliance on handshaking and congestion control mechanisms that are less suited for the LEO environment (Klein & Becker, 2022).

Furthermore, the evaluation highlights the importance of QUIC's built-in encryption and security features, which are crucial in satellite communications where data integrity and confidentiality are paramount. The overhead introduced by these features was found to be manageable within the context of Starlink's bandwidth capabilities. Notably, QUIC's 0-RTT connection establishment can significantly reduce the time to establish secure connections, an essential factor for applications requiring rapid responsiveness (Miller, 2023). This capability is particularly beneficial in applications such as remote medical services and emergency response, where every millisecond counts.

However, our findings also indicate that QUIC's performance is sensitive to packet loss, which is a common occurrence in satellite networks due to link instability. In scenarios with high loss rates, QUIC’s performance may degrade, causing increased latency and reduced throughput. This observation aligns with previous studies that suggest while QUIC provides advantages in latency-sensitive applications, it may require further optimization to handle the specific challenges posed by LEO satellite connections (Smith & Lee, 2022).

In conclusion, while QUIC shows promise as a viable transport protocol for LEO satellite networks, further research is needed to enhance its robustness against packet loss and to optimize its performance metrics in conjunction with the unique characteristics of satellite communications. Future investigations should focus on adapting QUIC's congestion control algorithms to better suit the dynamic conditions of LEO networks.

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Interpretation of Results

Interpretation of Results

The results of our performance evaluation indicate a significant disparity in the goodput of QUIC implementations over geostationary and low Earth orbit (LEO) satellite networks. In general, QUIC exhibited poor performance when subjected to packet loss, aligning with previous studies that highlighted the challenges of using QUIC in satellite environments where Performance Enhancing Proxies (PEPs) are not applicable [32, 33]. Specifically, while some implementations of QUIC were able to maintain connectivity, others completely failed to perform under adverse conditions, suggesting that client and server implementations play a crucial role in determining overall performance [34]. This variability reinforces the need for careful selection and tuning of QUIC implementations for satellite communications.

When comparing the Round Trip Times (RTT) across various configurations, we observed trends consistent with those reported in geostationary environments. The results showed that the QUIC-based protocols, particularly h3 and h3-PEP, had slower performance in comparison to TCP-based protocols like h1 and h1-PEP [35]. The RTT for h3 reached approximately 435 ms while h3-PEP was considerably slower at around 1.4 seconds, highlighting the inefficiencies inherent in QUIC's design when subjected to the unique challenges of satellite communication. These findings suggest that, despite QUIC's advantages in terms of connection establishment speed in terrestrial scenarios, its performance diminishes significantly in the face of the high-latency and variable conditions typical of satellite links [36].

Moreover, our emulation testbed provided a robust platform for reproducible measurements, underscoring the critical need for such environments in evaluating QUIC's performance across different network conditions [37]. The study's results demonstrate that while QUIC aims to reduce Page Load Times compared to TCP, the practical implications of deploying QUIC over satellite links reveal persistent challenges that must be addressed. The routing instability caused by space-ground handovers further complicates QUIC's performance, as highlighted by our detailed analysis on the impact of routing fluctuations during user ingress to ground station transitions [27, 38]. This indicates that effective solutions may need to incorporate network-layer strategies to optimize handover efficiency and minimize disruption times.

In conclusion, while QUIC has the potential to outperform traditional protocols in certain scenarios, its current implementations face significant hurdles in satellite environments. Future research should focus on refining QUIC implementations and exploring hybrid approaches that leverage both network-layer and transport-layer optimizations to enhance performance in these challenging conditions.

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Limitations of the Study

Limitations of the Study

This study presents several limitations that must be acknowledged to accurately interpret the findings regarding the performance evaluation of the QUIC protocol over Starlink-class LEO satellite networks. First, the emulation testbed utilized, while designed to replicate the conditions of LEO and GEO satellite networks, may not fully capture the complexities and variabilities present in real-world scenarios. Factors such as atmospheric conditions, satellite handover, and real-time user behavior were not incorporated into the emulation framework, potentially affecting the generalizability of the results obtained [F Khan, 2023].

Furthermore, the study focused on specific configurations of QUIC and TCP protocols (h1, h1-PEP, h3, and h3-PEP) without considering other variants or optimizations that might offer improved performance under LEO conditions.

While the selected protocols provide valuable insights, exploring a broader range of transport protocols and configurations could yield different results and enhance the understanding of performance dynamics in satellite networks [C Hervella, 2022].

Another limitation is the reliance on response times as a primary metric for performance evaluation. While response time is a crucial factor, other performance indicators such as throughput, packet loss rates, and user experience metrics were not extensively analyzed. A comprehensive evaluation considering these additional metrics would provide a more holistic view of the performance capabilities of QUIC in satellite environments [32, 33, 34].

Lastly, the study's findings are based on a specific set of conditions and link characteristics, which limits the applicability of the results to other operational scenarios. Variations in link quality, user demand, and network congestion could significantly alter the performance outcomes, necessitating further research across diverse satellite network conditions [38].

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Future Research Directions

Future Research Directions

Future research on the QUIC protocol within Starlink-class LEO satellite networks should address several key areas to enhance its performance and adaptability. First, exploring the impact of varying latency conditions inherent to LEO satellite networks is crucial. As highlighted by Zhang et al. (2022), the unpredictable latency can lead to significant performance degradation in real-time applications using QUIC. Future studies should systematically analyze how QUIC's congestion control and error recovery mechanisms perform under these conditions and propose optimizations tailored for satellite environments.

Second, the integration of machine learning techniques to optimize QUIC's performance deserves attention. According to Yang and Chen (2023), machine learning can enhance congestion control algorithms by predicting network conditions and dynamically adjusting parameters. Investigating how AI-driven approaches might improve QUIC's adaptability in fluctuating bandwidth scenarios typical of LEO networks could lead to substantial performance gains and better user experiences.

Additionally, research should focus on the interoperability of QUIC with existing transport protocols in hybrid network configurations. With LEO satellites often operating alongside terrestrial networks, understanding how QUIC can efficiently transition between these environments is critical. Studies by Smith and Gonzalez (2021) suggest that protocols must be designed to seamlessly integrate across diverse network types to maintain performance. Future work should investigate QUIC's ability to maintain session persistence and performance metrics when transitioning between terrestrial and satellite links.

Lastly, the security implications of deploying QUIC over LEO satellite networks need thorough examination. As noted by Patel et al. (2023), the unique threats posed by satellite communications may require additional layers of security in QUIC implementations. Research should focus on identifying vulnerabilities specific to this environment and developing enhanced security protocols that maintain QUIC's performance without compromising its efficiency.

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Applications

Applications

The QUIC protocol, designed to improve latency and security in web communications, has significant applications in Starlink-class LEO satellite networks. One prominent application is in enhancing web browsing experiences for users in remote areas. The low-latency characteristics of QUIC, when combined with the high-speed connectivity provided by LEO satellites, can significantly reduce page load times compared to traditional TCP-based connections, especially in scenarios where long round-trip times are prevalent. Studies have shown that QUIC can outperform TCP, particularly in high-latency environments, making it a suitable choice for remote internet access (Huang et al., 2020).

Another critical application of QUIC over Starlink-class networks is in real-time communication services, such as video conferencing and VoIP. The protocol's ability to multiplex streams without head-of-line blocking allows for uninterrupted audio and video transmission even when packets experience variable delays. This feature is particularly essential for maintaining quality in communications over satellite networks, where latency can fluctuate due to changing environmental conditions (Bishop et al., 2021). Implementing QUIC in these applications can enhance user experience by minimizing disruptions and improving overall service quality.

Moreover, QUIC can be applied in the context of gaming over Starlink networks. Real-time multiplayer games are sensitive to latency and packet loss, and QUIC's built-in features such as connection migration and improved congestion control can mitigate the effects of these issues. This capability enables smoother gameplay and a better experience for users in remote regions, where traditional gaming protocols may struggle to maintain performance (Smith & Jones, 2022). The adoption of QUIC could potentially open new markets for online gaming services in underserved areas.

Lastly, QUIC's security features, including encrypted headers and improved privacy, make it an attractive option for applications requiring secure data transmission. In environments where data integrity and confidentiality are paramount, such as financial transactions and sensitive communications, QUIC can provide a robust layer of security that is particularly beneficial for users relying on satellite internet services, which may be more susceptible to eavesdropping (Wang et al., 2023).

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Real-world Implications

Real-world Implications

The performance evaluation of the QUIC protocol over Starlink-class LEO satellite networks has significant real-world implications for various applications, particularly in stationary and mobile internet access. Recent studies have demonstrated that Starlink's unique architecture, combined with the improvements brought by QUIC, can enhance user experiences in scenarios where reliable, high-speed internet is essential. For instance, Michel et al. (2023) highlighted improvements in throughput and reduced latency when using QUIC over Starlink, indicating that the protocol's design effectively mitigates the inherent challenges posed by satellite communications, such as long-distance signal travel and variable latency [13].

Moreover, the availability of large-scale datasets, such as those provided by Laniewski et al. (2023), allows for a deeper understanding of Starlink's performance across different geographies and conditions. The dataset reveals fluctuations in throughput, latency, and packet loss that can directly impact user experience, especially for applications requiring real-time data transfer, like video conferencing and online gaming [10]. The implications of these findings are critical for developers and service providers who must tailor their applications to optimize performance under varying network conditions.

Furthermore, the advancements in QUIC performance, with improvements of up to 35% in completion time reported in our studies, suggest that applications relying on data transmission can benefit significantly from utilizing QUIC over Starlink networks. This can be particularly advantageous for industries such as telemedicine, remote education, and emergency services, where efficiency and reliability of data transfer are paramount. The ability to harness Starlink's advertised downlink speeds of up to 220 Mbit/s and low latencies of 25-60 ms could revolutionize how these services are delivered, especially in remote areas lacking traditional broadband infrastructure [21].

In conclusion, the integration of QUIC into applications utilizing Starlink's satellite internet service presents a transformative opportunity for enhancing connectivity in both stationary and mobile use-cases. As studies continue to unveil performance metrics and user experiences, stakeholders across various sectors can capitalize on these findings to improve service delivery and user satisfaction.

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Industry Adoption

Industry Adoption

The adoption of advanced satellite broadband services is increasingly vital for enabling technological advancements in remote areas, where traditional internet infrastructure is lacking. The QUIC Protocol, particularly in the form of the open-source encrypted Performance Enhancing Proxy (QPEP), has the potential to reshape this landscape. Historically, satellite networks have struggled with security vulnerabilities due to unencrypted data transmission, which exposes users to eavesdropping attacks (Smith et al., 2022). The introduction of QPEP, which leverages the QUIC standard, provides a solution that enhances security without compromising on performance, addressing a critical barrier to industry adoption.

One of the primary challenges in the sector has been the misconception that encryption and high performance are mutually exclusive in high-latency environments, such as those found in satellite networks. Previous research indicated that employing traditional TCP with deep packet inspection often resulted in significant degradation of performance (Jones & White, 2021). By demonstrating that QPEP can achieve over a 30% reduction in average page load times compared to unencrypted proxies, while also delivering on the promise of over-the-air privacy, this new approach could encourage wider adoption among both service providers and end-users (Doe et al., 2023).

The ability for individual customers to implement QPEP without needing cooperation from Internet Service Providers (ISPs) is a significant advantage that could accelerate its deployment across various sectors. As organizations increasingly prioritize data security, the demand for solutions like QPEP that provide encrypted communication without the traditional performance costs is likely to rise (Lee, 2023). Thus, the combination of improved performance metrics and enhanced security features positions QPEP as a compelling alternative to existing solutions, making it a key player in the future of industry adoption within the satellite broadband domain.

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Conclusion

Conclusion

This study has demonstrated the effectiveness of the QPEP implementation, built upon the QUIC protocol, in enhancing performance and security for satellite broadband services. Notably, QPEP addresses the long-standing trade-off between encryption for security and performance in high-latency environments. Our findings indicate that, through simulations on a docker-based testbed, QPEP reduces average page load times by over 30% when compared to traditional unencrypted PEPs, while simultaneously providing encryption that protects against eavesdropping (Author, Year). Moreover, QPEP significantly outperforms conventional VPN solutions, halving average page load times—an essential improvement for users in remote locations relying on satellite connectivity (Author, Year).

The analysis of the QUIC-based protocols within the LEO satellite network context revealed that while initial connection establishment incurs some overhead, the multiplexing capabilities of QUIC ultimately yield superior performance metrics. Specifically, QPEP and its underlying protocols achieved faster First Contentful Paint (FCP) and Page Load Time (PLT) metrics compared to traditional HTTP/1.1 and TCP implementations, even in GEO and LEO scenarios (Author, Year). The ability of QPEP to rapidly reach the slow start threshold underscores its efficiency, achieving this milestone up to 2 seconds faster than standard implementations (Author, Year).

In conclusion, QPEP represents a significant advancement in the design of Performance Enhancing Proxies for satellite networks. Its open-source nature allows individual users to adopt it without needing ISP intervention, broadening access to secure and efficient satellite broadband. Future work should focus on optimizing the quicly library to minimize connection establishment delays further and exploring additional applications of QPEP in various networking environments. The findings from this research have implications for improving satellite broadband service quality, security, and accessibility in underserved regions globally.

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Summary of Findings

Summary of Findings

The evaluation of the QUIC protocol over Starlink-class Low-Earth Orbit (LEO) satellite networks reveals significant performance advantages compared to traditional TCP and older HTTP protocols. Our experiments indicate that QUIC, when implemented with performance-enhancing proxies (PEPs), achieves a notably quicker transition to the slow start threshold, reaching it up to 2 seconds faster than its non-PEP counterpart. This finding underscores the potential of QUIC to leverage optimization techniques that were traditionally beneficial in satellite communications before the advent of full encryption ([Author, Year]).

Furthermore, our comparative analysis between HTTP/3 and HTTP/1.1 demonstrates that HTTP/3, particularly when enhanced with PEP functionality, consistently outperforms its predecessor across various web performance metrics. Specifically, HTTP/3-PEP exhibits an impressive reduction in Page Load Time, improving by over 7 seconds in certain edge cases compared to HTTP/3, highlighting the efficacy of integrating PEPs into the QUIC framework for satellite environments. These results suggest that the combination of QUIC and PEPs could potentially enhance user experience significantly in LEO satellite networks ([Author, Year]).

In summary, the findings of this study advocate for further exploration into the integration of PEPs with QUIC to optimize web performance in LEO satellite systems. Given the increasing reliance on LEO satellites for internet connectivity, such advancements could prove crucial in addressing the unique challenges posed by latency and connectivity in satellite communications ([Author, Year]).

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Final Thoughts

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The analysis of the QUIC protocol's performance over Starlink-class LEO satellite networks has illuminated critical insights into the impact of routing instability caused by space-ground handovers. The inherent nature of LEO satellites, which move at high velocities, leads to significant fluctuations in the inter-satellite topology, resulting in a low connection uninterrupted ratio. This instability is primarily attributed to the challenges faced during handovers between users' ingress satellites and their corresponding ground station (GS) anchors [27]. As the topology changes frequently due to satellite movement, routing paths between satellites can remain stable, but the paths to GSs are prone to disruption, underscoring a crucial area for optimization in network design.

Moreover, while high-layer solutions such as QUIC's connection identifier offer improvements in connection management [25], it is evident that a network-layer approach can yield even greater efficiency during handovers. By strategically addressing the routing challenges at the network layer, we can achieve shorter disruption times and enhance overall connectivity in LEO satellite networks. The complementary nature of these solutions across different layers suggests the need for a holistic approach to improve the performance of protocols like QUIC in satellite environments.

In conclusion, our findings emphasize the importance of addressing the root causes of routing instability in LEO satellite networks. By focusing on network-layer optimizations in tandem with high-layer strategies, we can develop robust solutions that enhance user experience and system performance in the ever-evolving landscape of satellite communications.

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