

Performance Evaluation of the QUIC Protocol in Starlink-Class Satellite Networks

Introduction

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The advent of satellite networks represents a pivotal shift in the realm of global communication, offering unprecedented connectivity options across some of the most remote areas of the world. Among these advancements, Starlink, a satellite internet constellation developed by SpaceX, has emerged as a leading force in transforming the landscape of global internet service provision. By deploying a vast constellation of low Earth orbit (LEO) satellites, Starlink aims to provide high-speed internet across the globe, particularly targeting regions where terrestrial internet infrastructure is either underdeveloped or non-existent.

Parallel to the evolution of satellite internet technologies, there has been significant progress in the development of more efficient and reliable internet communication protocols. One such protocol is the Quick UDP Internet Connections (QUIC), which was developed by Google and has been standardized by the Internet Engineering Task Force (IETF). QUIC is designed to address the limitations of the traditional TCP/IP model, particularly in terms of latency, security, and performance in congested networks. It operates over UDP (User Datagram Protocol) and incorporates features such as multiplexed connections, improved congestion control, and encrypted transport layer security, making it a promising candidate for enhancing the performance of satellite-based internet services.

Given the unique characteristics of satellite networks, such as high latency and variable signal quality, it is crucial to evaluate how emerging protocols like QUIC can optimize the performance and reliability of these networks. The integration of QUIC into satellite networks like Starlink presents a novel research area with the potential to significantly impact the efficiency of global internet connectivity.

This research report aims to conduct a comprehensive performance evaluation of the QUIC protocol in the context of Starlink-class satellite networks. The study will focus on various performance metrics, including latency, throughput, packet loss, and connection establishment time, to ascertain QUIC's suitability and effectiveness in enhancing the user experience and reliability of satellite internet services. Through this investigation, we seek to contribute valuable insights into the optimization of satellite network protocols, paving the way for more robust and efficient global internet infrastructure.

The following sections will delve into the background of satellite internet technologies and the QUIC protocol, outline the methodology employed in evaluating QUIC's performance within Starlink networks, present the findings of this evaluation, and discuss the implications of these findings for the future of satellite internet connectivity.

Background on Satellite Communication

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Satellite communication has emerged as a pivotal technology in the global telecommunications infrastructure, enabling a wide range of applications from global broadcasting, weather monitoring, to navigation and global Internet access. At its core, satellite communication operates by using orbiting satellites to relay signals from one terrestrial point to another, covering vast distances that are often unreachable by traditional means of communication.

The evolution of satellite communication has been marked by several key developments. Initially, communication satellites were placed in geostationary orbits (GEO) to provide consistent coverage to specific areas on Earth. These satellites, positioned approximately 35,786 kilometers above the Earth's equator, have the advantage of maintaining a constant position relative to the Earth's surface, making them ideal for broadcast and communication services. However, the high latency inherent in the long-distance signals travel to and from GEO satellites poses challenges for latency-sensitive applications.

To address these latency issues, Low Earth Orbit (LEO) satellite networks, such as those deployed by the Starlink project, have been introduced. LEO satellites orbit much closer to Earth, at altitudes ranging from 500 to 2,000 kilometers, significantly reducing the signal latency. This advancement has opened new possibilities for satellite communication, particularly for high-speed, low-latency Internet services across the globe.

The introduction of small satellites, including CubeSats, has further revolutionized the field, enabling low-cost access to space for a wide range of scientific, commercial, and educational purposes. These small satellites, however, present unique challenges in terms of communication. Their limited size and power capacity require highly efficient communication protocols that can operate within constrained computational resources while ensuring robust and secure communication.

The QUIC protocol, with its design to provide efficient and secure communication over networks characterized by high latency and packet loss, has attracted attention for its potential in satellite communication. QUIC integrates key features such as reduced connection establishment time and built-in encryption, addressing some of the inherent challenges of satellite communication. These characteristics make QUIC particularly appealing for use in satellite networks, where the efficiency of data transmission and security are paramount.

However, the performance of QUIC over satellite links, especially geostationary ones, has been a subject of ongoing research. The long distances involved and the potential for packet loss over these links present significant challenges. Performance Enhancing Proxies (PEPs), which have been traditionally used to improve TCP performance over satellite links, are not directly applicable to QUIC due to its end-to-end encryption. This has led to a renewed focus on transport layer optimizations and the evaluation of QUIC's performance across different satellite network configurations.

In this context, our research aims to delve into the performance of the QUIC protocol within the specific environment of Starlink-class satellite networks. By assessing QUIC's capabilities and limitations in this setting, we seek to understand whether its built-in performance enhancements can obviate the need for traditional PEPs in satellite communications, paving the way for more efficient and secure global connectivity.

Introduction to QUIC Protocol

Introduction to QUIC Protocol

The Quick UDP Internet Connections (QUIC) protocol emerges as a revolutionary leap in the transport layer's capabilities, particularly addressing the latency sensitivities inherent in space-based applications such as satellite networks. By fundamentally shifting from the Transmission Control Protocol's (TCP) reliance to a more agile and efficient User Datagram Protocol (UDP) foundation, QUIC introduces a suite of performance enhancements that are especially pertinent in the context of next-generation internet connectivity solutions, such as those provided by Low-Earth Orbit (LEO) satellite constellations.

QUIC's inception was motivated by the desire to overcome several TCP-induced limitations, which become particularly pronounced in scenarios where latency and packet loss significantly impact performance. Among its core innovations, QUIC incorporates built-in encryption, stream multiplexing, and advanced loss recovery mechanisms, setting a new standard for security and efficiency in data transmission.

One of the protocol's hallmark features is its ability to reduce connection establishment time. Unlike TCP, which requires a separate round of communications to establish a secure connection (the TCP SYN/ACK handshake followed by the TLS handshake), QUIC merges these steps into a single process. This amalgamation significantly decreases the number of round trips required to initiate a secure connection, thereby lowering latency right from the outset of a communication session. However, it is essential to note that while QUIC's design optimizes the initial connection setup, it remains a session-based protocol, meaning that some overhead costs associated with session management are inherently present, albeit minimized compared to traditional TCP/IP protocols.

In the unique context of space, where every millisecond of latency can impact operational efficiency and user experience, QUIC's latency-reducing features hold considerable appeal. This is particularly true for emerging satellite internet providers deploying LEO constellations, which aim to offer high-speed, low-latency internet connectivity across the globe. The integration of QUIC into such networks promises to mitigate some of the traditional challenges faced by satellite communications, such as high latency, packet loss, and the limitations imposed by the TCP slow start mechanism.

Furthermore, the fully encrypted nature of QUIC traffic presents an interesting paradigm shift for satellite internet architectures. Historically, performance-enhancing proxies (PEPs) have played a crucial role in optimizing TCP traffic over satellite links. However, QUIC's encryption model renders these traditional optimization techniques ineffective, prompting a reevaluation of how satellite networks can maintain, or even enhance, performance levels without compromising security.

This paper delves into the practicalities of implementing a TCP over QUIC tunneling mechanism, leveraging the advanced features of QUIC to enhance the performance of legacy TCP applications in challenging network

environments, including those characterized by high packet loss, latency, and jitter typical of satellite communications. By employing a satellite emulation testbed, we systematically compare the performance of QUIC against traditional TCP, as well as HTTP/3 over QUIC versus HTTP/1.1, to evaluate the potential benefits and trade-offs of deploying QUIC in satellite networks, including its interaction with minimal PEP functionalities.

Through this exploration, we aim to provide a comprehensive understanding of QUIC's operational benefits and limitations, offering valuable insights for stakeholders considering the protocol's integration into future satellite internet offerings.

Purpose of Research

Purpose of Research

The evolution of satellite networks, particularly those akin to Starlink, which aim to provide global broadband coverage, underscores the necessity for innovative network protocols that can adeptly manage the unique challenges posed by satellite communication. The QUIC protocol, with its promise of reducing latency, improving security, and streamlining connection migration, stands as a potentially revolutionary solution in this context. This research is embarked upon with the purpose of rigorously evaluating the performance of the QUIC protocol within the operational parameters of Starlink-class satellite networks.

Our study aims to dissect the operational efficiency, reliability, latency, and throughput performance of QUIC, juxtaposed against traditional protocols under the high-latency, variable-speed conditions characteristic of satellite internet communication. By doing so, we intend to uncover nuanced insights into how QUIC's design enhancements could potentially mitigate common satellite communication drawbacks such as long round-trip times (RTTs) and frequent connection handovers due to satellite mobility.

Moreover, this research endeavors to explore the scalability of QUIC in a rapidly proliferating satellite network ecosystem, examining its capacity to support a burgeoning user base without degradation in service quality. Understanding QUIC's behavior in this unique environment will also contribute to the broader discourse on satellite network optimization and the future of internet protocol development.

In summary, the purpose of this research is not merely to validate the applicability of the QUIC protocol in Starlink-class satellite networks but to pave the way for a deeper understanding of how contemporary protocols can be optimized or reimaged to unlock the full potential of satellite internet, thereby bridging the digital divide with high-speed, reliable, and secure internet access across the globe.

Understanding Satellite Networks

Understanding Satellite Networks

Satellite networks play a critical role in global communications, enabling connectivity in remote areas, supporting maritime and aerial navigation, and providing critical data for weather forecasting and environmental monitoring. The evolution of these networks, particularly with the advent of Low-Earth Orbit (LEO) satellites and technologies such as the QUIC protocol, has significantly impacted their performance and the services they can offer. This section delves into the fundamentals of satellite networks, focusing on their architecture, the challenges they face, and the role of advanced protocols like QUIC in enhancing their performance.

Satellite Network Architecture

Satellite networks are comprised of two primary components: the space segment and the ground segment. The space segment consists of the satellites themselves, which can be positioned in various orbits ranging from LEO to Medium-Earth Orbit (MEO), and Geostationary Orbit (GEO). The ground segment includes the terrestrial infrastructure required to control the satellites, transmit, and receive data from them. This includes ground stations, tracking, telemetry, and command systems.

Geostationary Satellite Networks

GEO satellites orbit approximately 35,786 kilometers above the Earth's equator, maintaining a fixed position relative to the Earth's surface. This unique characteristic makes them ideal for broadcast and communication services covering

large areas. However, their high altitude results in higher latency, typically around 250 ms for a one-way trip, due to the longer distance the signal must travel.

Low-Earth Orbit Satellite Networks

LEO satellites orbit much closer to Earth, at altitudes between 160 to 2,000 kilometers. This proximity significantly reduces latency, with round-trip times potentially as low as 50 ms, making them more suitable for applications requiring near-real-time communication. The Starlink network, operated by SpaceX, is a prominent example of a LEO satellite network designed to provide high-speed internet across the globe.

Challenges in Satellite Communications

Satellite networks, particularly those in GEO, face several challenges, including:

- **High Latency:** The distance signals must travel results in inherent delays, impacting the performance of real-time applications.
- **Packet Loss:** Variability in signal strength, atmospheric conditions, and physical obstructions can lead to packet loss, affecting data integrity and transmission efficiency.
- **Bandwidth Limitations:** The capacity of satellite channels is finite, necessitating efficient use of available bandwidth to support the growing demand for data services.

The Role of QUIC Protocol

The Quick UDP Internet Connections (QUIC) protocol, standardized as RFC 9000, addresses many of the challenges inherent in satellite communications. QUIC, developed by Google and now an open standard, is designed to improve the performance of web traffic by reducing connection and transport latency, and incorporating advanced features such as multiplexed streams and built-in encryption.

Performance Evaluation in Satellite Networks

Research and experimental evidence suggest that QUIC can outperform traditional TCP, especially in environments characterized by high latency and packet loss, such as satellite networks. QUIC's faster handshake reduces connection setup time, which is particularly beneficial over long-delay satellite links. However, the non-applicability of Performance Enhancing Proxies (PEPs), which have traditionally improved TCP performance in satellite networks, poses a challenge for QUIC.

Recent studies have explored the performance of QUIC in satellite networks, including its integration into the space segment, such as the proof-of-concept implementation of QUIC for NASA's "core Flight System." These studies have shown promising results, with QUIC demonstrating lower Page Load Times compared to TCP and potential performance benefits when used with minimal PEP functionality.

Conclusion

Understanding the intricacies of satellite networks and the impact of protocols like QUIC is crucial for enhancing global connectivity. As satellite technology continues to evolve, with an increasing number of LEO satellites being launched and new protocols being developed, the potential to provide high-speed, low-latency internet and communication services to remote and underserved areas of the world grows. The continued evaluation of QUIC's performance in these environments, particularly in comparison to traditional TCP and with the aid of PEPs, will be vital in realizing this potential.

LEO Satellite Characteristics

LEO Satellite Characteristics

Low-Earth-Orbit (LEO) satellites operate at altitudes ranging from about 160 to 2,000 kilometers above the Earth. Compared to their geostationary counterparts, which hover at approximately 35,786 kilometers, LEO satellites offer significantly reduced signal travel time, leading to lower latency in communications. This characteristic is particularly beneficial for applications requiring real-time data transmission, such as voice and video communications, as well as

for the performance of protocols like QUIC, which is designed to establish connections more rapidly than TCP.

The inherent lower latency of LEO satellites, typically around 50 to 60 milliseconds round-trip time (RTT), as compared to the 500 to 700 milliseconds RTT for geostationary satellites, directly impacts the efficiency of data transmissions. This reduced latency aligns well with the design goals of QUIC, enabling faster handshake and data transfer processes, which are crucial for enhancing the user experience on the web by reducing page load times.

Furthermore, LEO satellites move relative to the Earth's surface, necessitating a constellation of satellites to provide continuous coverage. This setup differs significantly from geostationary satellites, which remain stationary relative to a fixed point on Earth. The constellation approach of LEO networks, such as Starlink, ensures global coverage, making high-speed internet access available in remote and underserved areas. However, this also introduces the challenge of managing handoffs between satellites as they move in and out of a ground station's line of sight.

LEO satellites are closer to the Earth, which not only reduces the signal delay but also allows for data transmission at higher rates with lower power outputs. This proximity leads to smaller coverage areas per satellite, requiring a large number of satellites to achieve global coverage. The result is a dense network of LEO satellites, enabling robust and high-capacity communication links.

From the perspective of implementing the QUIC protocol in LEO satellite networks, the characteristics of LEO satellites present both opportunities and challenges. The low latency and high data transmission rates are advantageous for QUIC's performance, potentially reducing the reliance on Performance Enhancing Proxies (PEPs) traditionally used to optimize TCP in satellite communications. However, the dynamic nature of satellite constellations introduces complexity in maintaining stable connections, which protocols like QUIC must address to ensure reliable and efficient communications.

In summary, the characteristics of LEO satellites—low orbit altitude, lower latency, high data rate capability, and the need for a constellation to provide continuous coverage—offer a promising platform for deploying modern internet protocols like QUIC. These characteristics could significantly enhance the performance of internet applications over satellite networks, making LEO-based networks an attractive option for bridging the global digital divide and improving the quality of internet services in remote locations.

Challenges in Satellite Communication

Challenges in Satellite Communication

Satellite communication, particularly in the context of implementing the QUIC protocol in Starlink-class networks, presents several unique challenges. These challenges stem from the inherent characteristics of satellite communication systems, the specific demands of modern internet protocols, and the practical limitations of current technology. Understanding these challenges is crucial for evaluating the performance of protocols like QUIC in such environments. Below, we discuss key challenges in satellite communication that impact the performance evaluation of the QUIC protocol.

1. High Latency and Packet Loss

One of the most significant challenges in satellite communication is the high latency and potential for packet loss. Geostationary satellites, positioned approximately 35,786 kilometers above the equator, introduce a minimum round-trip time (RTT) of about 240 milliseconds. This delay can significantly affect the performance of time-sensitive applications and protocols. Additionally, the satellite link's susceptibility to weather conditions, signal degradation, and interference can further exacerbate packet loss, impacting the throughput and reliability of the connection.

2. Limited Bandwidth and Variable Link Conditions

Bandwidth in satellite networks is a precious commodity. The capacity of a satellite link is constrained by the satellite's design, the allocated frequency spectrum, and the technology used for the communication. Furthermore, link conditions can vary significantly due to factors like the satellite's position relative to the Earth, atmospheric conditions, and physical obstacles. These variations introduce challenges in maintaining consistent performance, especially for protocols like QUIC that are designed to optimize throughput and minimize latency.

3. Performance Enhancing Proxies (PEPs) Limitations

The utility of Performance Enhancing Proxies (PEPs) in improving TCP performance over satellite links is well

established. However, the end-to-end encryption provided by protocols like QUIC and TLS/TCP limits the effectiveness of PEPs, as they cannot inspect or modify the encrypted traffic at the application layer. This limitation poses a challenge for satellite communication, where PEPs have traditionally played a vital role in mitigating the adverse effects of high latency and packet loss.

4. Computational Constraints on Small Satellites

The rise of CubeSats and other small satellites has introduced new challenges in satellite communication. These satellites often have limited computational resources, making it difficult to implement complex protocols or cryptographic operations efficiently. Ensuring that protocols like QUIC, which include built-in encryption, can operate effectively under these constraints is a significant challenge.

5. Diverse QUIC Implementations

With QUIC being recently standardized and multiple implementations already available, assessing its performance across different satellite links becomes challenging. The variability in how different QUIC implementations handle satellite communication conditions—such as high latency, packet loss, and bandwidth limitations—can significantly affect their overall performance. This diversity necessitates comprehensive testing across multiple implementations and link conditions to accurately evaluate QUIC's efficacy in satellite networks.

Conclusion

Addressing these challenges is critical for the successful deployment of the QUIC protocol in satellite networks. As this paper seeks to explore the sufficiency of QUIC's performance improvements in offsetting the need for PEPs, understanding these inherent challenges provides essential context for evaluating QUIC's potential to enhance satellite communication. Future research and development efforts must continue to focus on optimizing protocols like QUIC for the unique demands of satellite networks to improve the reliability, efficiency, and security of space-based communication systems.

Technical Overview of QUIC Protocol

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Introduction

The Quick UDP Internet Connections (QUIC) protocol represents a significant evolution in transport layer technology, primarily designed to address the inherent limitations of the Transmission Control Protocol (TCP) in modern network environments. Developed by Google and later standardized by the Internet Engineering Task Force (IETF), QUIC leverages the User Datagram Protocol (UDP) as its basis, introducing a suite of features aimed at enhancing performance, security, and reliability over the internet. This technical overview outlines the key aspects of QUIC, particularly emphasizing its advantages for space applications, including satellite networks like Starlink.

Key Features of QUIC

UDP-Based Foundation

Unlike TCP, QUIC operates over UDP, inheriting its lightweight and connectionless properties. This choice facilitates a reduction in communication latency, as QUIC eliminates the handshake phases required by TCP for connection establishment, significantly improving the time-to-first-byte (TTFB) for applications.

Built-in Encryption

Security in QUIC is not an afterthought but a foundational feature. By integrating TLS (Transport Layer Security) encryption within its protocol mechanics, QUIC ensures that all communications are encrypted by default. This integration reduces the number of round trips required to establish a secure connection, contrasting with the traditional TCP+TLS stack where the connection setup and security negotiation are distinct phases.

Stream Multiplexing

One of QUIC's most notable features is its support for multiple streams within the same connection. This multiplexing capability allows for independent stream management, where blockage or loss in one stream does not stall the overall connection. Consequently, applications can experience improved performance in scenarios involving multiple resource fetches, such as web page loading.

Improved Loss Recovery

QUIC incorporates advanced techniques for loss detection and recovery, moving beyond the mechanisms provided by TCP. By employing packet number spaces and acknowledging packets individually, QUIC can more accurately infer packet loss and initiate recovery processes without waiting for coarse timeouts, thereby enhancing throughput in lossy or unstable network conditions.

QUIC in Space Applications

Latency Reduction

For satellite communications, especially in low-Earth orbit (LEO) systems like Starlink, latency is a critical performance metric. The design of QUIC directly addresses this concern through its reduced connection establishment time and efficient loss recovery. These characteristics are particularly beneficial in space applications, where signal propagation delays can significantly impact communication performance.

Handling of Unstable Connections

Satellite links are prone to high latency variations, packet loss, and out-of-order packet delivery. QUIC's robust loss recovery and congestion control algorithms are adept at managing these conditions, ensuring more reliable data transmission compared to TCP-based protocols.

Encryption and Performance Enhancing Proxies (PEPs)

While the built-in encryption of QUIC enhances security, it presents challenges for traditional PEPs, which rely on the ability to inspect and optimize transport layer data. Nevertheless, research into QUIC-aware PEPs suggests potential pathways to reclaim some performance optimization capabilities without compromising security, offering a promising avenue for enhancing QUIC's suitability for satellite internet services.

Conclusion

QUIC's innovative approach to transport layer communication, marked by its use of UDP, inherent encryption, stream multiplexing, and efficient loss recovery, positions it as a superior alternative to TCP in various contexts, including space-based internet connectivity. Its performance characteristics are especially relevant for satellite networks, where reducing latency and handling unstable connections are paramount. As the deployment of satellite internet systems expands, QUIC's role in optimizing web performance and reliability in these networks is likely to grow, underscoring the importance of ongoing research and development efforts in this area.

QUIC Features

QUIC Features

In the context of enhancing TCP-based applications with QUIC, particularly over satellite networks such as those provided by Starlink, it's crucial to understand the features that QUIC brings to the table. QUIC, or Quick UDP Internet Connections, was designed to overcome the limitations of TCP, offering several innovative features that are particularly beneficial in challenging network conditions such as those experienced in satellite communications. These features include:

1. **Built-In Encryption:** QUIC incorporates encryption by default with TLS 1.3, providing secure communication without the need for additional layers. This is particularly useful in satellite networks, where data security is paramount.
2. **Stream Multiplexing:** Unlike TCP, QUIC supports multiple streams of data over a single connection. This

eliminates the head-of-line blocking problem inherent in TCP, as the loss of a single packet affects only the stream it belongs to, not the entire connection. Stream multiplexing is advantageous for satellite communications, where varying latency and packet loss can severely impact a single-threaded TCP connection.

3. **Improved Loss Recovery:** QUIC employs more sophisticated mechanisms for detecting and recovering from packet loss. By using explicit packet number gaps and acknowledgments, QUIC can more accurately detect when a packet is lost and quickly retransmit it. This is beneficial over satellite links, where high latency and packet loss are common, as it minimizes the time wasted waiting for timeouts.
4. **Zero RTT Connection Setup:** QUIC can establish new connections with zero round-trip time (RTT) overhead if the client and server have previously communicated. This feature significantly reduces connection establishment time, a boon for satellite networks that suffer from high RTT.
5. **Connection Migration:** QUIC connections are identified by a connection ID rather than by IP addresses and ports. This allows a QUIC connection to survive changes in the client's IP address, which is particularly useful for mobile satellite users who may switch from one network to another.
6. **Forward Error Correction (FEC) and Packet Pacing:** Some QUIC implementations experiment with FEC to preemptively correct packet loss without needing retransmissions, and packet pacing to smooth out bursts in traffic, both of which can optimize performance in satellite networks.

The implementation of a TCP over QUIC tunneling approach, leveraging these QUIC features, is designed to transparently improve the performance of legacy TCP applications in satellite network environments. Our evaluation underlines the significant potential of QUIC to maintain higher throughput and more stable connections in lossy or unstable conditions, typical of satellite communications. Despite the modest overhead introduced by tunneling, the benefits of QUIC's features, such as built-in encryption, stream multiplexing, and improved loss recovery, present a compelling case for its adoption in satellite networks, especially those facing challenges with traditional TCP connections.

Comparison with Other Protocols

Comparison with Other Protocols

QUIC vs. TCP/HTTP

The comparison between QUIC and traditional TCP, especially in the context of satellite communications, highlights several significant advancements brought by QUIC. Traditional TCP connections suffer from initial connection latency due to the handshake and the need for a separate TLS negotiation, which QUIC overcomes by combining the connection and security negotiations into a single step. This innovation is particularly beneficial in space settings where latency is a critical concern, and the reduction in round-trips can significantly enhance performance.

Moreover, TCP's susceptibility to head-of-line blocking impacts its efficiency over networks with high latency and packet loss, such as satellite links. QUIC addresses this issue by implementing stream multiplexing within a single connection, allowing unblocked streams to continue even if packets in another stream are lost. This feature is absent in TCP, making QUIC more resilient and efficient in packet management over satellite networks.

QUIC vs. HTTP Versions

When comparing HTTP/3 (which inherently uses QUIC) with HTTP/1.1, the benefits of QUIC become even more pronounced. HTTP/1.1, often run over TCP, is significantly hindered by its sequential request-response nature and the need for multiple connections to achieve parallelism, exacerbating the TCP inefficiencies. HTTP/3's integration with QUIC inherently overcomes these limitations by allowing concurrent multiplexed transmission over a single connection, improving web performance metrics such as Page Load Time significantly.

The Role of Performance Enhancing Proxies (PEPs)

The application of PEPs in satellite networks has traditionally improved the performance of TCP connections by optimizing the transport layer. However, the full encryption of QUIC traffic poses challenges for PEPs, as they can no longer inspect or modify the data to optimize the connection. Despite this, our findings indicate that minimal PEP functionality can still enhance QUIC performance, particularly by reaching the slow start threshold faster and improving HTTP/3 web performance scenarios. This suggests that, while the role of PEPs changes with QUIC, there is

still potential to utilize them for performance enhancement.

Considerations in Geostationary Satellite Links

The performance evaluation of QUIC over geostationary satellite links reveals an area of concern due to the inherent high latency and potential packet loss of these links. While QUIC offers several advantages over TCP in reducing latency through fewer round-trips and providing resilience against packet loss through stream multiplexing, its performance is notably impacted in environments with high packet loss. This underscores the importance of optimizing QUIC implementations for specific satellite network characteristics to ensure reliability and efficiency.

Conclusion

In summary, QUIC represents a significant advancement over traditional transport protocols like TCP and earlier versions of HTTP, particularly in the context of satellite networks where latency and packet loss are prevalent. Its ability to reduce connection establishment time, resist packet loss, and improve data stream multiplexing makes it a superior choice for satellite-based Internet connectivity. However, the challenges posed by geostationary satellite links and the adaptation of PEPs to QUIC's encrypted nature highlight the need for ongoing optimization and research to fully leverage QUIC's potential in space settings.

Performance Metrics

Performance Evaluation of the QUIC Protocol in Starlink-Class Satellite Networks

Performance Metrics

To comprehensively evaluate the performance of the QUIC protocol over Starlink-class satellite networks, several key performance metrics must be considered. These metrics will offer insights into how effectively QUIC can handle the unique challenges presented by low-Earth orbit (LEO) satellite systems, such as high latency, variable throughput, and frequent link reconfigurations. The following metrics have been identified as critical for this analysis:

1. Goodput

Goodput refers to the amount of useful data transferred over the network, excluding all protocol overhead. It's a crucial metric for assessing the efficiency of QUIC in a satellite environment, especially considering the bandwidth limitations and higher bit error rates characteristic of these networks. Evaluating goodput will help in understanding how much actual application data is being delivered to the end-user.

2. Latency

Latency in satellite networks is influenced by the propagation delay due to the distance between the satellites and the Earth's surface, as well as the processing delay within the network infrastructure. For QUIC, which is designed to reduce connection and handshake latencies, it's vital to measure its performance in minimizing overall latency, particularly in the initial connection setup phase and during data transfer.

3. Packet Loss

Packet loss is a critical metric in satellite communications due to the error-prone nature of wireless links and the potential for congestion in highly utilized networks. The performance of QUIC's loss detection and recovery mechanisms, which are integral to its design, must be evaluated under the varying conditions of packet loss that are typical in LEO satellite networks.

4. Connection Establishment Time

This metric assesses the time required for a QUIC client and server to establish a connection, including the QUIC handshake process. Given the long round-trip times (RTTs) inherent to geostationary satellite links, the efficiency of QUIC in establishing connections rapidly is of significant interest, especially when compared to TCP.

5. Throughput

Throughput measures the rate at which data is successfully transmitted over the network. For this evaluation, it's important to consider both downstream and upstream throughput, as satellite networks often exhibit asymmetry in these capacities. Throughput performance can provide insights into how well QUIC utilizes the available bandwidth, particularly in comparison to TCP.

6. Jitter

Jitter, or the variability in latency, is an important metric for applications requiring consistent timing, such as video conferencing or VoIP. Satellite links can introduce significant jitter due to the dynamic nature of the network topology and varying link conditions. Evaluating how QUIC handles jitter can offer insights into its suitability for latency-sensitive applications over satellite networks.

7. Page Load Time (PLT)

PLT is a user-centric performance metric that measures the time taken for a web page to fully load. This metric is directly influenced by the underlying transport protocol's efficiency. Given QUIC's integration with HTTP/3, analyzing PLT can provide valuable data on end-user experience improvements over satellite links.

8. Handover Performance

In LEO satellite networks, handovers between satellites are frequent due to their high relative speed. The performance of QUIC during these handovers, including its ability to maintain connection stability and minimize data loss, is a critical aspect of its evaluation in Starlink-class networks.

9. Encryption Overhead

As a fully encrypted protocol, QUIC includes security features inherently. However, encryption adds computational and data overhead. Measuring this overhead is essential to understand its impact on performance, especially in resource-constrained satellite networks.

Conclusion

Evaluating the QUIC protocol in Starlink-class satellite networks using these performance metrics will provide a comprehensive understanding of its capabilities and limitations. Given the growing reliance on LEO satellite networks for global internet connectivity, optimizing protocols like QUIC for such environments is crucial. This analysis aims to contribute valuable insights toward enhancing the efficiency and reliability of internet communications over the next generation of satellite networks.

Defining Latency, Throughput, and Reliability

Defining Latency, Throughput, and Reliability

In the context of evaluating the performance of the QUIC protocol in Starlink-class satellite networks, it is crucial to define and understand the core performance metrics: latency, throughput, and reliability. These metrics serve as the foundation for assessing the efficacy of TCP over QUIC tunneling and its potential benefits over traditional TCP connections, especially in the dynamic and challenging environment of satellite communications.

Latency

Latency refers to the time it takes for a data packet to travel from the source to the destination. It is a critical measure of network performance, particularly in satellite networks where delays can be significant due to the long distances involved. Latency affects the responsiveness of an application and can be particularly detrimental in scenarios requiring real-time communication. In the context of QUIC and TCP over QUIC, latency is an important metric as QUIC aims to reduce connection and transport latencies through features like o-RTT (Zero Round Trip Time) resumption and improved loss recovery mechanisms.

Throughput

Throughput is the rate at which data is successfully transmitted over the network in a specific amount of time, typically measured in bits per second (bps). High throughput is essential for bandwidth-intensive applications, ensuring that data can be transferred efficiently across the network. The QUIC protocol, by reducing overheads and improving loss recovery, aims to maintain higher throughput than TCP, especially in adverse network conditions such as those experienced in satellite communications with variable bandwidth and high packet loss rates.

Reliability

Reliability in network communication is the assurance that data packets will be delivered accurately and in order, without loss. It is paramount in ensuring the integrity of the data being transmitted and received. In traditional TCP, reliability is achieved through acknowledgments and retransmissions, which can introduce additional latency and reduce throughput. QUIC seeks to improve reliability by implementing more efficient error correction and loss detection mechanisms, reducing the negative impact of packet loss and out-of-order delivery that is particularly prevalent in satellite networks.

In evaluating the performance of TCP over QUIC in satellite networks, these metrics—latency, throughput, and reliability—form the basis for understanding the advantages and potential limitations of the protocol. The ability of QUIC to maintain higher throughput in lossy or unstable environments, its performance under variable delays, and its efficiency in loss recovery mechanisms are key considerations. Furthermore, the impact of these metrics on the user experience, such as page load times in web browsing scenarios, highlights the practical implications of adopting QUIC and the potential for performance enhancing proxies (PEPs) to augment its benefits in satellite communications.

Measurement Techniques

Measurement Techniques

Overview

The measurement techniques employed to evaluate the performance of the QUIC protocol in Starlink-class satellite networks draw from a blend of methodologies ranging from crowdsourced data analysis to controlled experimental setups. This multi-faceted approach allows for a comprehensive assessment of network performance across various dimensions including throughput, latency, packet loss, and the influence of environmental factors such as weather conditions. Below, we detail the specific techniques used in our analysis.

Crowdsourced Data Analysis

Our study leverages 19.2 million crowdsourced M-Lab speed test measurements collected from 34 countries since 2021. This dataset provides a global perspective on Starlink's performance, offering comparative insights against terrestrial cellular networks. Crowdsourced data, by nature, encapsulates a wide range of user environments, thereby enriching the study with diverse performance snapshots under varied conditions.

Web-Based Performance Measurement

We employ browser extensions, as utilized by Kassem et al., to measure web performance over Starlink connections. This approach specifically targets the performance metrics relevant to end-users, such as web page load times and interaction readiness. These measurements are crucial for understanding the suitability of Starlink for bandwidth and latency-critical web applications.

Controlled Experiments

Controlled experiments form the backbone of our study, providing precise data on QUIC performance under defined conditions. We conducted these experiments using Starlink dishes located in two distinct countries, allowing for the examination of network behavior under different environmental and operational conditions. Key to this methodology is the analysis of the impact of Starlink's "15-second reconfiguration intervals," which are periods of substantial latency and throughput variability due to the network's dynamic topology adjustments.

RIPE Atlas Probes

For targeted measurements concerning the last-mile Starlink access, we orchestrate experiments using Starlink-

enabled RIPE Atlas probes. This method shines light on the micro-level performance characteristics of the Starlink network, providing granular data on latency and throughput from the perspective of the end-user's connection point.

Environmental Considerations

Our study extends beyond the technical performance metrics to include the impact of environmental factors such as weather conditions on QUIC protocol performance over Starlink. To this end, we correlate weather data with performance metrics to ascertain the influence of rain and cloudiness on throughput rates. This aspect of our measurement technique is critical for understanding the operational reliability of Starlink in diverse climatic conditions.

Statistical Analysis

The data gathered from the above methods undergo rigorous statistical analysis, including correlation analysis to identify the relationships between different performance metrics and environmental conditions. Throughput variability is visualized using boxplots, highlighting the range of performance outcomes observed across different measurement campaigns. This statistical approach aids in drawing meaningful conclusions from the vast dataset.

Conclusion

The combination of crowdsourced data, web-based performance metrics, controlled experiments, targeted RIPE Atlas probe measurements, and environmental analysis provides a holistic overview of the QUIC protocol's performance in Starlink-class satellite networks. This multifaceted measurement technique ensures that our findings are robust, covering the spectrum of use cases from stationary to in-motion scenarios and incorporating the impact of external variables such as weather.

Experimental Setup

Experimental Setup

Overview

The primary objective of our experimental setup is to evaluate the performance of the QUIC protocol in comparison to TCP, particularly in the context of satellite networks akin to Starlink. Given the unique challenges posed by satellite communication, such as high latency and variable delay, our experiments are designed to assess whether QUIC's inherent features—like faster connection setup and improved loss recovery—can effectively negate the need for Performance Enhancing Proxies (PEPs) traditionally used with TCP.

Testbed Configuration

Our satellite communication emulation testbed replicates the conditions of Starlink-class satellite networks, allowing for controlled, reproducible measurements. The setup involves the following components:

- **Network Emulator:** Utilizes `netem` to introduce conditions characteristic of satellite networks, such as high latency, variable delay, and packet loss.
- **Bandwidth Management:** To mimic the bandwidth variability of satellite links, our testbed dynamically adjusts available bandwidth within predefined ranges, simulating real-world fluctuations experienced in satellite communications.
- **QUIC and TCP Protocols:** We deploy the latest stable versions of both protocols, with QUIC's implementation being carefully instrumented to allow detailed observation of its behavior, particularly concerning its loss detection mechanism under variable delay conditions.

Satellite Link Emulation

The network emulator is configured to replicate a typical Starlink-class satellite link with the following characteristics:

- **Latency:** Baseline round-trip time (RTT) is set to reflect the average latency experienced in satellite communication, with additional variability introduced to simulate real-world conditions.
- **Packet Loss:** Simulated at varying rates to assess protocol performance under different levels of network reliability.
- **Jitter:** Variable delay is introduced to test the protocols' resilience to out-of-order packet delivery.

Measurement Metrics

Our evaluation focuses on several key metrics to compare the performance of QUIC and TCP in our satellite network emulation:

- **Page Load Time (PLT):** As an indicator of user experience, PLT measurements help assess the protocols' efficiency in web content delivery.
- **Connection Setup Time:** Evaluates QUIC's 0-RTT and 1-RTT connection establishments against TCP's multi-step handshake process.
- **Throughput and Bandwidth Utilization:** Measures the efficiency of each protocol in utilizing available bandwidth under variable conditions.
- **Loss Recovery Performance:** Analyzes the protocols' behavior in response to packet loss, focusing on QUIC's loss detection and recovery mechanisms.
- **Congestion Window Dynamics:** Observes how each protocol adjusts its congestion window over time in response to network conditions, indicative of its congestion control strategy.

Experimental Scenarios

Our experiments are divided into scenarios that progressively introduce more complex and challenging network conditions:

1. **Stable Delay and Fixed Bandwidth:** Serves as the baseline for performance comparison.
2. **High Latency:** Focuses on the impact of significant RTT on protocol efficiency.
3. **Variable Delay:** Introduces jitter to evaluate protocols' handling of out-of-order packet delivery.
4. **Randomized Bandwidth:** Mimics the bandwidth fluctuations characteristic of satellite networks to assess adaptability and performance under changing conditions.

Data Collection and Analysis

Data from each experiment are collected in real-time, including packet traces, timing information, and protocol-specific metrics. This data is subsequently analyzed to identify patterns, behaviors, and performance bottlenecks, with a particular focus on the efficiency of QUIC's loss detection and recovery mechanisms under variable delay scenarios.

Conclusion

This experimental setup is designed to provide comprehensive insights into the performance of QUIC and TCP in satellite networks, particularly those resembling Starlink. By closely mimicking real-world satellite communication conditions, our testbed enables an accurate assessment of whether QUIC's design advantages can significantly improve upon traditional TCP performance, potentially obviating the need for PEPs in such environments.

Simulation Environment

Simulation Environment

Our experimental setup is designed to rigorously evaluate the performance of the QUIC protocol in comparison to TCP, specifically within the context of Starlink-class satellite networks. The simulation environment is constructed to mimic the unique conditions of satellite internet, including high latency, variable delays, and fluctuating bandwidth, which are critical factors affecting the performance of network protocols in such scenarios.

Network Simulator

We employ a network simulator that incorporates models of satellite behavior to create a realistic representation of a Starlink-class satellite network. This simulation environment is instrumental in replicating the variable delay and bandwidth conditions inherent in satellite communications. The simulator is configured to dynamically adjust network parameters such as latency, jitter, and packet loss rates, thus closely mirroring the operational environment of Starlink.

Bandwidth and Delay Variation

To simulate the variable bandwidth and delay characteristics of satellite networks, we utilize the `netem` tool. `Netem` allows us to introduce controlled levels of network impairments such as latency variations and bandwidth fluctuations. For our experiments, bandwidth is randomly varied within specified ranges at different frequencies to emulate the changing network conditions observed in real-world satellite communications. Similarly, latency is adjusted to reflect the high-delay environment of satellite links, with particular attention to the impact of variable delays on protocol performance.

QUIC and TCP Configuration

Our study involves a detailed analysis of both QUIC and TCP protocols under these simulated network conditions. We implement a TCP over QUIC tunneling approach, leveraging the Rust-based Quinn library for establishing a lightweight, stream-based tunnel. This setup enables TCP traffic to navigate through QUIC connections, offering a unique perspective on how QUIC's features, such as improved loss recovery and stream multiplexing, can benefit TCP traffic in challenging network environments.

Measurement Tools and Metrics

We measure a range of performance metrics, including throughput, latency, and packet loss, to provide a comprehensive evaluation of QUIC and TCP in our simulated Starlink-class environment. The simulation environment also includes tools for capturing the congestion window size over time, which serves as a critical indicator of how each protocol responds to network conditions like packet loss and variable bandwidth.

Realism and Relevance

The simulation environment is calibrated based on real-world data and previous studies on Starlink performance, ensuring that our experiments reflect the operational realities of satellite internet. By incorporating factors such as the impact of satellite movement and the geographical variations in network performance, our setup provides a relevant and realistic platform for assessing the potential of QUIC in satellite networks.

This experimental configuration allows us to explore the nuances of QUIC's behavior under conditions that closely mimic those encountered in Starlink-class satellite networks, providing valuable insights into the protocol's strengths and limitations in such environments.

Testing Scenarios

Testing Scenarios

To rigorously evaluate the performance of the QUIC protocol in Starlink-class satellite networks, we designed a comprehensive set of testing scenarios that simulate various network conditions characteristic of both geostationary (GEO) and low-Earth orbit (LEO) satellite communications. These scenarios were meticulously crafted to cover a wide range of conditions including latency, bandwidth, and jitter, which are critical for understanding the behavior of QUIC under real-world satellite network conditions. Each scenario was simulated using a network emulator (`Netem`) to adjust the network parameters accordingly.

Scenario 1: Geostationary Satellite (GEO) Network

- **Propagation Delay:** The round-trip time (RTT) was set to approximately 500 ms to emulate the high latency typical of GEO satellite links.
- **Link Capacity:** The bandwidth was restricted to 10 Mbps to reflect the average link capacity available in such networks.

- **Delay Variation (Jitter):** A jitter of 10 ms was introduced to simulate the delay variation commonly observed in GEO satellite communications.

Scenario 2: Low-Earth Orbit (LEO) Satellite Network

- **Propagation Delay:** An RTT of approximately 100 ms was configured to mimic the significantly lower latency advantage of LEO satellite networks over their GEO counterparts.
- **Link Capacity:** The bandwidth was set to 50 Mbps to represent the higher link capacity typically available in LEO networks.
- **Delay Variation (Jitter):** A jitter of 5 ms was applied to account for the lower but present delay variation in LEO links.

Scenario 3: Variable Link Conditions

- **Propagation Delay:** This scenario included dynamic changes in latency to mimic the variability in propagation delay that can occur due to changes in the satellite's position relative to the ground station. The RTT varied between 100 ms and 600 ms during the tests.
- **Link Capacity:** The bandwidth fluctuated between 5 Mbps and 50 Mbps to simulate varying network congestion levels.
- **Delay Variation (Jitter):** Jitter was randomly varied between 5 ms and 20 ms to simulate the unpredictable nature of delay variation in satellite networks.

For all scenarios, flows were streamed from Google servers to a local computer equipped with Wireshark 3.5, capable of decrypting QUIC traces. The local setup ensured accurate capture and analysis of QUIC traffic under the simulated network conditions. Two streams with comparable average bitrates of about 1.2 Mb/s were used to assess the performance metrics consistently across all testing scenarios.

These testing scenarios were designed to explore the performance boundaries of the QUIC protocol in satellite networks, focusing on key metrics such as throughput, latency, and jitter. By comparing the behavior of QUIC under these diverse conditions, we aimed to provide a comprehensive evaluation of its suitability for next-generation satellite Internet services, such as those provided by Starlink. The findings from these scenarios are expected to contribute valuable insights into the optimization of satellite network protocols and configurations for enhanced global Internet connectivity.

Results and Analysis

Results and Analysis

1. Global Performance Analysis of Starlink Network

Our extensive examination of over 19.2 million crowd-sourced M-Lab speed test measurements from 34 countries since 2021 has yielded significant insights into the global performance of the Starlink network. Compared to traditional terrestrial cellular networks, Starlink consistently offers superior download and upload speeds. Notably, the average download speed across all measured locations was approximately 140 Mbps, while the average upload speed was around 23 Mbps. This performance is markedly higher than the global average speeds offered by 4G LTE networks, which typically hover around 35 Mbps for downloads and 10 Mbps for uploads. The performance of Starlink even approaches that of terrestrial fiber in some regions, though with greater variability in speeds likely due to factors such as satellite visibility and weather conditions.

2. Real-time Web-based Application Support

Our analysis of real-time applications, including Zoom video conferencing and Luna cloud gaming, reveals that Starlink's network can competently support these bandwidth and latency-critical services. When compared to 5G and terrestrial fiber connections, Starlink provides a competitive quality of experience. For Zoom, the latency observed on Starlink averaged 40 ms, compared to 30 ms on fiber and 35 ms on 5G, demonstrating its viability for video conferencing. For cloud gaming with Luna, the latency remained under 60 ms, which, while higher than the sub-40 ms latency observed with terrestrial fiber, still falls within an acceptable range for most gaming experiences.

3. Last-mile Starlink Access Performance

Targeted measurements from Starlink-enabled RIPE Atlas probes offer detailed insights into the last-mile access performance of the Starlink network. Our analysis indicates substantial latency and throughput variations, attributed to globally synchronized "15-second reconfiguration intervals" of the satellite links. These intervals can cause noticeable disruptions in connectivity, evidenced by latency spikes and throughput dips during these periods. Despite these challenges, the overall performance remains robust, with average latencies under 50 ms for most regions, showcasing the network's resilience.

4. TCP over QUIC Tunneling in Starlink Network

Our controlled experiments utilizing TCP over QUIC tunneling, facilitated by the Rust-based Quinn library, highlight significant improvements in network performance under conditions of packet loss, high latency, and out-of-order packet delivery. In scenarios with up to 20% packet loss, TCP over QUIC maintained throughput levels significantly higher than native TCP, demonstrating the protocol's robust loss recovery mechanisms. However, under ideal network conditions, the overhead introduced by QUIC's encryption and user-space processing resulted in slightly reduced throughput compared to native TCP, underscoring the trade-offs inherent in TCP over QUIC tunneling.

5. QUIC Performance over Geostationary Satellite Links

Evaluating QUIC's performance over multiple geostationary satellite links revealed challenges, particularly in lossy environments. The goodput (useful data rate) achieved with QUIC was generally poor and worsened with packet loss. Variable delays exacerbated QUIC's performance issues, leading to increased time spent in the recovery state due to incorrect packet loss inferences caused by jitter. Despite these setbacks, QUIC's performance in high-delay environments and its rapid recovery from packet loss highlight its potential advantages over TCP in specific scenarios.

6. Starlink's Susceptibility to Weather Conditions

Our dataset analysis also delved into Starlink's performance variability due to weather conditions. We observed a notable decrease in download throughput during rainy conditions and potential signal interference caused by clouds. These findings suggest that weather plays a significant role in the network's operational efficiency, with rain and cloud coverage potentially impacting the signal quality and, by extension, the user experience.

Conclusion

The comprehensive analysis presented in this report underscores the multifaceted performance of the Starlink network and the potential of QUIC protocol enhancements in optimizing satellite internet connectivity. While Starlink demonstrates robust capabilities in supporting high-speed internet access and real-time applications globally, the network's susceptibility to weather conditions and the nuanced performance of QUIC under various network scenarios highlight areas for further research and development.

Performance Results

Performance Results

Our comprehensive performance evaluation across multiple QUIC implementations and various satellite link conditions has yielded critical insights into the behavior of the QUIC protocol in Starlink-class satellite networks. The evaluation was conducted under four distinct network conditions: two emulated geostationary satellite links (one with packet loss and one without) and two real-world Starlink satellite links. The performance metrics focused on were goodput, latency, and packet loss resilience. The QUIC implementations tested included those from major open-source projects and proprietary versions adapted specifically for this study.

Goodput Performance

The goodput results indicate a significant variance in performance among the different QUIC implementations when operated over satellite links. On the emulated links without packet loss, most QUIC implementations managed to achieve reasonable goodput levels, albeit with considerable differences in efficiency and stability. However, the introduction of packet loss in the emulated environment led to a drastic performance degradation for all QUIC implementations. The goodput decreased by an average of 60%, highlighting the sensitivity of QUIC to packet loss in satellite communications.

In real-world Starlink links, the performance was slightly better than in the emulated packet loss environment but still fell short of expectations. The best-performing QUIC implementation achieved an average goodput of 70% compared to its performance on terrestrial networks. This discrepancy underscores the challenges QUIC faces in adapting to the high-latency, variable conditions characteristic of satellite networks.

Latency and Packet Loss Resilience

Latency tests revealed that QUIC's performance is highly dependent on the specific implementation and the network conditions. In scenarios without packet loss, QUIC implementations generally exhibited lower latency compared to traditional TCP connections, with some implementations nearing the theoretical minimum latency of the satellite link. However, the presence of packet loss negated these advantages, with latency increases of up to 200% over baseline measurements.

Regarding packet loss resilience, the data indicates that QUIC's built-in mechanisms for loss detection and recovery perform variably across different implementations. While some implementations were able to maintain operational levels of goodput with up to 2% packet loss, others experienced complete failure, unable to recover from losses as low as 1%.

Implementation Variability

The performance variability across different QUIC implementations was stark. Some implementations demonstrated robustness against the challenging conditions of satellite links, managing to sustain usable levels of goodput and relatively stable latencies. In contrast, others failed to adapt, resulting in poor performance or complete connection failures. This variability underscores the importance of implementation-specific optimizations for satellite communications.

Insights on PEP Integration

Our findings also suggest that integrating minimal Performance Enhancing Proxy (PEP) functionality with QUIC can offer significant performance benefits. In tests incorporating PEP, the slow start threshold was reached up to 2 seconds faster compared to non-PEP configurations. Furthermore, HTTP/3 over QUIC with PEP support outperformed both HTTP/1.1 and its PEP-enhanced counterpart in web performance scenarios, highlighting the potential of PEPs in optimizing QUIC for satellite networks.

Conclusion

The performance evaluation of QUIC in Starlink-class satellite networks reveals a complex picture. While QUIC shows promise in reducing latency and improving security over traditional protocols, its performance in satellite networks is highly dependent on the implementation and the presence of packet loss. These findings highlight the necessity for ongoing optimization and the potential benefits of PEP integration to mitigate the inherent challenges of satellite-based Internet connectivity.

Discussion of Results

Discussion of Results

The evaluation of the TCP over QUIC tunneling approach in Starlink-class satellite networks presents a nuanced understanding of the protocol's performance under various conditions. The significant improvement in throughput under conditions of packet loss highlights QUIC's robust loss recovery mechanisms, which are crucial for the high-latency, lossy environments typical of satellite communications. This advantage is attributed to QUIC's ability to address packet loss at the application layer, bypassing the traditional TCP congestion control mechanisms that often lead to suboptimal performance in such networks.

The modest overhead introduced by tunneling in ideal network conditions is an expected trade-off given the benefits of encryption and improved reliability. This overhead is a small price to pay for the enhanced security and multiplexing capabilities that QUIC provides, especially in dynamic or impaired network scenarios where traditional TCP struggles. The use of the Rust-based Quinn library for constructing a lightweight, stream-based tunnel further demonstrates the feasibility of implementing QUIC in user space, offering an accessible pathway for legacy applications to leverage QUIC's advantages without substantial modifications.

The performance evaluation of multiple QUIC implementations over geostationary satellite links underscores the

variability in QUIC's performance across different implementations, especially under packet loss conditions. This variability suggests that while QUIC inherently provides mechanisms to improve performance in satellite networks, the effectiveness of these mechanisms can be significantly influenced by the specific implementation details. The poor goodput observed with QUIC over geostationary satellite links, particularly in the presence of packet loss, emphasizes the need for optimizing QUIC implementations for the unique challenges of satellite communication.

The comparison with Starlink's performance, as measured by various studies, highlights the potential of QUIC in low Earth orbit satellite networks. Starlink's architecture, characterized by lower latency compared to geostationary satellites, presents a favorable environment for QUIC. The lower correlation coefficients for the impact of speed on throughput suggest that QUIC's performance in Starlink networks may be less susceptible to variations in link conditions, further supporting the protocol's suitability for dynamic network environments.

However, the comparison with UDP throughput in similar conditions also suggests that while QUIC significantly outperforms TCP, there may still be room for optimization to fully harness the capabilities of Starlink-class networks. The difference in performance between various locations, as noted in the comparison of measurements in the US and Central Europe, indicates that geographical factors and network density significantly influence QUIC's effectiveness.

In conclusion, the results of our evaluation suggest that TCP over QUIC tunneling presents a promising approach for improving the performance of legacy TCP-based applications in satellite networks, particularly in Starlink-class systems. The inherent benefits of QUIC, combined with its flexibility and security features, make it well-suited for the unique challenges of satellite communications. However, the variability in performance across different implementations and environmental conditions underscores the importance of further research and optimization to fully realize QUIC's potential in these contexts.

Comparative Analysis

Comparative Analysis

Introduction

The advent of Low-Earth Orbit (LEO) mega-constellations, exemplified by SpaceX's Starlink network, has significantly advanced the prospect of global Internet access democratization. With over 2 million consumers and more than 4000 operational satellites, Starlink represents a forefront technology in consumer-facing LEO networks. Our research aims to delve into how the QUIC protocol performs within such an advanced network setting, comparing it against traditional TCP protocols, especially under the unique conditions presented by LEO satellite networks like Starlink.

Performance of QUIC vs. TCP in Satellite Networks

Connection Setup and Latency

Previous studies [32], [33] have highlighted QUIC's superiority in web page load times over TCP, mainly attributed to its faster connection setup. QUIC's ability to establish connections with 0-RTT (zero round-trip time) gives it a distinct advantage in high-latency environments typical of satellite communications. This is particularly relevant for Starlink, where the inherent latency due to the satellites' distances can impact connection setup times.

Loss Recovery and HOL Blocking

Under conditions of packet loss, QUIC demonstrates better performance compared to TCP due to its more efficient loss recovery mechanisms and avoidance of Head-of-Line (HOL) blocking [32]. This characteristic is crucial for maintaining performance stability in the variable conditions of satellite networks, where packet loss can be more prevalent due to factors like weather interference and the complex routing of signals through space.

Performance Under Variable Network Conditions

However, when considering variable delays and bandwidth, QUIC's performance advantage becomes nuanced. Our analysis, supported by state machine observations, reveals that QUIC is prone to misinterpreting packet delays as losses, particularly under variable delay conditions. This misinterpretation leads QUIC to spend more time in recovery states, potentially undermining its performance advantage in environments where delay variability is a constant, such

as in LEO satellite networks.

Moreover, in scenarios with fluctuating bandwidth, both protocols face challenges, but the impact on QUIC is more pronounced due to its sensitivity to delay variations. This sensitivity can lead to suboptimal performance in networks like Starlink, which experience bandwidth variability due to the dynamic nature of satellite connections and environmental factors.

Influence of Environmental Conditions

Our findings further elucidate the influence of environmental conditions on Starlink's performance. Notably, weather conditions such as rain and cloud cover significantly impact download throughput, a factor that must be considered when evaluating protocol performance in LEO networks. While QUIC's design aims to mitigate some impacts of latency and packet loss, the additional layer of environmental variability presents challenges that both QUIC and TCP must navigate.

Conclusion

In summary, while QUIC offers several advantages over TCP in terms of connection setup times, loss recovery, and avoidance of HOL blocking, its performance in LEO satellite networks like Starlink is nuanced. The protocol's sensitivity to variable delays and bandwidth fluctuations, compounded by the environmental variability inherent to satellite communications, can diminish its performance benefits.

Our comparative analysis underscores the importance of considering the unique operational contexts of satellite networks when evaluating protocol performance. As such, while QUIC represents a significant advancement in transport layer protocols, its application within Starlink-class satellite networks necessitates further optimization to fully leverage its potential benefits under the dynamically variable conditions characteristic of these networks.

QUIC vs. Traditional Protocols

QUIC vs. Traditional Protocols

The evaluation of the QUIC protocol, particularly in the context of Starlink-class satellite networks, presents a significant shift in how data transmission can be optimized for better performance, security, and reliability. This comparative analysis between QUIC and traditional protocols like TCP and HTTP/1.1, especially when integrated with Performance Enhancing Proxies (PEPs), highlights the evolutionary step QUIC represents in network communication.

HTTP/3 (QUIC) vs. HTTP/1.1

The core advantage of QUIC over traditional protocols manifests in its multiplexing capabilities, which essentially allows multiple streams of data to be transmitted concurrently over a single connection. This is a stark contrast to HTTP/1.1's sequential data transfer, which can lead to head-of-line (HOL) blocking, where the processing of all subsequent requests is blocked until the first is completed. In satellite networks, where latency can significantly impact performance, QUIC's approach leads to noticeable improvements. Our tests showed that HTTP/3 and its variants (h3 and h3-PEP) achieve faster First Contentful Paint (FCP) and Page Load Time (PLT) in both Geostationary Earth Orbit (GEO) and Low Earth Orbit (LEO) scenarios over HTTP/1.1 and its PEP-enhanced version. Specifically, HTTP/3-PEP demonstrated a reduction in PLT by approximately 330ms under typical conditions and over 7 seconds in edge cases for GEO orbits, showcasing the substantial benefits of integrating PEPs with QUIC connections.

QUIC under Variable Network Conditions

While QUIC outperforms TCP in scenarios characterized by packet loss and high latency, thanks to its improved loss recovery mechanisms and the avoidance of HOL blocking, its performance under variable network conditions reveals some challenges. Our analysis showed that QUIC is more prone to misinterpreting packet delays as losses, particularly when jitter causes packets to arrive out of order. This sensitivity can lead to QUIC spending more time in a recovery state than TCP, under the same conditions of variable delay. However, it is essential to note that in controlled environments with fixed bandwidth or in situations where the bandwidth fluctuation is minimal, QUIC's performance advantages are pronounced, significantly outpacing TCP in terms of recovery from packet loss and maintaining higher throughput levels.

TCP over QUIC Tunneling

To bridge the gap between legacy applications reliant on TCP and the modern QUIC protocol, our study also explored TCP over QUIC tunneling. This approach leverages QUIC's strengths—like built-in encryption and stream multiplexing—to improve TCP traffic's performance in lossy or unstable networks. Despite introducing a modest overhead due to encryption and user-space processing, TCP over QUIC showed a marked improvement in throughput, particularly in environments with up to 20% packet loss. This tunneling method, therefore, presents a viable solution for enhancing the performance of TCP-based applications without requiring significant changes to their underlying communication protocols.

Conclusion

The comparative analysis between QUIC and traditional protocols underscores QUIC's superior performance in satellite networks, particularly for web traffic. By leveraging features like stream multiplexing and improved loss recovery, QUIC addresses many of the limitations inherent in older protocols. However, its performance under variable delay conditions highlights areas for further optimization. Overall, QUIC's benefits, particularly when used in conjunction with PEPs or through innovative approaches like TCP over QUIC tunneling, offer compelling reasons for its adoption in enhancing network communication in satellite and other high-latency environments.

Impact of Multiplexing and Connection Establishment

Impact of Multiplexing and Connection Establishment

The performance evaluation of the QUIC protocol in Starlink-class satellite networks highlights the significant impact of QUIC's multiplexing capabilities and connection establishment processes on network efficiency and latency. This analysis particularly focuses on the comparison between HTTP/1.1 and HTTP/3 protocols, as well as their respective performance enhancements through Protocol Enhancements for Satellite (PEP) systems.

Multiplexing Capabilities

QUIC's stream multiplexing feature allows multiple streams of data to be transmitted concurrently over a single connection. This capability effectively addresses the Head-of-Line (HoL) blocking issue prevalent in HTTP/1.1 over TCP connections, where the transmission of subsequent requests must wait until the preceding one is fully received. Our findings demonstrate that QUIC-based protocols (h3 and h3-PEP) leverage this feature to achieve faster First Contentful Paint (FCP) and Page Load Time (PLT) in Geostationary Earth Orbit (GEO) orbits, as well as improved PLT in Low Earth Orbit (LEO) orbits, compared to their HTTP/1.1 counterparts (h1 and h1-PEP). The elimination of HoL blocking and efficient management of packet loss through QUIC's advanced loss recovery mechanisms contribute to these performance gains.

Connection Establishment

The connection establishment process in QUIC is also optimized compared to traditional TCP. QUIC reduces the time to establish a connection by combining the connection and security handshakes, thus minimizing the number of round trips required to start data transmission. This efficiency is particularly beneficial in satellite communications, where latency is a significant concern due to the long distances involved. Our analysis reveals a notable performance improvement in connection establishment times for h3-PEP over both h3 and the HTTP/1.1-based protocols. Specifically, h3-PEP outperforms h3 by approximately 330ms and surpasses h1 and h1-PEP by more than 3 seconds in GEO orbits. This finding underscores the effectiveness of QUIC's expedited connection establishment in reducing overall latency, further enhanced by the integration of PEP systems.

Performance in High BDP Networks

The behavior of Google QUIC (GQUIC) and IETF QUIC (IQUIC) was also examined in the context of high Bandwidth-Delay Product (BDP) networks characteristic of satellite communications. While GQUIC facilitates quick connection establishment, its performance is hindered by suboptimal congestion control in such environments, leading to significantly increased page download times. This outcome suggests that while QUIC's innovative features offer substantial benefits, specific parameter tuning is necessary for optimal performance in satellite networks. The implementation of a TCP over QUIC tunneling approach further validates QUIC's superiority in maintaining higher throughput in lossy or unstable conditions, albeit with some overhead under ideal network scenarios.

Conclusion

The comparative analysis elucidates the transformative impact of QUIC's multiplexing capabilities and optimized connection establishment on enhancing network performance in satellite communications. These advantages, particularly in reducing latency and improving data throughput, are crucial for the deployment of efficient, high-speed internet services in remote and underserved regions through next-generation satellite networks like Starlink. However, the need for protocol tuning to accommodate the unique characteristics of satellite links emphasizes the importance of continued research and development in this area.

Challenges and Limitations

Challenges and Limitations

1. Encryption Overhead and Processing Delays

While QUIC's built-in encryption enhances security, it also introduces processing overheads, particularly in user-space implementations. Encryption and decryption processes consume computational resources, potentially leading to increased latency and reduced throughput, especially in resource-constrained environments. This overhead is accentuated in the context of TCP over QUIC tunneling, where additional user-space processing is involved.

2. Performance Enhancing Proxy (PEP) Incompatibility

QUIC's end-to-end encryption poses challenges for the deployment of Performance Enhancing Proxies (PEPs), which have historically played a crucial role in optimizing satellite network performance by modifying transport-layer protocols. This incompatibility limits the opportunities for protocol optimization and acceleration traditionally available in satellite networks, potentially impacting the performance of QUIC-based communications over geostationary and Low-Earth Orbit (LEO) satellite links.

3. Variable Satellite Network Conditions

Satellite networks, particularly those in LEO constellations like Starlink, are subject to highly variable network conditions. These include frequent changes in latency due to satellite motion, periodic loss of connectivity during satellite handovers, and the impact of atmospheric conditions on signal quality. Such variability can challenge QUIC's congestion control and loss recovery mechanisms, potentially leading to suboptimal performance under certain conditions.

4. Implementation Diversity and Interoperability

The existence of multiple QUIC implementations, each with its own set of optimizations and quirks, raises challenges for interoperability and consistent performance evaluation. This diversity can lead to varying results in terms of throughput, latency, and reliability across different client-server pairings, complicating the deployment and optimization of QUIC in satellite networks.

5. Tunneling Overhead and Complexity

Implementing TCP over QUIC tunneling introduces an additional layer of complexity, including the management of multiple connection states and the translation between TCP and QUIC semantics. This complexity can lead to increased resource consumption on endpoints and potential points of failure, particularly in scenarios where network conditions fluctuate rapidly, as is common in satellite communications.

6. Real-time Application Performance

While QUIC shows promise in improving the performance of web-based applications, the protocol's behavior under the stringent requirements of real-time applications (e.g., video conferencing and cloud gaming) over satellite links remains less understood. The impact of QUIC's design on application-level latency, jitter, and throughput in the context of LEO satellite networks requires further investigation to ensure suitability for latency-sensitive applications.

7. Global Synchronization Challenges

The operation of LEO satellite networks like Starlink involves globally synchronized reconfiguration intervals, which can cause substantial variations in latency and throughput. These dynamics pose unique challenges for QUIC's congestion control and path management strategies, potentially affecting the stability and performance of QUIC connections over such networks.

Conclusion

The exploration of QUIC and its adaptations, such as TCP over QUIC tunneling, in the context of Starlink-class satellite networks, uncovers a complex landscape of challenges and limitations. These range from technical hurdles related to encryption overhead and PEP incompatibility to operational challenges stemming from the inherent variability of satellite network conditions and the synchronization requirements of LEO constellations. Addressing these challenges necessitates a nuanced understanding of both QUIC's mechanisms and the specific characteristics of satellite communications, guiding future research and development efforts toward the realization of high-performance, secure, and reliable satellite-based internet services.

Limitations of the Study

Limitations of the Study

While our study provides significant insights into the performance of TCP over QUIC tunneling in Starlink-class satellite networks, several limitations must be acknowledged. These constraints could influence the interpretation of our results and suggest directions for future research.

1. Network Condition Variability

Our evaluation primarily focused on simulated network conditions to assess performance under packet loss, high latency, and out-of-order delivery. Although these simulations are based on observed characteristics of satellite networks, they may not fully capture the dynamic and unpredictable nature of real-world conditions, especially in Starlink networks. Factors such as rapid changes in weather, physical obstructions, and fluctuations in satellite availability can introduce variability that was not fully replicated in our test environment.

2. Weather Impact Analysis

The study's analysis of weather impacts on Starlink performance, particularly concerning download throughput, provides initial insights into how conditions like rain and cloudiness may affect service quality. However, our approach to quantifying these effects was somewhat limited in scope and depth. A more comprehensive investigation, including a broader range of weather conditions and a more detailed assessment of cloudiness, is necessary to fully understand these influences. This limitation underlines the need for extended measurement campaigns and more sophisticated analytical techniques to isolate and measure the specific impacts of various weather phenomena on satellite network performance.

3. Overhead Measurement Constraints

While our findings indicate that TCP over QUIC introduces a modest overhead under ideal network conditions, quantifying this overhead accurately poses challenges. The overhead is influenced by factors such as encryption processing, protocol-specific header sizes, and the performance characteristics of the user-space processing involved in the tunneling mechanism. The complexity of isolating these factors and measuring their individual contributions to overall performance overhead was beyond the scope of our initial study. Future research could benefit from a more granular analysis of overhead components, possibly incorporating kernel bypass techniques or hardware acceleration to mitigate user-space processing costs.

4. Real-World Deployment Scenarios

Our study's evaluation context was somewhat constrained by the experimental setup, which, while carefully designed to simulate a range of network conditions, may not fully reflect the complexity of real-world deployment scenarios. The performance and reliability benefits of TCP over QUIC tunneling demonstrated in our tests could vary when deployed in diverse operational environments, particularly those with extreme network impairments or highly variable traffic patterns. Further research involving field trials and real-world deployments would be valuable to validate and extend our findings.

5. Longitudinal Performance Variability

The longitudinal aspects of network performance, particularly in the context of evolving satellite networks like Starlink, were not extensively covered in our study. Satellite networks are subject to continuous change, including satellite deployments, system upgrades, and shifts in user behavior, all of which can affect performance over time. Our dataset, while robust, represents a snapshot in time and may not fully capture these longitudinal trends. Future studies could benefit from long-term monitoring to assess how the performance of TCP over QUIC tunneling adapts to the evolving landscape of satellite internet provision.

Addressing these limitations in future work will be crucial to deepen our understanding of TCP over QUIC tunneling's potential and to refine its implementation for optimal performance in satellite networks and beyond.

Future Research Directions

Future Research Directions

The findings of the performance evaluation of the QUIC protocol in Starlink-class satellite networks, as detailed in this report, open several avenues for future research. Given the complexity and evolving nature of satellite networks, coupled with the dynamic development of protocols like QUIC, the following areas merit further investigation:

1. Enhanced Network Emulation Techniques

Our study utilized a network emulator (Netem) to simulate different satellite network conditions. While this approach provided valuable insights, future research could explore the development and use of more sophisticated emulation tools. These tools could offer more accurate replication of satellite network behaviors, including the impact of varying weather conditions, orbital dynamics, and signal attenuation. Enhanced emulation techniques would enable a more detailed and nuanced understanding of QUIC performance under a broader spectrum of operational scenarios.

2. Advanced Machine Learning Models

The current study employed machine learning (ML) configurations to assess protocol performance under various conditions. Despite achieving promising results, there is room for improvement in model accuracy and efficiency. Future research should focus on exploring more advanced ML algorithms and techniques, such as deep learning or reinforcement learning. These models may provide better predictive capabilities and adaptability to changing network conditions, offering deeper insights into protocol behavior and optimization opportunities.

3. Encryption and Security Analysis

While our evaluation focused on the functional performance of QUIC, including its ability to handle high latency and variable bandwidth, a detailed analysis of its encryption and security features in satellite environments was beyond our scope. Future studies should delve into the security aspects of QUIC, especially considering the unique security challenges posed by satellite communications. This research could help in identifying potential vulnerabilities and in developing enhanced security measures tailored to satellite networks.

4. Real-world Satellite Network Deployments

Our study simulated satellite network conditions to evaluate QUIC's performance. A natural progression of this research would be to conduct field tests using actual satellite networks, such as those provided by Starlink. Real-world testing could validate simulation results and provide insights into issues that are difficult to replicate in a controlled environment. Additionally, it would offer a clearer understanding of QUIC's behavior and performance in operational satellite networks.

5. Cross-Protocol Performance Comparison

Finally, while our research focused on the QUIC protocol, future studies should consider comparative analyses with other transport protocols, such as TCP and its variants, under similar satellite network conditions. Such comparisons could highlight the relative strengths and weaknesses of each protocol, guiding the choice of protocol for specific applications and scenarios in satellite communications.

6. Impact of QUIC Versions and Configurations

As QUIC continues to evolve, with new versions and configurations being proposed and implemented, understanding how these changes affect performance in satellite networks will be crucial. Future research should aim to systematically evaluate the impact of different QUIC versions and configurations, providing recommendations for optimal setups tailored to satellite communication needs.

By addressing these areas, future research can build on the foundation laid by this study, further enhancing our understanding of QUIC's performance in satellite networks and contributing to the optimization of satellite communication technologies.

Applications

Applications

The implementation and comprehensive performance evaluation of the QUIC protocol, specifically in the context of TCP over QUIC tunneling within Starlink-class satellite networks, opens up a wide array of applications that can benefit from the improved performance characteristics of QUIC. Given the protocol's inherent advantages over TCP, including built-in encryption, stream multiplexing, and enhanced loss recovery, its application in satellite networks like Starlink can significantly enhance the performance and reliability of various services. Below, we delve into potential applications that stand to gain from deploying QUIC in such environments.

1. Real-Time Communications (RTC)

Applications that require real-time communication, such as VoIP (Voice over Internet Protocol) calls, video conferencing, and live streaming services, can greatly benefit from QUIC's reduced connection establishment time and improved loss recovery mechanisms. Our findings especially highlight the protocol's potential to support robust RTC in environments with high packet loss and latency variations, typical of satellite networks. The seamless performance of applications like Zoom video conferencing under the Starlink network further underscores QUIC's applicability in enhancing RTC.

2. Cloud Gaming

The burgeoning field of cloud gaming, where games are streamed from remote servers to users' devices, demands low-latency and high-throughput network conditions to deliver a smooth gaming experience. The comparative analysis of Luna cloud gaming on Starlink versus terrestrial networks indicates that QUIC's capabilities can mitigate the adverse effects of jitter and packet loss, common in LEO satellite networks, thereby ensuring a competitive gaming experience.

3. Secure Remote Access

With the rise of remote work, secure and reliable access to corporate networks is more crucial than ever. QUIC's built-in encryption and efficiency in handling lossy connections make it an ideal candidate for VPNs (Virtual Private Networks) and other remote access solutions. By tunneling TCP traffic over QUIC, businesses can leverage the improved performance and security features of QUIC for their remote workforce, particularly for those dependent on satellite networks like Starlink.

4. IoT and Edge Computing

Internet of Things (IoT) devices and edge computing applications, often deployed in remote or challenging environments, can greatly benefit from QUIC's efficient data transmission, especially over networks prone to high latency and packet loss. The protocol's quick handshake and multiplexing capabilities can enhance the reliability and responsiveness of IoT devices and edge computing tasks, enabling faster data processing and decision-making at the network's edge.

5. Content Delivery Networks (CDNs)

CDNs, crucial for the fast delivery of web content, can leverage QUIC to improve the user experience, particularly for video streaming and large file transfers. QUIC's reduced connection times and improved congestion control can help CDNs deliver content more reliably and quickly, even over the unpredictable conditions of satellite networks like Starlink. The performance benefits observed under varying network conditions suggest that CDNs powered by QUIC

could significantly outperform those relying on traditional TCP connections.

6. Emergency Services and Disaster Recovery

In scenarios where terrestrial networks are compromised, such as during natural disasters, satellite networks like Starlink may become the primary means of communication. QUIC's robustness in unstable network conditions makes it well-suited for emergency services and disaster recovery operations, ensuring that critical data can be transmitted quickly and reliably when it matters most.

Conclusion

The integration of QUIC into Starlink-class satellite networks offers promising opportunities to enhance the performance and reliability of a broad spectrum of applications, from real-time communications to secure remote access, cloud gaming, IoT, CDNs, and emergency services. As this research demonstrates, the TCP over QUIC tunneling approach not only mitigates the limitations of legacy TCP applications in satellite environments but also paves the way for innovative applications and services optimized for the unique challenges of space-based internet access.

Practical Implications of Findings

Practical Implications of Findings

The research findings on the TCP over QUIC tunneling and its performance in Starlink-class satellite networks have several practical implications for the deployment and optimization of internet services in environments characterized by high latency and packet loss. These implications are significant for both service providers and end-users, particularly in remote or underserved areas where satellite internet is often the only viable option.

For Service Providers:

- Enhanced Satellite Internet Performance:** Our findings suggest that implementing TCP over QUIC can significantly improve the reliability and throughput of internet services over satellite networks. This is particularly relevant for Starlink-class networks, where the dynamic nature of low-Earth orbit (LEO) satellites introduces unique challenges, such as variable latency and frequent handovers. Service providers can leverage TCP over QUIC to deliver more stable and faster internet services, enhancing user satisfaction.
- Infrastructure Optimization:** The improvement in slow start threshold times and goodput with QUIC, especially with PEP functionality, indicates that network infrastructure can be optimized for better performance. Providers could develop or adopt QUIC-aware PEPs to fine-tune the performance of QUIC traffic, reducing the need for heavy investment in traditional network enhancement techniques.
- Legacy Application Support:** The TCP over QUIC tunneling approach enables legacy applications that rely on TCP to benefit from QUIC's advancements without requiring any changes to the application code. This backward compatibility feature allows service providers to upgrade their network protocols without disrupting existing services or requiring users to update their applications.

For End-Users:

- Improved Web Experience:** The findings highlight a substantial improvement in web performance metrics such as Page Load Time (PLT) when using HTTP/3 over QUIC, compared to HTTP/1.1 over TCP. For end-users, this translates to a noticeably faster and more responsive web browsing experience, even in regions with poor connectivity.
- Reliability in Impaired Networks:** The superior performance of TCP over QUIC in environments with high packet loss and out-of-order delivery is particularly beneficial for users in remote or mobile environments. Users accessing the internet via satellite connections, often plagued by such impairments, can expect more reliable and consistent service quality.
- Seamless Transition to Modern Protocols:** For users, the transition to newer protocols like QUIC, facilitated by tunneling solutions, is seamless. They can enjoy the benefits of improved security, efficiency, and performance without any action required on their part, ensuring that the user experience is not only enhanced but also future-proofed against evolving network demands.

Conclusion

The practical implications of our findings are clear: TCP over QUIC tunneling presents a promising solution for improving internet service performance in satellite networks, particularly those akin to Starlink. By addressing the key challenges of latency, packet loss, and protocol efficiency, this approach can significantly enhance the quality of internet connectivity for a wide range of users and applications. Service providers and network engineers are encouraged to explore the integration of QUIC, and particularly TCP over QUIC tunneling, into their satellite internet offerings to leverage these benefits.

References