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LEO transport problem statement
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Abstract

LSN, Starlink and OneWeb, can provide global Internet connectivity with latency comparable to terrestrial networks, but their fast movement and frequent handovers result in highly dynamic connectivity changes. The fast movement of LSN will introduce frequent handover and varying link delays every few minutes. As the path over LSN varies, TCP cannot tell whether changes in packet loss or RTT are due to path changes or network congestion, thus it might not be able to make proper adjustment. This greatly impact the performance of TCP.

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1. Introduction

LSN, Starlink and OneWeb, can provide global Internet connectivity with latency comparable to terrestrial networks, but their fast movement and frequent handovers result in highly dynamic connectivity changes. The fast movement of LSN will introduce frequent handover and varying link delays every few minutes. As the path over LSN, TCP cannot tell whether changes in packet loss or RTT are due to path changes or network congestion, thus it might not be able to make proper adjustment. This greatly impact the performance of TCP.

[Izhikevich2024] by Netflix analyzed on-demand video streaming over LEO with one million LEO households across 85 countries for over two years. Starlink users experience overall perceptual video quality similar to non-Starlink networks, they are more likely to experience bitrate switches and network rebuffers due to Starlink’s network conditions. About half of sessions with a bitrate switch experience a resolution of less than 1080p. Video rebuffers are significantly more likely to occur over Starlink than a Top 10 ISP, and 40% more likely to occur relative to any non-Starlink network. It also finds that over 95% of Starlink’s throughput is lower than alternative networks, which is nearly always 50% of what a top 10 ISP offers and falls below 20 Mb/s. This eventually leads to bitrate switching and rebuffer, which contributes negatively to overall quality of experience over Starlink.

[Hu2023] investigated the performance of TCP and UDP in the Starlink network. TCP vs. UDP downlink test results consistently reveal that UDP outperforms TCP in satellite networks, with the mean throughput being 128 Mbps and 29 Mbps, respectively. And the root cause is there is a much higher occurrence of packet loss in both the uplink and downlink directions in Starlink network. Based on this finding, they verified that TCP parallelism can optimize bandwidth utilization by distributing data across multiple connections, thereby mitigating the impact of TCP congestion control.

[Li2024] reveals that the endless and bursty packet losses over unstable LEO satellite links impose significant challenges on guaranteeing the quality of experience (QoE) of Web applications. They found that in the Starlink network environment, both page load time and speed index are much higher than those in the wired network. Specifically, the 60th/80th/90th percentile page load time in Starlink are about 245.0%/202.4%/136.3% higher than those in Optimum. Similarly, the 60th/80th/90th percentile speed index in Starlink is about 185.3%/241.6%/219.3% higher.

1.1. Terminology

BBR: Bottleneck Bandwidth and Round-trip propagation time is a loss-tolerant congestion control algorithm designed by Google.

CCA: Congest control algorithms.

GEO: Geosynchronous orbit with the altitude 35786 km.

LEO: Low Earth Orbit with the altitude from 200 km to 2000 km.

MEO: Medium Earth Orbit with the altitude from 2000 km to 35786 km.

ISL: Inter Satellite Link.

GS: Ground Station, which connect to the satellite and provide L2 and/or L3 functionality.

LSN: LEO satellite networks.

RTT: Round Trip Time.

NTN: Non-Terrestrial Network.

1.2. Requirements Language

The key words "MUST", "MUST NOT", "REQUIRED", "SHALL", "SHALL NOT", "SHOULD", "SHOULD NOT", "RECOMMENDED", "NOT RECOMMENDED", "MAY", and "OPTIONAL" in this document are to be interpreted as described in BCP 14 [RFC2119] [RFC8174] when, and only when, they appear in all capitals, as shown here.

2. Problem Statement

LSN differ significantly from terrestrial networks, and some of the design assumptions of TCP no longer hold in satellite environments. The unique characteristics of LSN networks-highly dynamic topologies, long and variable propagation delays, time-varying channel errors pose fundamental challenges to conventional transport layer protocols like TCP. These protocols, designed for terrestrial networks, fail to adapt to the space environment, leading to degraded throughput, increased latency, and unreliable connectivity.

* Bursty Packet Losses: bursty packet losses are a common phenomenon in LEO satellite networks due to various factors such as signal blockage from obstacles, rapid movement of satellites, and interference from other signals. These bursty losses can severely disrupt data transmission, leading to retransmission delays and increased latency. Traditional error correction and recovery mechanisms may not be effective in handling such bursty losses, requiring the development of more robust and adaptive techniques.

* Under-utilized link: TCP’s throughput is only about half the maximum possible over LSN, which is noticeably lower than that of the terrestrial network. The maximum achievable throughput is measured through UDP bursts. TCP throughput test has been done with all five congestion control algorithms: BBR, Cubic, Reno, Veno and Vegas. BBR indeed achieves much higher throughput than the other algorithms.

* Variable round trip times: the dynamic nature of LEO satellite networks results in highly variable Round Trip Times (RTTs). As satellites move rapidly across the sky, the distance between the sender and receiver changes constantly, causing fluctuations in signal propagation delay. Additionally, network load and routing changes can further exacerbate RTT variations. These unpredictable RTTs can lead to inefficient resource utilization and performance degradation in transmission protocols that rely on accurate timing and synchronization.

* Variable link rates: satellite-to-ground link rate is highly impacted by atmospheric absorption, rain attenuation, scattering and diffraction, ionospheric scintillation and multipath effects. The above factors will lead to fluctuations in the signal-to-noise ratio, thereby affecting the modulation mode of the channel, which will ultimately be reflected in the changes in the rate of the satellite-to-ground link. This will create large and variable delay-bandwidth products. This makes it challenging to maintain efficient data flow and congestion control.

* High bit error rates: the wireless communication environment of LEO satellites is prone to high bit error rates (BER) due to factors like signal attenuation, interference, and noise. These errors can corrupt data packets, leading to retransmissions and reduced overall network efficiency. Effective error detection and correction mechanisms are essential to mitigate the impact of high BER in LEO satellite transmission protocols.

* Out-of-order delivery: In the NTN scenario, when a mobile phone directly connects to a LEO (Low Earth Orbit) satellite, user packets are forwarded via the LSN (Link Switching Node). Due to frequent link switching and faults such as sun outages, routing adjustments become inevitable. This causes a single data stream to be forwarded over different paths, leading to packet reordering.

* TCP Fairness: there will be competing connections with different RTTs. The connections with high RTTs cannot allocate enough bandwidth. Traditional TCP protocols may not perform well in such environments due to their inherent assumptions about network conditions. Developing fair and efficient resource allocation mechanisms that consider the unique characteristics of LEO satellite networks is necessary to prevent certain users or applications from dominating network resources.

3. Transport Protocol over LEO Considerations

Various optimizations at the transport protocol level have been proposed, such as end-to-end optimizations like SCPS-TP and M-TCP, redundancy coding like FEC, cross-layer optimizations like ECN, and congestion control algorithm optimizations like TCP Westwood and TCP Eifel, as well as AI-enhanced congestion control. This gives some clues on what problem we should focused on.

3.1. Congestion Control

The rapidly varying satellite link capacity and latency introduced by LSN is unique. Existing CCAs are unable to discriminate whether RTT/ bandwidth variation or packet loss are caused by a congestion event or not. Based on how congest events are awared, CCA can be classified into 4 categories, loss-based, delay-based, model-based or learning-based [I-D.LSNCC]. Since the packet loss has obvious burst loss over some period characteristics, it is possible to learn that by the CCA in order to isolate the congestion event more precisely. Especially in NTN case, the mobile terminal will be directly connected to satellite.

3.2. Multi-session TCP

Since the link is under-utilized with single TCP connection, multiple concurrent connections can be able to utilize a larger fraction of the available capacity on the path. This has been verified by [Izhikevich2024] can improves overall video quality of experience. However, retransmit rates increase by 300% on average.

3.3. Less Retransmission

Since packet loss at the LSN is of the burst type, in the case of Go-Back-N, retransmissions will consume a large amount of bandwidth and increase the overall transmission completion time of the flow. In the NTN scenario, when the satellite-to-ground link switches, the user terminal should stop sending data until the switch is completed to reduce retransmissions. In non-NTN scenarios, without the collaboration of the LSN network, the situation is more complex. One method is to automatically predict future switching time points by learning the regularity of burst packet loss times, thereby reducing the sending rate near the switching time points to minimize retransmissions.

4. IANA Considerations

N/A.

5. Security Considerations

N/A.

6. References

6.1. Normative References

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