Evaluating QUIC Protocol Performance Across Starlink-Class Satellite Networks

Introduction

The landscape of internet connectivity is rapidly evolving, with Low Earth Orbit (LEO) satellite networks emerging as a significant paradigm shift in providing global internet access. Among these, Starlink, spearheaded by SpaceX, stands out as a pioneering example, promising to deliver high-speed, low-latency internet to regions previously underserved by traditional infrastructure.[1] This new generation of satellite networks holds the potential to overcome the inherent limitations of Geostationary Earth Orbit (GEO) satellites, particularly the high propagation delays that have historically plagued satellite internet.[5] LEO constellations, orbiting at much lower altitudes, offer the possibility of significantly reduced latency, making them attractive for a wider range of internet applications, including those sensitive to delay.[8] However, the dynamic nature of LEO networks, characterized by the constant movement of satellites and the resulting frequent handovers, introduces unique challenges for transport protocols that were primarily designed for the more static conditions of terrestrial networks.[8]

In parallel with these advancements in satellite technology, the internet transport layer is also undergoing a transformation with the rise of the QUIC (Quick UDP Internet Connections) protocol.[9] Developed by Google and now undergoing standardization by the Internet Engineering Task Force (IETF), QUIC aims to enhance the performance of connection-oriented web applications that have traditionally relied on the Transmission Control Protocol (TCP).[9] QUIC achieves this through a multitude of features, including operating over the User Datagram Protocol (UDP), multiplexing multiple streams over a single connection, integrating TLS 1.3 for robust security, enabling faster connection establishment with 0-RTT (zero Round-Trip Time) for returning clients, incorporating improved congestion control and loss recovery mechanisms, and supporting connection migration.[9] The design of QUIC incorporates several key aspects that could potentially address the inherent limitations of TCP when operating in high-latency and dynamic network environments.[10] For example, the 0-RTT connection establishment can reduce the overhead associated with setting up a connection, which is particularly advantageous in scenarios where latency is a significant factor. Furthermore, QUIC's multiplexing capabilities, which avoid the head-of-line blocking issue prevalent in TCP, can lead to improved performance when packet loss occurs.

This report seeks to evaluate the performance of the QUIC protocol specifically across Starlink-class satellite networks. By examining the interplay between the characteristics of these advanced LEO networks and the features of QUIC, this analysis aims to identify the potential benefits and drawbacks of employing QUIC in this context. Moreover, it will explore opportunities for optimization and configuration that could further enhance QUIC's performance and make it an even more compelling transport protocol for Starlink and similar satellite-based internet services.

Characteristics of Starlink-Class Satellite Networks

Starlink represents a significant leap forward in satellite internet technology through its deployment of a vast constellation of LEO satellites, orbiting at an altitude of approximately 550 kilometers.[3] This lower orbit is a key differentiator from traditional GEO satellites, which reside at a much higher altitude, leading to substantially reduced latency for Starlink users. While advertised latencies can be as low as 20ms, users typically experience ranges between 25 and 60ms for terrestrial destinations, with slightly higher latencies in remote locations.[2] This latency, while a vast improvement over GEO satellites, is still higher and more variable than that of typical wired networks.[5] The variability is often attributed to the dynamic nature of the LEO constellation and the handovers between satellites.

In terms of bandwidth, Starlink offers impressive capabilities, with download speeds generally ranging from 25 to 220 Mbps and upload speeds typically between 5 and 20 Mbps.[2] These speeds can vary depending on the user's service plan, their geographic location, and the overall network load at any given time. While these speeds are suitable for most common internet applications, including streaming and video conferencing, real-world performance can fluctuate, especially during peak usage hours when network congestion might occur.[22]

Like all wireless communication systems, satellite networks are susceptible to packet loss. On Starlink, packet loss can arise from various factors, including physical obstructions such as trees or buildings, a weak connection to the user's router, interference from other wireless networks, and the brief drops in coverage that can occur as satellites move overhead and the user terminal hands over to a new satellite.[4] Research has indicated that packet loss rates on Starlink can vary depending on the network load and the type of traffic being transmitted.[4]

A unique challenge presented by LEO satellite constellations like Starlink is the frequent satellite handovers that occur due to the high orbital speed of the satellites. These handovers, which happen roughly every 15 seconds in Starlink's network, as the user terminal switches its connection from one satellite to another, can introduce brief latency spikes and packet losses.[8] Transport layer protocols, including TCP and QUIC, which rely on similar congestion control algorithms, can misinterpret these temporary disruptions as signs of network congestion, potentially leading to performance degradation.[8] However, the globally time-synchronized nature of these handover events in Starlink offers a potential opportunity for transport protocols to be optimized to anticipate and mitigate these impacts.[8] Additionally, Starlink employs dynamic channel rate control, adjusting the modulation and coding scheme in response to the constantly varying Signal-to-Noise Ratio (SNR), which can also influence network performance.[24]

Metric	**Starlink (Typical Range)**	**Traditional SatCom (Inferred Range)**
Latency	25-60 ms	600+ ms

Download Speed	25-220 Mbps	Up to 100 Mbps
Upload Speed	5-20 Mbps	Up to 10 Mbps
Typical Use Cases	Streaming, Video Calls, Gaming, General Use	Basic Web Browsing, Email

QUIC Protocol: An Overview

QUIC represents a significant evolution in internet transport protocols, designed to address some of the inherent limitations of TCP, particularly in modern network environments. Unlike TCP, which operates directly over the Internet Protocol (IP), QUIC is built on top of UDP.[9] This foundational choice allows QUIC to be implemented in user space rather than the operating system kernel, which facilitates faster updates and the deployment of new features without requiring system-level changes.[11]

One of QUIC's key advancements is its support for multiplexing multiple independent streams of data within a single connection.[9] This feature is crucial for improving performance as it prevents the head-of-line blocking issue that can occur in TCP-based protocols like HTTP/2. In TCP, if a packet is lost in one stream, it can delay the delivery of packets in all other streams within the same connection. QUIC, by contrast, allows each stream to progress independently, ensuring that packet loss in one stream does not impede others.[10]

QUIC also incorporates robust stream management capabilities, providing ordered and reliable delivery of data within each individual stream.[13] Furthermore, security is a fundamental aspect of QUIC's design, with mandatory end-to-end encryption using TLS 1.3.[10] This built-in security enhances privacy and protection compared to TCP, where encryption via TLS is often an optional layer added on top.

For users on the move, QUIC offers support for connection migration.[10] Instead of being tied to a specific IP address like TCP, a QUIC connection is identified by a connection ID. This allows the connection to persist even if the client's IP address changes, such as when a mobile device switches between Wi-Fi and cellular networks, a feature particularly relevant in mobile satellite environments.[27]

In terms of network management, QUIC includes its own congestion control mechanisms.[9] These are designed to be more efficient and adaptive than TCP's congestion control, allowing QUIC to perform better in varying network conditions, including those with high latency or packet loss.

Compared to TCP, QUIC offers several potential advantages, especially in challenging network environments.[10] For repeat connections, QUIC can establish a connection with zero round-trips (0-RTT), significantly reducing latency, which is particularly beneficial over high-delay links.[10] Its more efficient packet loss recovery, thanks to multiplexing, and improved congestion control algorithms make it more resilient to network impairments. The built-in security and connection migration capabilities further enhance its suitability for modern internet applications and mobile environments.

Performance Evaluation: QUIC vs. TCP over Satellite Networks

The performance characteristics of QUIC in the context of satellite networks have been the subject of several research studies. Evaluations over GEO satellite links, which are characterized by high latency and the traditional domain of satellite internet, have shown that QUIC can indeed help in reducing the overall time taken to retrieve web pages, particularly when propagation delays are long and packet loss rates are elevated.[16] This suggests that QUIC's design is inherently better suited to handle the challenges of high-latency environments compared to traditional protocols. Some research has specifically highlighted QUIC's superior performance over HTTPS and HTTP/2 in satellite networks, especially under conditions of high latency and packet loss, which are typical for GEO mobile satellite communications.[16]

However, the performance of QUIC over satellite links is not universally optimal. Some studies have indicated that QUIC can achieve poor goodput, especially when there is packet loss, and that the performance can vary significantly depending on both the client and server QUIC implementations used.[16] This highlights the importance of the specific QUIC implementation and its tuning for satellite environments. Furthermore, there are instances where the UDP-based QUIC stack has shown a reduction in data rate compared to TCP-based stacks over fast internet connections, with the performance gap widening as bandwidth increases. This suggests that while QUIC offers benefits in challenging conditions, it may not always be the superior choice in all scenarios.[16]

When specifically looking at LEO satellite networks like Starlink, the performance comparison between QUIC and TCP reveals nuanced findings. One study indicated that TCP might be more susceptible to throughput drops due to interruptions such as the satellite handover process, which occurs frequently in LEO constellations.[32] This susceptibility could be due to TCP's congestion control mechanisms reacting more aggressively to the temporary disruptions caused by handovers. Conversely, research on Starlink has shown that QUIC can achieve goodput comparable to or even better than TCP in LEO environments, especially when utilizing optimized congestion control algorithms that are tailored to the specific characteristics of these networks.[6]

The impact of high latency and packet loss, inherent challenges in many satellite networks, affects both QUIC and TCP. High latency can significantly hinder TCP's performance by slowing down its connection establishment, slow start, and retransmission processes, ultimately leading to lower throughput and longer transfer times.[7] Packet loss in TCP can exacerbate these issues due to head-of-line blocking and the increased time required for retransmissions over long-distance links.[7] QUIC's design, with its improved loss recovery and multiplexing, aims to mitigate these impacts, but its performance can still suffer in highly lossy environments, and high latency can affect its connection establishment and congestion control efficiency.[10]

Scenario	Metric	QUIC Performance	TCP Performance	Key Findings/Outcomes
GEO Satellite (Emulated, High Latency/Loss)	Page Retrieval Time	Reduced compared to HTTPS/HTTP/2 [16]	-	QUIC helps reduce page load times in challenging GEO conditions [16]
GEO Satellite (Emulated, Various Conditions)	Goodput	Poor in general, especially with loss; varies by implementation [16]	-	Performance highly dependent on QUIC implementation [16]
Fast Internet	Data Rate	Up to 45.2% reduction compared to TCP+TLS+HTTP/2; gap grows with bandwidth [16]	Higher data rate in some scenarios [16]	QUIC overhead can be higher over fast, low-latency links [16]
Starlink (LEO, Real-world)	Throughput	Less susceptible to drops during handovers compared to TCP (Hypothesis) [32]	More susceptible to drops during handovers (Observed) [32]	TCP might struggle more with frequent LEO handovers [32]
LEO Satellite (Emulated & Real-world)	Goodput/Transfer Time	Comparable to or better than TCP with optimized CC [6]	Comparable or worse than QUIC, depending on CC [6]	QUIC shows promise in LEO with appropriate congestion control, especially handover-aware mechanisms [8]
GEO Satellite (Emulated, RFC9000)	Throughput	Slightly better for small objects; no benefit for web browsing [34]	-	QUIC's advantages over TCP in satellite might be limited to specific scenarios [34]

Impact of Starlink's Unique Characteristics on QUIC Performance

The frequent satellite handovers inherent in Starlink's LEO constellation pose a unique challenge to the performance of transport layer protocols like QUIC. These handovers, occurring at predictable 15-second intervals, can result in temporary latency spikes and packet losses.[8] Congestion control algorithms within QUIC, which typically react to packet loss or increased latency by reducing the congestion window, might misinterpret these handover-induced disruptions as signs of network congestion.[8] This misinterpretation can lead to an unnecessary reduction in the sending rate, ultimately degrading the overall throughput performance.[8] Research has shown that TCP's downlink throughput over Starlink is significantly affected by the handover process, often requiring the congestion control algorithm to initiate a slow start phase after each handover to recover its sending rate.[8] It is reasonable to expect that QUIC, which employs similar congestion control principles, could be affected in a comparable manner by these frequent handover events. Therefore, addressing the impact of handovers is crucial for optimizing QUIC's performance over Starlink networks.

On the other hand, QUIC's connection migration feature presents a significant advantage in the context of LEO network dynamics. Unlike TCP, which ties a connection to specific IP addresses, QUIC uses connection IDs that are independent of the underlying IP address.[10] This allows a QUIC connection to persist seamlessly even when the network path changes, such as during a satellite handover where the user terminal might be associated with a different satellite or ground station.[27] This capability is particularly beneficial in the highly mobile environment of LEO networks, where the association between users and network infrastructure can change frequently. While client-initiated connection migration in QUIC does require the initial handshake to be completed and secure keys to be established, the ability to maintain a connection across network changes offers a distinct advantage over TCP, which would typically require re-establishing a new connection upon an IP address change.[28] This seamless connection migration can contribute to a more stable and reliable user experience in the face of the dynamic topology of LEO satellite networks.

QUIC Optimizations and Configurations for Starlink-Class Networks

To achieve optimal performance of QUIC over Starlink-class networks, careful consideration of congestion control algorithms and other configurable parameters is essential. QUIC's architecture allows for pluggable congestion control, meaning that the specific algorithm used can be chosen and potentially tuned based on the underlying network environment.[11] In high-latency, high-bandwidth environments like satellite links, rate-based congestion control algorithms such as BBR (Bottleneck Bandwidth and RTT) may be more suitable than traditional loss-based algorithms like Cubic, which can react aggressively to packet loss that might not be indicative of congestion in such networks.[8]

Given the unique challenge of frequent satellite handovers in LEO networks, research has explored modifications to QUIC's congestion control to incorporate handover awareness.[8] One promising approach is a "congestion window freeze" mechanism, where the congestion window is prevented from being reduced upon detection of packet loss if the loss event coincides with a predicted handover.[8] This helps to avoid unnecessary rate reductions that can occur when the handover-induced disruptions are misinterpreted as congestion. Furthermore, the 0-RTT-BDP (zero Round-Trip Time Bandwidth-Delay Product) extension for QUIC could potentially help in more rapidly reaching the link's capacity during the initial connection phase, which is particularly important in high-BDP networks like satellite links.[37]

Beyond congestion control, other QUIC features and parameters can be configured to enhance performance over Starlink. Efficient management of acknowledgements (ACKs) is crucial, especially on satellite links that might have asymmetric bandwidth capacities. Strategies to reduce the frequency of ACKs can help to minimize overhead, particularly on the return link, without unduly impacting RTT measurements and loss detection.[37] Adjusting parameters like the ACK delay and threshold can be beneficial in this regard.[39]Additionally, the default maximum window sizes in QUIC might need to be increased to fully utilize the high bandwidth offered by Starlink, considering the potentially large Bandwidth-Delay Product of the connection.[37]Finally, exploring the use of Forward Error Correction (FEC) within QUIC could provide a mechanism to recover from expected packet loss without relying solely on retransmissions, which can be inefficient over high-latency links.[11]

The IETF and the broader research community are actively engaged in understanding and improving QUIC performance in non-terrestrial networks, including satellite links.[41] Several relevant IETF drafts and ongoing research efforts focus on addressing the specific challenges posed by these environments.[37] These include proposals for extensions like 0-RTT-BDP, mechanisms for detecting ground segment congestion based on loss bits, and adjustable ACK ratios to better suit asymmetric links. This continued focus indicates the growing recognition of the importance of QUIC in satellite communications and the potential for future standardization of satellite-specific optimizations.

QUIC and Performance Enhancing Proxies (PEPs) in Satellite Networks

Historically, Performance Enhancing Proxies (PEPs) have played a significant role in optimizing TCP performance over satellite communication links.[4] These proxies, often deployed at the satellite gateway and sometimes at the user terminal, work by splitting the end-to-end TCP connection into multiple segments. This allows for the application of different congestion control mechanisms tailored to the specific characteristics of each segment, particularly the high-latency satellite link.[48] PEPs can also employ techniques like local acknowledgements to mask the long round-trip time from the end hosts, accelerate slow start, and improve error recovery by handling retransmissions locally.[48] These optimizations have been crucial in delivering acceptable user experiences over traditional satellite internet services.

However, the inherent end-to-end encryption in QUIC presents a significant challenge to the use of traditional TCP PEPs.[16] Because QUIC encrypts not only the application data but also most of the transport layer headers, middleboxes like traditional PEPs, which rely on deep packet inspection to function, are unable to effectively process and optimize QUIC traffic.[16] This incompatibility means that the performance benefits offered by TCP PEPs are not directly available to applications using QUIC over satellite links.[16]

In response to this challenge, emerging approaches like QPEP (QUIC-based PEP) are being explored as a way to provide performance enhancement while maintaining end-to-end encryption.[16] QPEP aims to combine the performance-enhancing techniques of traditional PEPs with the security features of QUIC by establishing an encrypted QUIC tunnel between two end nodes.[51] This approach allows for a distributed PEP architecture where optimizations can be applied at the endpoints without breaking the end-to-end encryption. Initial research into QPEP has shown promising results, with the potential to improve goodput and reduce page load times over high-latency satellite links compared to using traditional VPN encryption.[51] These emerging solutions suggest a path forward for achieving performance optimization in satellite networks while embracing the security benefits of protocols like QUIC.

Case Studies and Experimental Results

A growing body of research has focused on evaluating the performance of QUIC over satellite networks, with several studies specifically examining LEO constellations like Starlink. Early work often involved simulations of GEO satellite links to understand QUIC's behavior in high-latency environments.[16] These studies provided initial insights into QUIC's potential advantages in reducing page load times under high latency and loss conditions, but also highlighted the variability in performance depending on the QUIC implementation used.[16]

As LEO networks like Starlink became more prevalent, researchers began conducting real-world experiments to measure QUIC's performance. These measurements typically focused on metrics such as latency, throughput, and packet loss.[4] Some studies found that TCP might be more susceptible to throughput drops during Starlink's frequent satellite handovers [32], while others showed that QUIC, especially with optimized congestion control, could achieve comparable or better performance than TCP in LEO environments.[6]

Specifically addressing the handover challenge in Starlink, researchers have proposed and evaluated handover-aware congestion control mechanisms for QUIC.[8] By leveraging the predictable timing of these handovers, algorithms like StarQUIC, which incorporates a congestion window freeze mechanism, have demonstrated significant improvements in transfer times over real Starlink networks.[8] This indicates the potential for tuning QUIC's congestion control to the unique characteristics of LEO networks.

Furthermore, the combination of QUIC with other techniques like lossless compression has been explored to enhance data transfer performance in LEO satellite network emulators.[9] These studies suggest that for smaller file sizes, using QUIC with compression can lead to better performance in satellite environments.

Conclusion and Recommendations

The evaluation of QUIC protocol performance across Starlink-class satellite networks reveals a complex interplay of factors. While Starlink's LEO architecture offers significantly lower latency compared to traditional GEO satellites, the environment still presents unique challenges for transport protocols due to inherent latency, potential packet loss, and frequent satellite handovers. QUIC, with its modern design and features like multiplexing, integrated security, and connection migration, holds considerable promise for enhancing user experience over these networks.

The strengths of QUIC in the context of Starlink include its ability to mitigate head-of-line blocking, its built-in security, and its connection migration capability which is well-suited for the dynamic nature of LEO constellations. Moreover, QUIC's user-space implementation allows for faster innovation and deployment of optimizations tailored to satellite environments.

However, the evaluation also highlights weaknesses. Standard QUIC congestion control algorithms may not optimally handle the frequent handovers in Starlink, potentially leading to performance degradation. Additionally, QUIC's end-to-end encryption prevents the use of traditional TCP Performance Enhancing Proxies, which have historically been crucial for optimizing satellite links.

Based on the analysis, several recommendations can be made to improve QUIC's performance over Starlink-class networks:

1. **Implement Handover-Aware Congestion Control:** Given the predictable nature of Starlink's satellite handovers, incorporating mechanisms into QUIC's congestion control algorithms to anticipate and mitigate the impact of these events is crucial. Techniques like the "congestion window freeze" show significant promise.[8]
2. **Explore and Standardize Satellite-Optimized Congestion Control:** Further research and standardization efforts within the IETF should focus on developing congestion control algorithms specifically designed for the characteristics of LEO satellite networks, considering their unique latency profiles and potential for packet loss.
3. **Fine-Tune ACK Management:** Optimizing the frequency and behavior of QUIC acknowledgements can help reduce overhead, especially on potentially asymmetric satellite links, without negatively impacting reliability or RTT estimation.[39]
4. **Consider Increasing Initial and Maximum Congestion Windows:** Given the high bandwidth available on Starlink, appropriately increasing QUIC's initial and maximum congestion windows could allow for faster ramp-up and better utilization of the link capacity, especially for bulk data transfers.

5. **Investigate and Potentially Implement FEC:** Exploring the use of Forward Error Correction mechanisms within QUIC could enhance resilience to packet loss, which is still a factor in satellite communications, without relying solely on retransmissions.
6. **Support and Develop Encrypted Performance Enhancement Solutions:** As traditional PEPs are incompatible with QUIC, continued research and development into encrypted performance enhancement solutions like QPEP are essential to bridge the gap between security and performance optimization in satellite networks.

Future research should continue to evaluate the performance of various QUIC implementations and configurations over real-world Starlink and similar LEO networks. Gathering more extensive data on latency variations, packet loss patterns, and the impact of handovers will be crucial for guiding further optimizations and ensuring that QUIC can effectively meet the demands of next-generation satellite internet services.