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The Use Cases for Optimizing Transport Layer Protocols in LEO and MEO Satellite Networks

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Abstract

This document introduces the use cases for the performance of existing transport protocols in LEO and MEO satellite networks. The use cases identify and demonstrate the current challenges faced by transport layer protocols in these environments.

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1. Introduction

With the rapid advancement of Low Earth Orbit (LEO) and Medium Earth Orbit (MEO) satellite networks, these systems have become increasingly important for providing global connectivity, especially in remote and underserved areas. However, compared to traditional terrestrial networks, LEO and MEO satellite networks face significant challenges due to their unique characteristics, such as frequent handovers, highly variable latencies, and periodic connection drops. These extreme network dynamics pose substantial difficulties for existing transport layer protocols, which are primarily designed for more stable and predictable network environments.

Existing transport protocols, such as TCP, fail to perform optimally in LEO and MEO satellite networks. For example, TCP's congestion control mechanisms, which rely on packet loss as a primary signal for congestion, can misinterpret the packet loss by handovers in satellite networks as a sign of network congestion, leading to unnecessary throughput reductions. Transport layer protocol requirement for LEO satellite was introduced at [I-D.yang-tsvwg-leo-transport-req] .

This document introduces the use cases for the performance of existing transport protocols in LEO and MEO satellite networks. The use cases identify and demonstrate the current challenges faced by transport layer protocols in these environments.

2. Conventions and Definitions

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.

3. Use Cases

3.1. Video Streaming Service over LEO

Netflix, as a major video streaming service, analyzed data over one million Starlink users across 85 countries over two years in [Izhikevich2024] . Starlink dominates the LEO satellite network market as the service provider with near 6,000 satellites and over 2.6 million users. The analysis reveals that while Starlink’ s overall video quality matches traditional terrestrial networks, inherent LEO network variability, including throughput fluctuations and packet loss, causes a 60% rise in bitrate switches and a 200% increase in rebuffering events.

Furthermore, the study highlights that Starlink exhibits lower throughput and higher variance compared to non-LEO terrestrial networks. For instance, Starlink’s throughput is typically about 50% of that offered by top 10 ISPs and falls below 20 Mb/s. Over 90% of bitrate switches occur at throughputs below 20 Mb/s. Additionally, Starlink’s throughput recovery is slower: while non-LEO networks recover to above 10 Mb/s in about 5 seconds, Starlink takes approximately 15 seconds.This delay coincides with Starlink’ s static route reconfiguration intervals between satellites and ground stations.

To investigate the causes of low throughput, Netflix deployed A/B tests on over 1 million users. The study identified that Starlink’s high packet round trip times (RTTs) and increased retransmit rates contribute to low TCP congestion windows, resulting in lower throughput. Nearly two times longer RTTs, double the retransmit rate, and smaller congestion windows compared to other networks were observed to confirm that. The higher latency is attributed by longer routing paths. The increase in Starlink retransmits is likely influenced by random loss on satellite links; the use of Active Queue Management on the Starlink WiFi router which minimizes latency at the expense of packet loss; and potential packet reordering which may lead to duplicate acknowledgments and spurious retransmits. Increases in RTTs and retransmit rates can cause loss-based congestion controllers to take a long time to grow the TCP congestion window. In addition, loss-based congestion controllers assume that any packet loss is due to congestion in the network, and therefore, back off when seeing indications of packet loss. Congestion windows for Netflix sessions over Starlink paths being lower than over other networks. With lower congestion windows, Starlink sessions are more likely to underutilize the true available bandwidth for a single TCP connection, and therefore experience lower throughput.

To achieve higher throughput, Netflix approximated the use of multiple connections with MulTCP and created a modified version of New Reno: it grows the congestion window by three bytes for every acknowledged byte, and when it detects packet loss, it reduces the congestion window as if only one of the three emulated flows had seen a loss event. However, a 30%-40% throughput increase came at the cost of increased retransmit rates by 300% and latency by 77%. Further solution is needed to better handle the dynamic characteristics of LEO networks and improve transmission performance.

3.2. 3GPP UE-SAT-UE Communication for 5G VN Group Service

3GPP is a Standard Development Organization or SDO that develops and maintains technical spec. for mobile networks. It is currently working on the final 5G-A spec. and simultaneously exploring various kinds of domains for the coming 6G evolution.

3GPP has, in different releases, (near-) completed a few satellite-related working lis, including Satellite-access, Satellite-backhaul, Satellite regenerative forwarding mode, etc [TS.23.501]. As of now, for satellite operators who are operating 5G network with satellite access globally, the 3GPP plenary has concluded the requirements of supporting UE-satellite-UE communication for 5G VN group service [_GPP.SP-250400] . The 3GPP UE-Sat-UE service indicates the communication, between UEs under the coverage of one or more NGSO satellites, uses satellite access without the inter-UE traffic transiting thru the ground segment.

As per the 3GPP [TS.23.501] , the 5G VN Group communication service is comprised of two traffic forwarding types, i.e.,

* local-switch type: for which the UL/DL traffic is locally forwarded by a single (on-board satellite) UPF (functioning like a router) if this UPF is the ‘anchor’ for all the participating UEs of the same 5G VN group;

* inter-UPF type: for which the UL/DL traffic for the 5G VN group communication is forwarded between/among ‘anchors’ of different participating UEs.

Here, both the local-switch and the inter-UPF forwarding types involve the impacts & implications as introduced by inter-satellite links or ISLs. Note that, while the 3GPP simplifies the satellite network architecture by assuming the existence of ISL(s) have no or insignificant impacts on the 5G VN group service, we IETF must consider various types of implications associated with the dynamic satellite constellation networks, e.g.,

* High latency: thanks to potential long-distance satellite paths.

* high loss: harsh environment in outer space impairing the transmission quality, e.g., radiation, solar storm, etc.

* Path instability: thanks to extremely dynamic topology of satellite network, leading to frequent ISLs break-up & reconnection between satellites, satellite handover, etc.

* Path switchover & multi-path impacts: related to equipment features and network design, e.g., frequent beam scanning of (phased array) antennas, peering changes between/among neighboring satellites, UE mobility, etc.

Compared to the deployment over terrestrial networks (or TNs), the traditional transport-level congestion control mechanism, e.g., TCP CUBIC, etc., would perform much worse due to the above adversarial factors. The APNIC blog [APNIC-blog] , based on investigational survey, suggests it be possible to adjust the traditional TCP CUBIC by conducting a lost packet repair using Selective Acknowledgement (SACK) [RFC2883] if a packet loss event might occur at the time of a scheduled satellite handover or path switchover. Remember that SACK is a big reason why modern TCP protocols perform well over mobile services. Fortunately, the 3GPP-based UE-Sat-UE 5G VN service does own the capability of knowing in advance satellite scheduled changes. In 5G network [TS.23.501] , the 5GC NF AMF can get the satellite ephemeris information via different schemes and provide the satellite footprints to UEs for the optimization of transport services, i.e., UEs leveraging satellite scheduled events to optimize the communication during satellite handover. At UEs, these add-on information helps the TCP control algorithm distinguish between isolated packet loss and loss-inducing levels of network congestion.

3.3. LEO Satellite Networks vs. Cellular Network

In this use case [Hu2023] , a measurement study was conducted to understand the performance characteristics of Starlink satellite networks and compare them with cellular networks. The study involved a large-scale data collection campaign across five states in the US, covering diverse geographical areas and user populations. The dataset includes experimental results from both Starlink and cellular networks, involving two types of Starlink configurations (Roam and Mobility) and three major cellular carriers (AT&T, T-Mobile, and Verizon). The analysis reveals several key findings:

TCP vs. UDP downlink performance. While cellular networks show minimal TCP/UDP throughput differences, UDP dominates in satellite environments with mean rates of 128 Mbps vs. TCP’s 29 Mbps. This disparity stems from TCP’s reliability mechanisms (e.g., congestion control), which amplify performance degradation under Starlink’s elevated packet loss rates (0.3%-1.3% vs. cellular’s 0.0%-0.2%). High loss rates trigger frequent TCP retransmissions and window size reductions, ultimately decreasing throughput.

Uplink vs. downlink throughput. Starlink’s downlink throughput exceeds uplink by 10x, aligning with typical user behavior favoring data consumption (e.g., video streaming) over generation.

Latency. Starlink’s Round-Trip Time (RTT) matches cellular networks at 50-100 ms, with only 1.8 ms (550km÷300000km/s) added per hop by space-ground transmission, despite the 550 km satellite altitude.

Moving speed. Throughput remains stable across both networks during high-speed movement. For Starlink, ground terminals’ mobility is negligible relative to satellites’ 28,000 km/h speed. For cellular networks, efficient handovers contribute to maintaining consistent throughput.

TCP parallelism optimization. Starlink achieves a better throughput improvement, over 50% with 4 parallel TCP connections and over 130% improvement with 8 connections. TCP parallelism optimizes bandwidth utilization by distributing data across multiple connections, thereby mitigating the impact of TCP congestion control. It also improves packet loss handling. In case of packet loss in one connection, other connections continue data transmission, minimizing the impact on overall throughput.

In summary, Starlink experiences higher packet loss compared to cellular networks, while latency remains similar. This high packet loss significantly impacts TCP performance, resulting in TCP throughput being only 1/5 of UDP throughput over Starlink. TCP parallelism offers more benefits to Starlink than cellular networks, likely due to its effective handling of packet loss.

To address these issues, multipath UDP experiments are conducted. However, multipath UDP initially showed only marginal throughput gains compared to single-path transfer. By tuning the buffer settings, they achieved more significant throughput improvements. The results highlight the need for better solutions that can handle the specific characteristics of LEO networks.

4. Security Considerations

TBD.

5. IANA Considerations

This document has no requests for IANA.

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