Optimization of QUIC for Deep Space Transmission

An Architecture of Performance Enhancement and Security Extension

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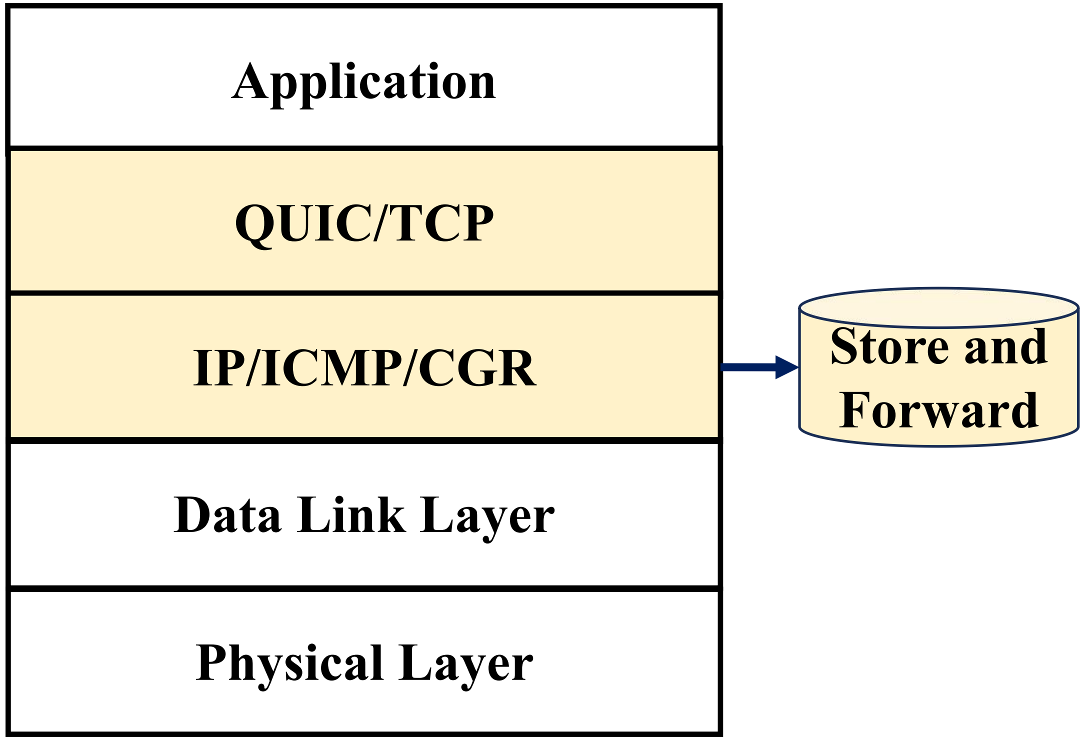
Why Traditional TCP/QUIC Fails

Their fast packet loss recovery and congestion control mechanisms heavily rely on low-latency ACK feedback.



DeepSpace Transport Architecture

In deep-space scenarios with large RTT and random packet loss, Their mechanisms result in:

- Strong coupling between recovery delay and RTT.
- Failure of congestion detection under long RTT.
- Severe head-of-line (HOL) blocking

Part 1: QUIC-Space Extensions

Technical Concept: Use Prior Knowledge from deep-space transmission missions planning such as maximum RTT and link bandwidth instead of probing.

Deep Space Constraints

- **Extreme Latency:** Standard ACK-based mechanisms are inefficient due to high RTT (2 sec–40 mins).
- **Asymmetry:** Extreme difference in uplink/downlink power and antenna size.
- **High Bit Error Rate (BER):** Traditional protocols mistake loss for congestion, triggering window reduction and killing throughput.

QUIC-Space Solution

- **Fixed Window:** Set congestion window to BDP and large flow window to absorb reordering, eliminating probing overhead.
- **Pacing:** Rate-limit transmissions to match link capacity, preventing bottlenecks.
- **Packet-level Forward Error Correction (FEC):** Embed repair packets in the send queue for proactive error recovery.

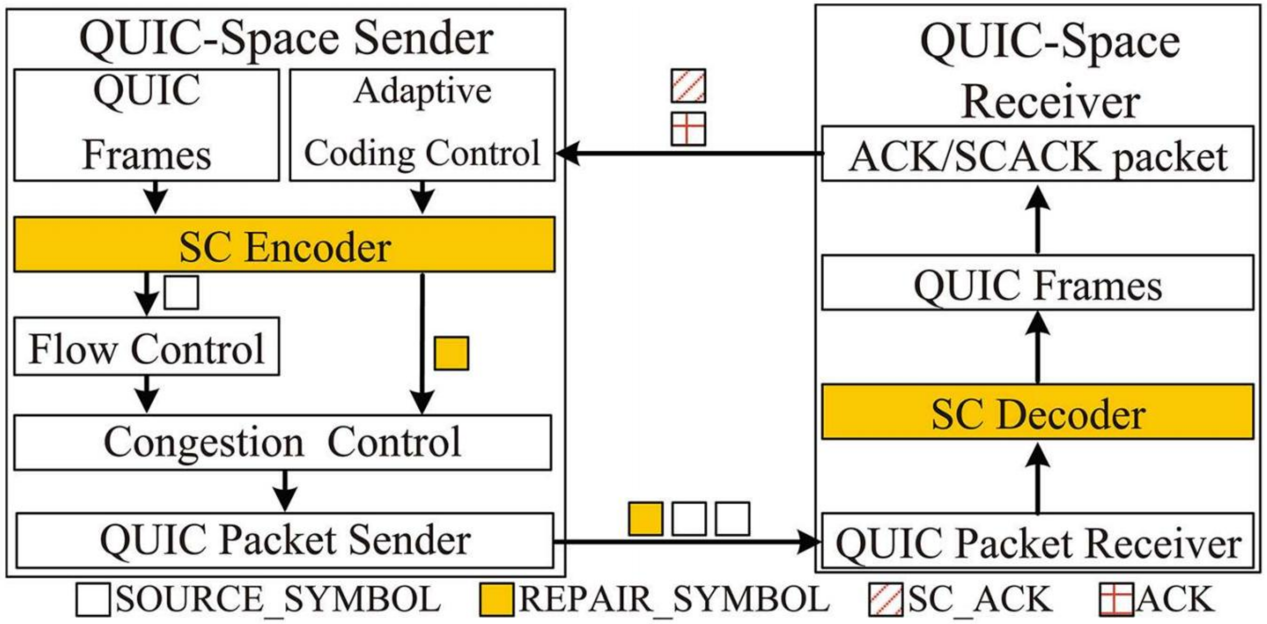
Based on the draft QUIC Profile for Deep Space

[1] *Yu, J., Li, Y., Li, W. et al. QUIC-Space: adaptive FEC-enhanced QUIC for reliable deep space communication. Sci. China Inf. Sci. 68, 229301 (2025). https://doi.org/10.1007/s11432-025-4574-3*

Part 1: QUIC-Space Extensions

Standard QUIC (RFC 9000) relies on retransmissions to ensure reliability, which leads to extremely high delivery latency in Deep Space Networks.

**Although QUIC-FEC Internet-Draft has been proposed, its benefits are limited in near-earth networks due to relatively low RTT.*



QUIC-Space System Model

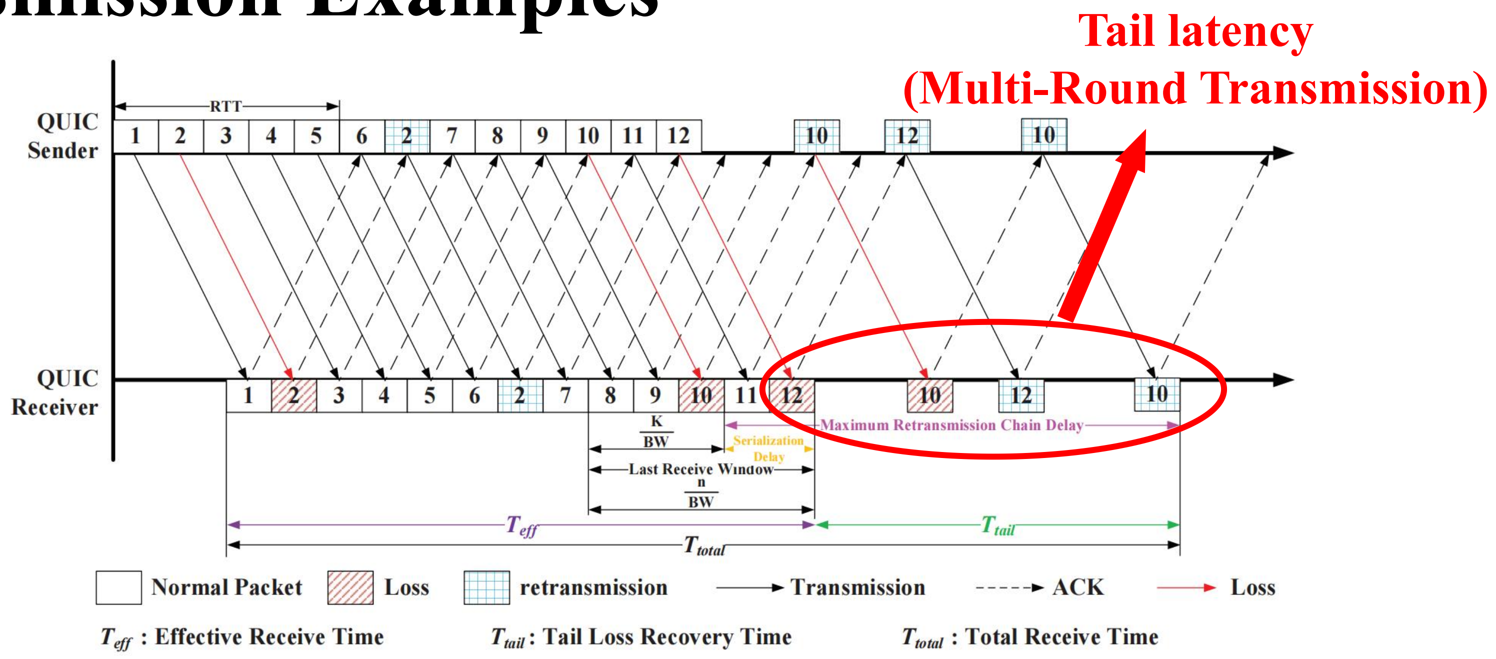
The Solution: Adaptive packet-level Forward Error Correction Called Streaming Codes (SC)

Key features:

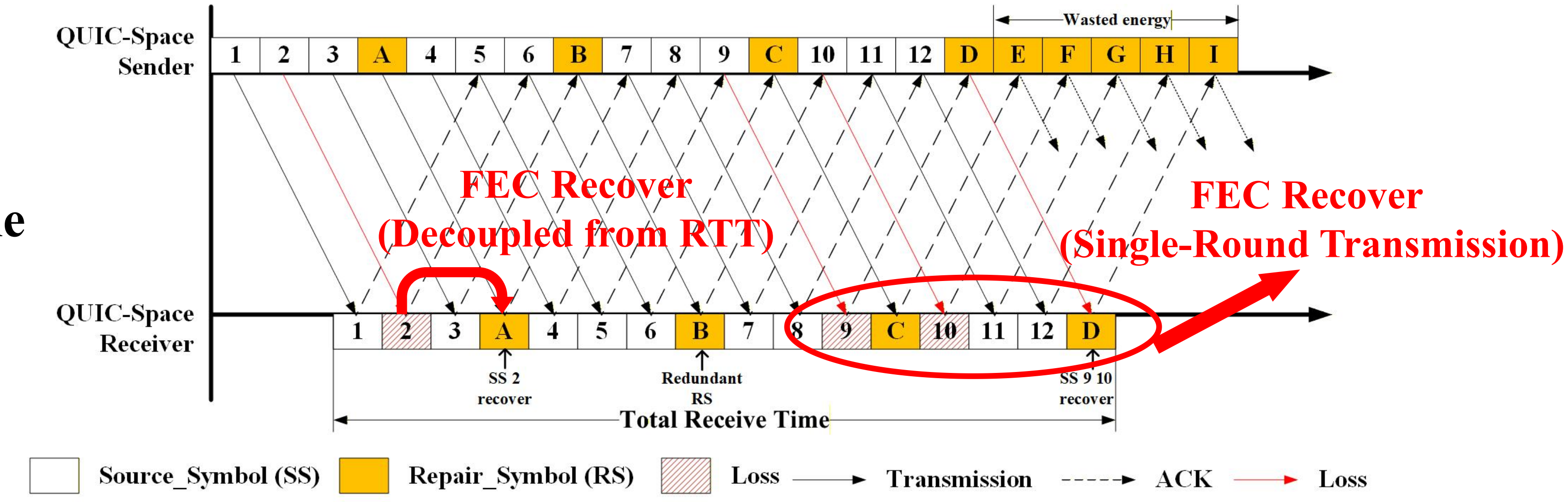
- **Sliding window coding:** Linear combinations of all unacknowledged packets.
- **Progressive recovery:** Data is recovered immediately when enough repair symbols arrive. Incremental decoding without waiting for block boundaries.
- **Adaptive redundancy:** Redundancy adjusted dynamically based on loss rate.

Part 1: QUIC-Space Transmission Examples

Standard QUIC Transmission Example



QUIC-Space Transmission Example



Summary of QUIC-Space

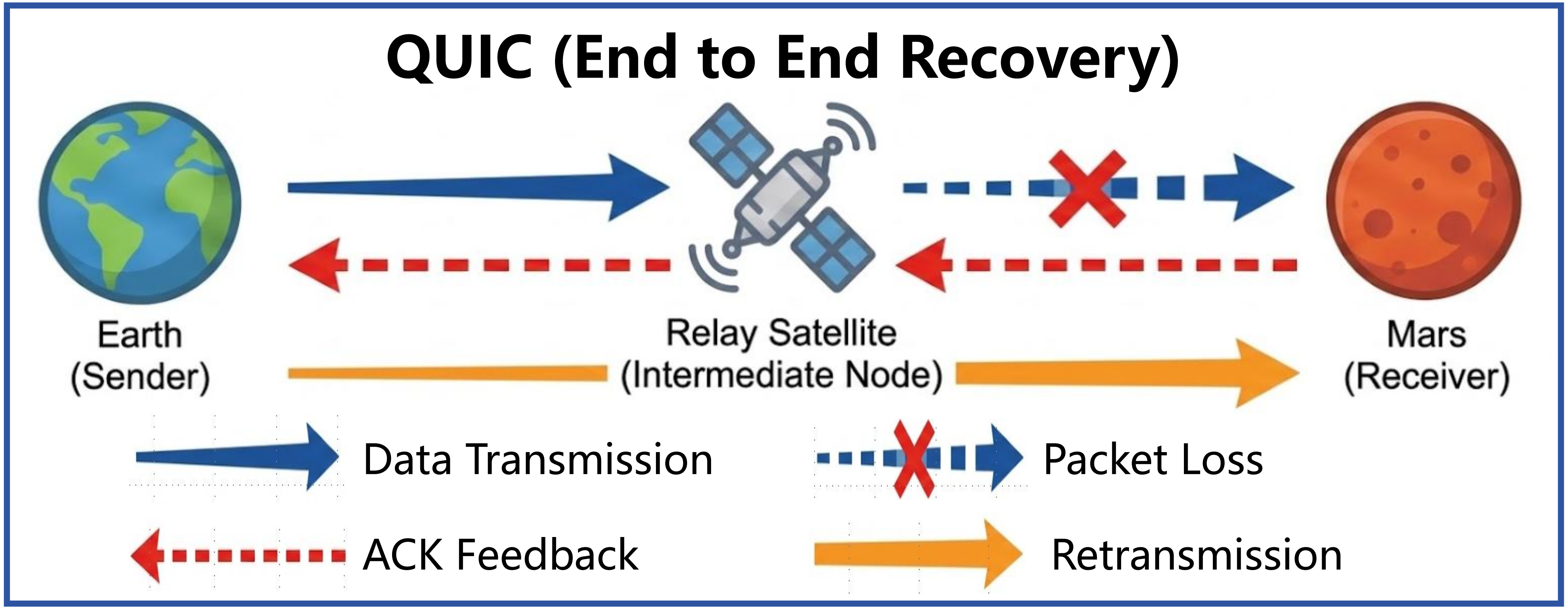
Our contributions:

- RTT-Independent Recovery: Integrate streaming FEC via custom frames—replace retransmissions to decouple loss recovery from round-trip time.
- Deep-Space Tailored Mechanisms: Align with IETF Draft QUIC Profile for Deep Space—fixed BDP window, large flow window to absorb reordering, and rate pacing.
- Verified Performance Gains: Discrete-time model with Earth-Moon simulations shows 46.6% higher goodput, 77.9% lower latency, and reduced buffer occupancy over QUIC/QUIC-FEC.

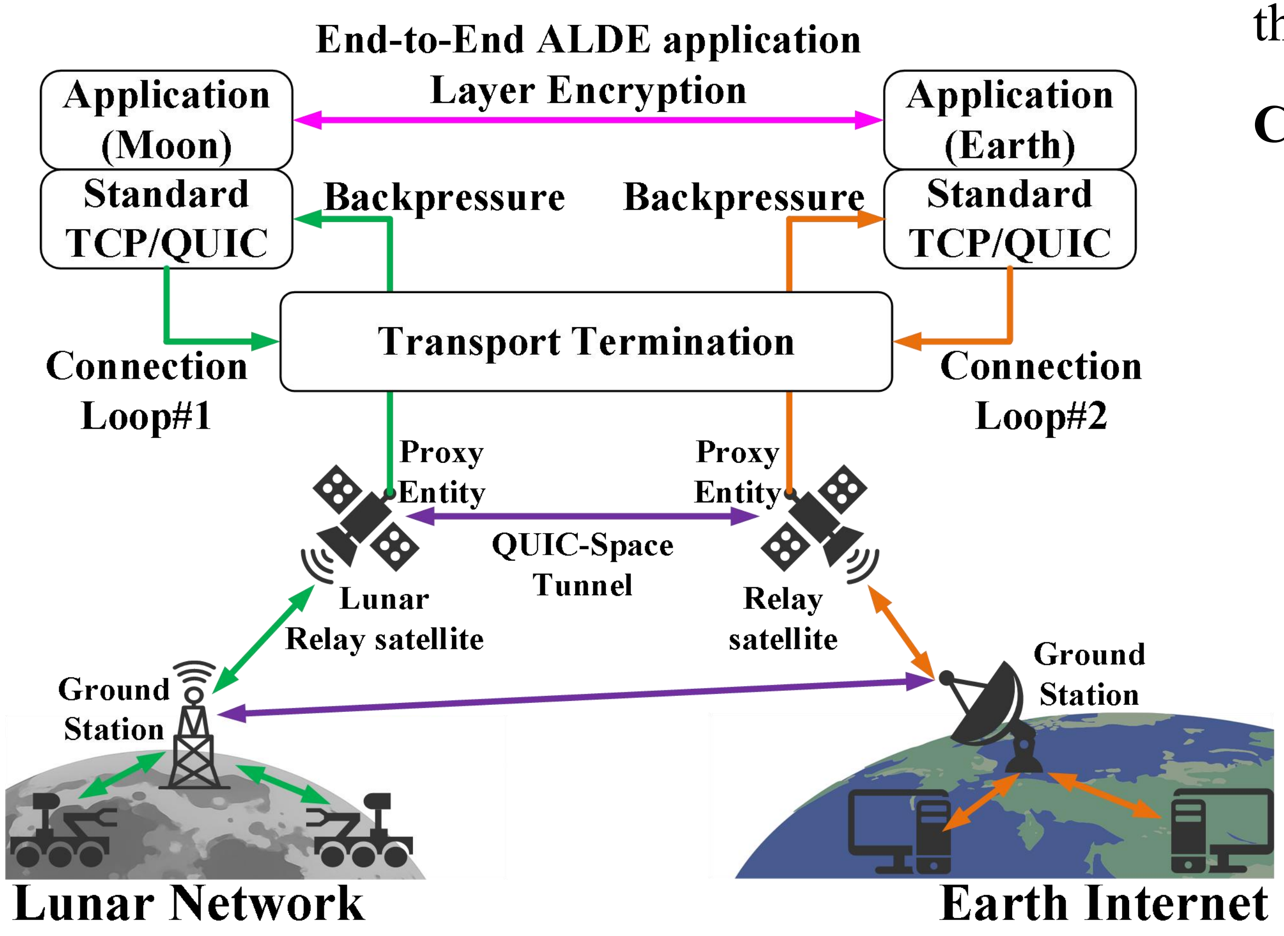
[1] *Yu, J., Li, Y., Li, W. et al. QUIC-Space: adaptive FEC-enhanced QUIC for reliable deep space communication. Sci. China Inf. Sci. 68, 229301 (2025). https://doi.org/10.1007/s11432-025-4574-3*

Part 2: Encryption vs. Segmented Optimization

- End-to-end optimizations alone are insufficient for multi-user deep-space relay links.
- End-to-end encrypted QUIC invalidates traditional transparent PEPs.
- Segmented optimization is essential in deep-space heterogeneous relay scenarios.



Part 2: Non-Transparent Secure Proxy (NTSP)



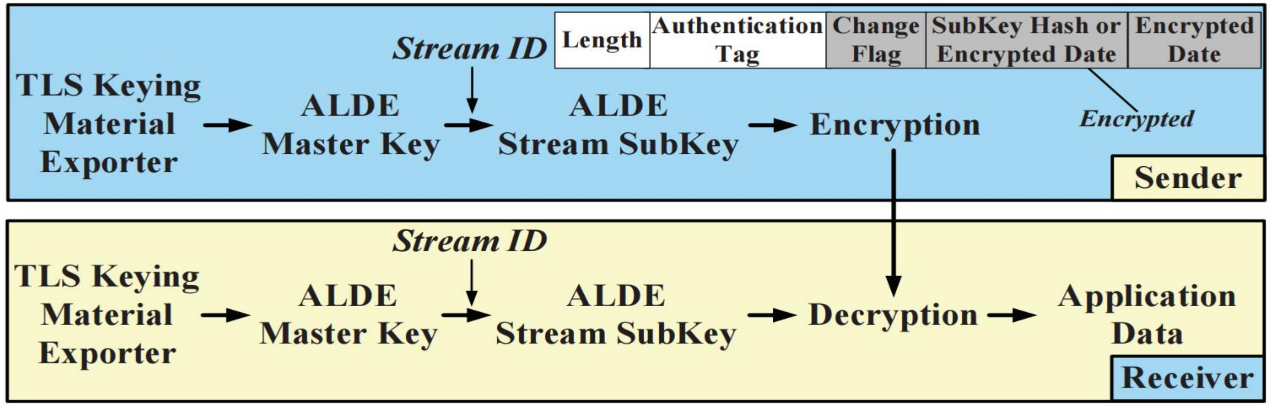
We propose a novel architecture that splits the connection at the gateway without breaking Application security.

Core Concept

- **Explicit authorization:** No implicit hijacking; negotiation via explicit signaling.
- **Connection splitting:** Terminate transport layer at proxy; apply FEC and rate control independently.
- **ALDE (Application Layer Data Encryption):**
  - Operational Trust: Endpoints trust the proxy for availability and routing.
  - Zero Data Trust: The proxy remains opaque to application-layer payloads.
- **Flow Control Backpressure:** Pace terrestrial transmission to align with constrained space link bandwidth.

[2] *J. Yu et al., "A Secure Splitting and Acceleration Strategy for TCP/QUIC in Interplanetary Networks," arXiv preprint (submitted to IEEE, under review), 2026.*

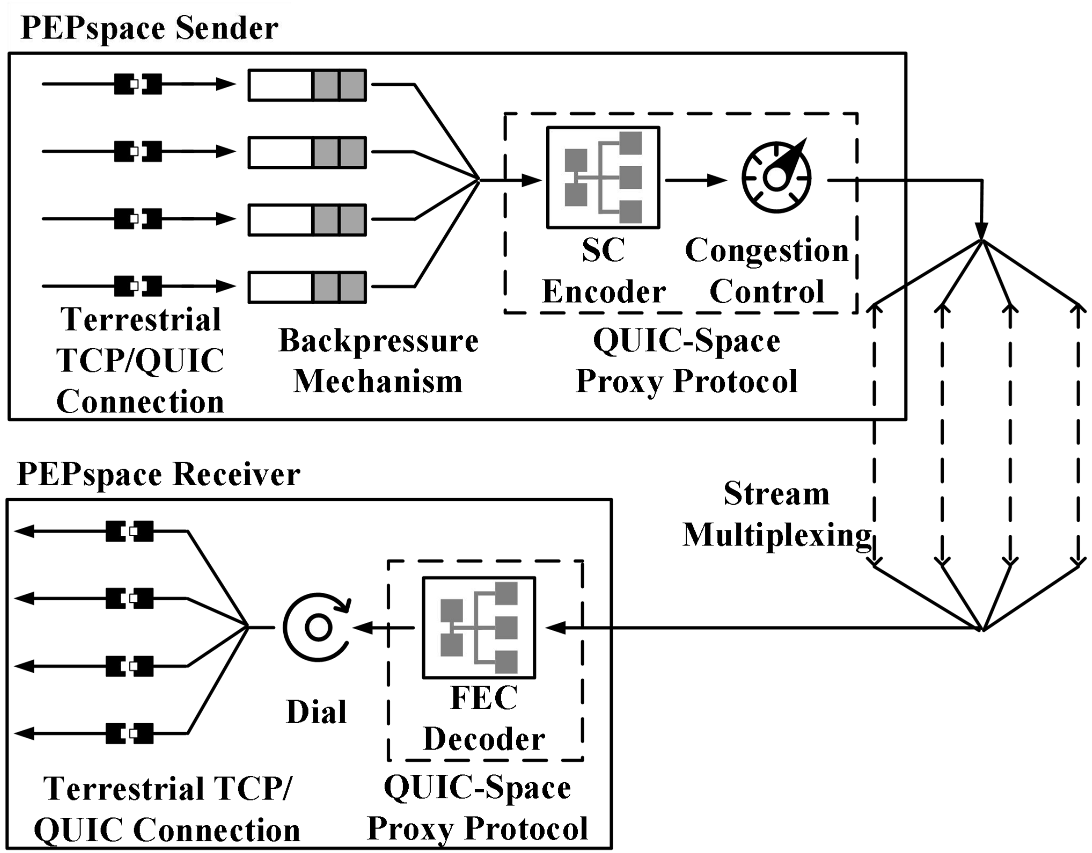
Part 2: Trust Balance: ALDE Layered Encryption Model



NTSP Key Derivation Process

- **Application-Layer Isolation (ALDE):** Payload is end-to-end encrypted by Application Key.
- **Key Derivation:** Keys derived from 1-RTT End to End TLS 1.3 Handshake
- **Security boundary:** Proxy cannot decrypt, tamper with or replay user data.

Part 2: Prototype System-PEPspace



- Multiplexes TCP/QUIC flows into one deep-space QUIC tunnel with unified FEC & fixed CWND.
- Backpressure flow control prevents proxy buffer overflow.
- Derived optimal flow control size balancing throughput and queuing delay: $K_{opt} = \frac{BW_{out} \cdot RTT_{in}}{N}$
- fixed CWND preserves bandwidth in deep space;
- K_{opt} prevents buffer bloat in the access segment.

Summary of NTSP

Our contributions:

- **Explicitly Authorized Splitting:** Terminate transport at gateway via explicit signaling—enabling per-hop optimization without compromising end-to-end security.
- **Application-Layer Encryption (ALDE):** End-to-end payload encryption keeps user data opaque to the proxy, achieving zero data trust.
- **Buffer-Bounded Flow Control:** Backpressure pacing from the space link regulates terrestrial transmission, eliminating bufferbloat and optimizing queuing delay.

Future Work & RFC Standardization Plan

Toward a Unified Deep-Space Proxy Architecture RFC

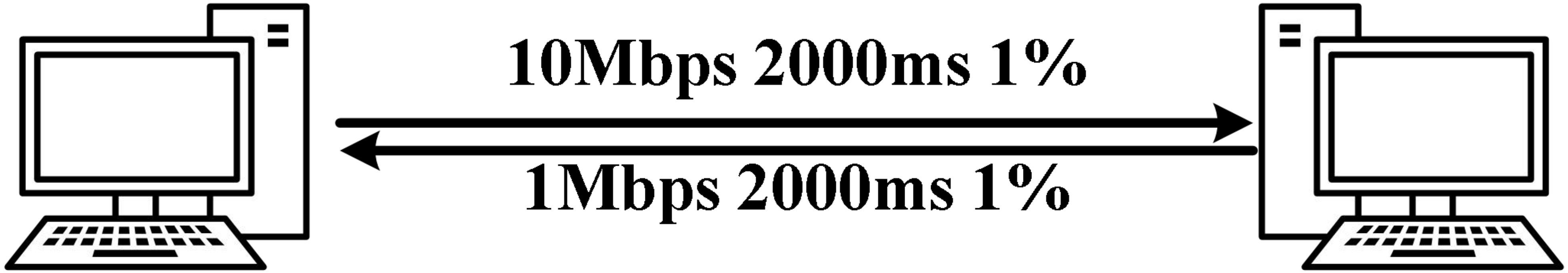
We propose an IETF RFC consolidating the following core innovations:

- Explicitly Authorized Splitting: Securely terminate connections at the gateway via explicit signaling, enabling per-hop optimization.
- Application-Layer Encryption (ALDE): Preserve end-to-end payload confidentiality—the proxy remains opaque to user data, achieving zero data trust.
- Deep Space Link Segmentation Optimization: Employ QUIC-Space mechanisms—streaming FEC, fixed BDP window, and rate pacing—tailored for deep-space link characteristics.
- Backpressure Flow Control: Regulate high-speed terrestrial transmission via buffer-bounded pacing, preventing overflow at the space link proxy.

Goal: Enable secure, high-performance, and deployable IP transport over deep-space networks.

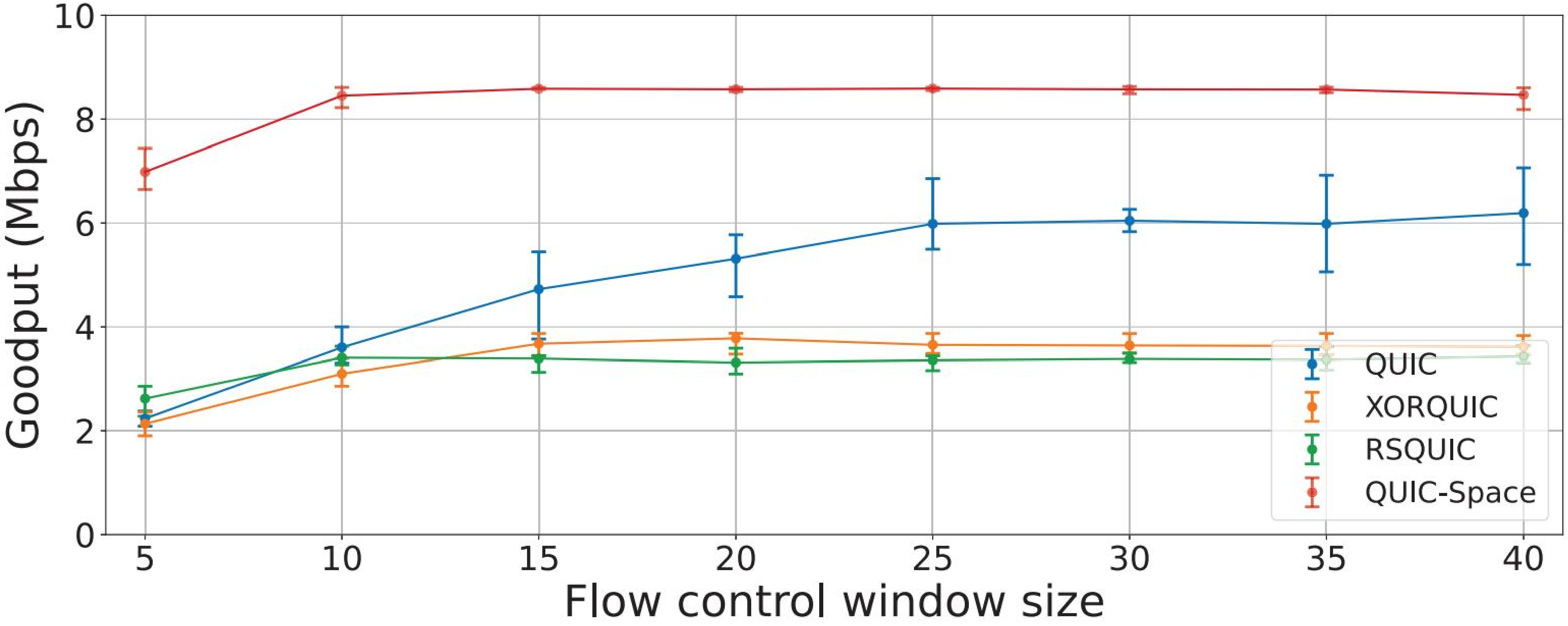
Part 1: QUIC-Space Performance Evaluation (If Time)

Mininet Network Environment (Single Hop):



Part 1: QUIC-Space Performance Evaluation (If Time)

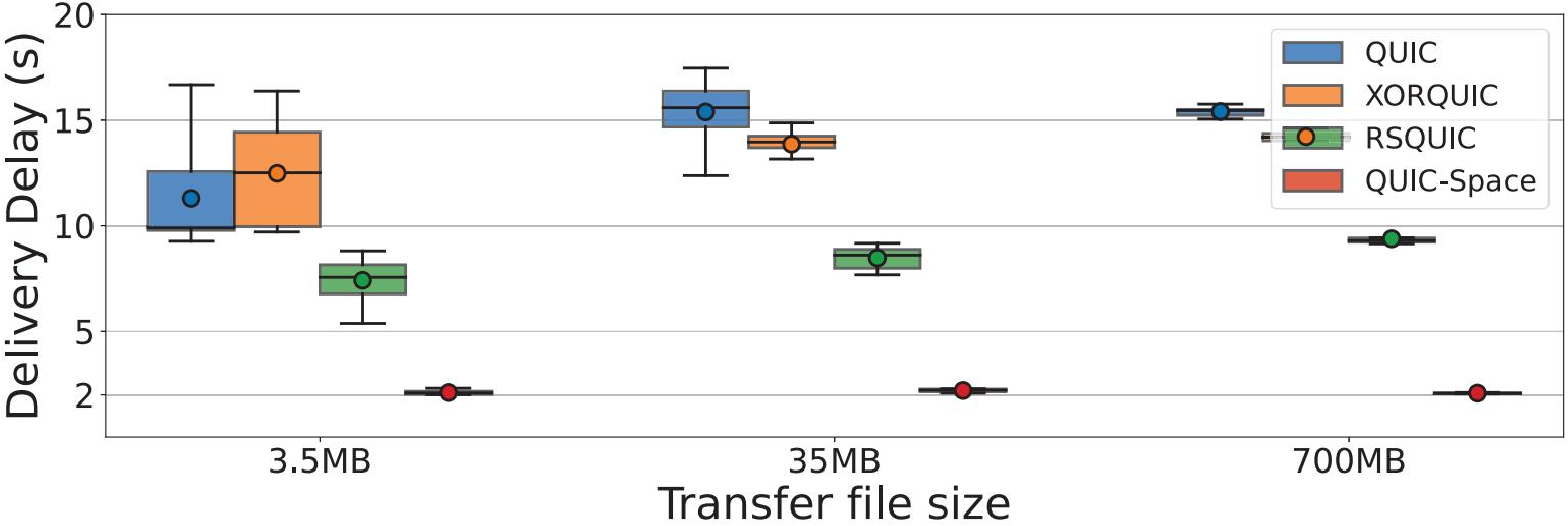
Average Goodput under Different Flow Control Windows



Goodput Increased By 46.6%.

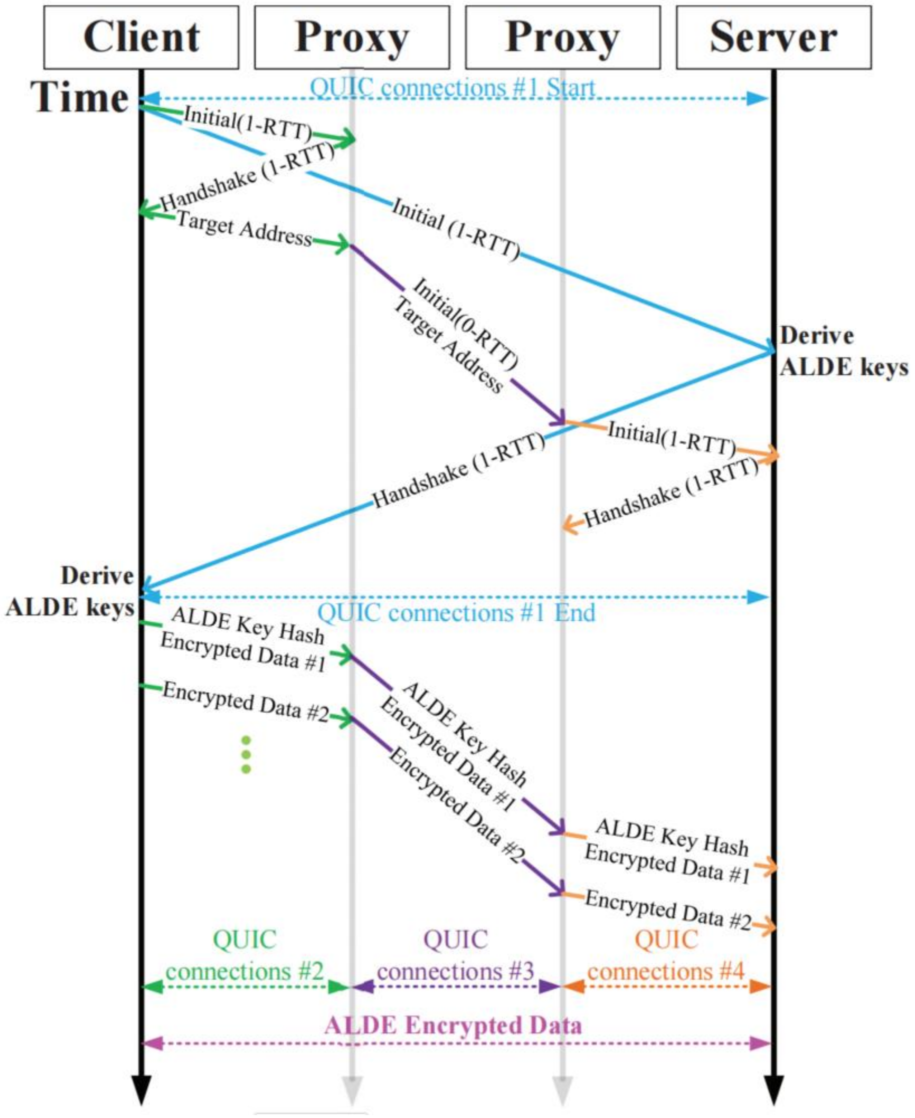
Part 1: QUIC-Space Performance Evaluation (If Time)

Inorder Delivery delay under a 40 MB flow control window



In-order Delivery Latency Reduced by 77.9%.

Part 2: Non-Transparent Secure Proxy (NTSP) (If Time)

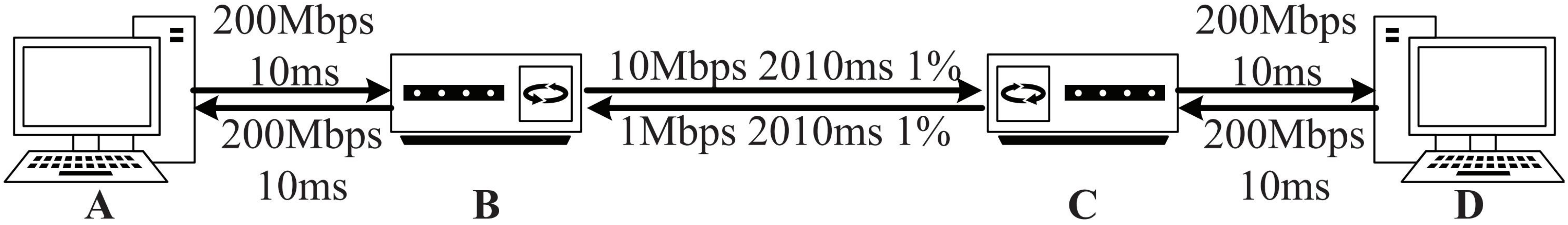


NTSP 1-RTT Establishment Procedure.

Part 2: Performance Evaluation (If Time)

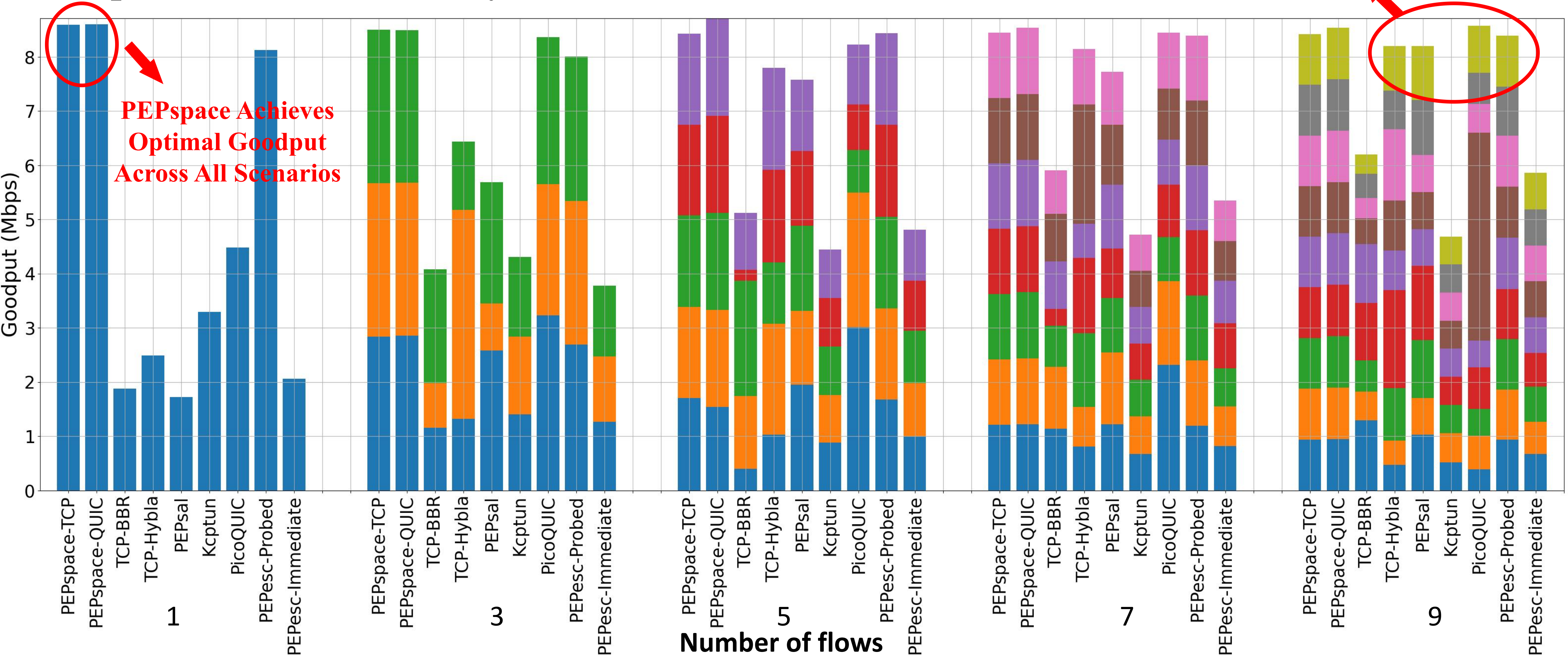
Mininet Network Environment (Multi Hop):

PEPspace Proxying: Standard TCP-Cubic & quic-go-NewReno



Part 2: Performance Evaluation (If Time)

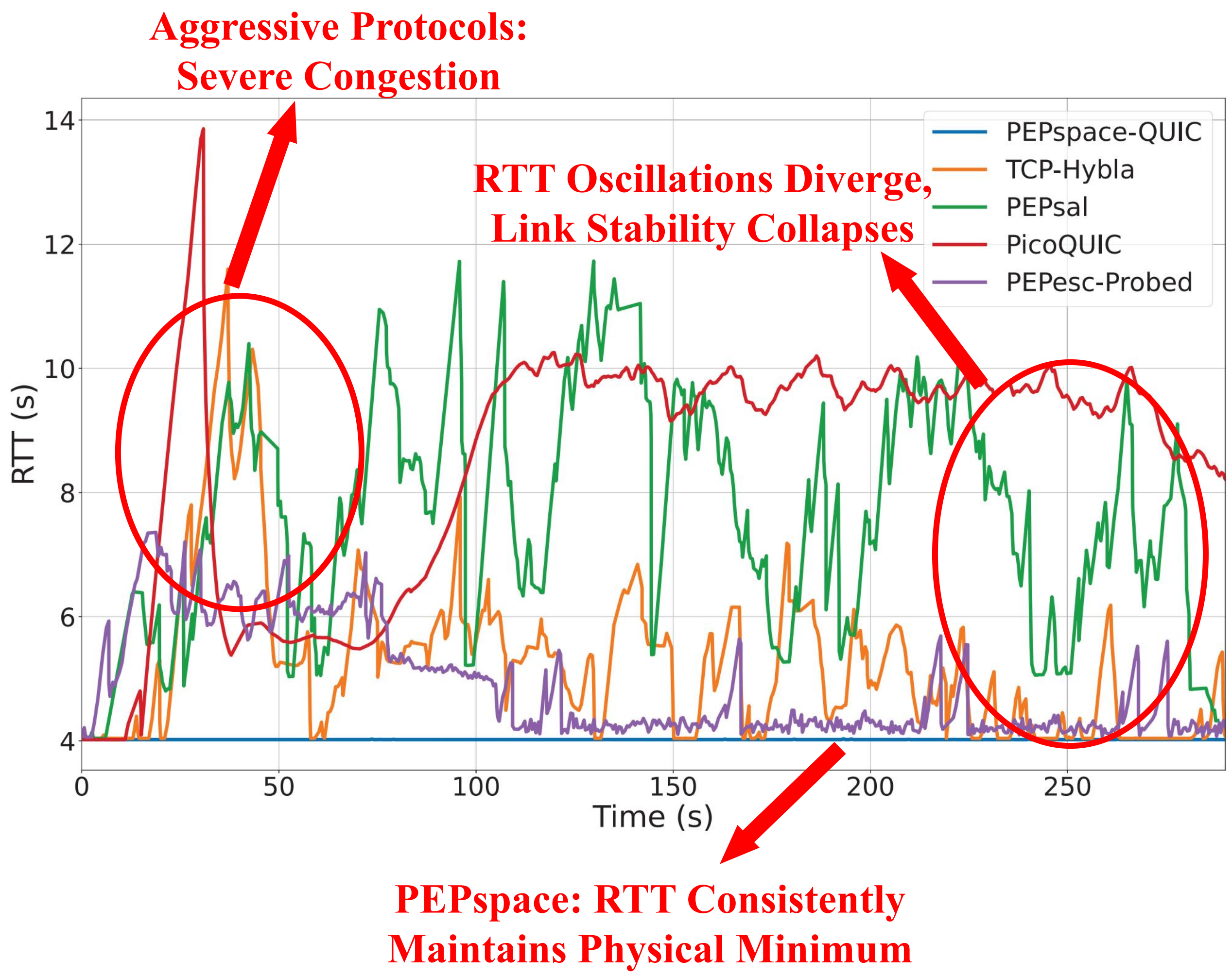
Compare with TCP BBR/Hybla; PEPsal; KCPTUN; PEPesc; PicoQUIC



As traffic grows, aggressive protocols saturate the link, triggering severe congestion, but PEPspace Achieves Optimal Goodput Across All Scenarios

Part 2: Performance Evaluation (If Time)

RTT in 10-Flows Scenario



Aggressive Protocols (PicoQUIC, Hybla):

- Cause severe link congestion (Bufferbloat) in multi-flow environments.
- High and fluctuant RTTs indicate a breakdown in network stability.

PEPspace-QUIC:

- Simultaneous Speed & Stability: Sustains high goodput while keeping RTT near the physical minimum.
- No Congestion Penalty: Efficiently utilizes bandwidth without causing queuing delays.