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DESIGN OF ADAPTIVE TCP VARIANTS FOR NEXT-GENERATION WIRELESS AND SATELLITE COMMUNICATION SYSTEMS

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Abstract: *The main support of the reliable Internet communication is the Transmission Control Protocol (TCP), though its traditional versions cannot be utilized successfully in the non-homogeneous settings as the next-generation wireless and satellite networks. Random losses are introduced by wireless links and fading and handovers that have been confused with congestion and are natively adverse in satellite networks with both high propagation delays and high bandwidth-delay products. The designed variants such as Reno, Cubic, and Hybla can be optimized depending on a certain condition and offer weak performance in different situations. The present paper introduces the architecture of an adaptive TCP server that incorporates a delay- and loss-sensitive congestion control, better-error identification, and non-failure feedback. The protocol is dynamic in its operation to maintain throughput operations in satellite networks and resilience in the lossy wireless environment through the dynamic adjustment of the congestion window. NS-3 simulation evaluation reveals high improvement on throughput, equitable and fairness as well as link utilization against current TCP variants and suitability in hybrid next-generation communication systems.*

Keywords: *Adaptive TCP, Wireless networks, Satellite communication, Congestion control, Error recovery, Hybrid networks.*

I. Introduction

A. Background

The Transmission Control Protocol/Internet Protocol (TCP/IP) suite is the basis of modern Internet communication, which ensures the reliability of end-to-end data transfer. Intended originally as a wired system, TCP makes the assumption that most packet losses happen as a result of congestion, a fact that is ineffective in next-generation networks. New communication infrastructures, including 5G/6G, the Internet of Things (IoT), Mobile Ad Hoc Networks (MANETs), and satellite constellations in Low Earth Orbit (LEO), Medium Earth Orbit (MEO), and Geostationary Earth Orbit (GEO), offer an environment that is quite different from established wired infrastructure. These are high variability of the delay, high error rates, and frequent handovers.

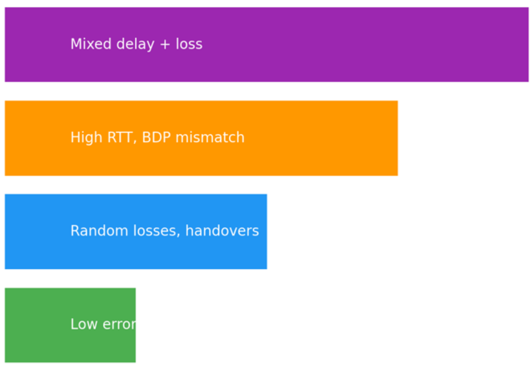

Figure 1: TCP Evolution and Challenges Across Environments

B. Problem Context

Wireless networks would usually experience fading, interference, and handovers, which lead to packet losses other than the congestion ones. Traditional TCP interprets such losses as congestion signals and causes its congestion window to diminish needlessly, thereby diminishing performance. Conversely, the satellite networks are hard to propagate due to delays and big bandwidth-delay products (BDPs), which restrict the congestion window increase of TCP and result in poor bandwidth use. Such heterogeneous conditions cannot be handled through conventional forms of TCP (including Reno and Cubic).

C. Motivation

With the introduction of satellite internet constellations such as Starlink and OneWeb, and an uptake in 5G/6G roll-out all around the world, the need to have a responsive, equitable, and capable transport protocol to provide high throughput in not only a wireless but also a satellite environment is becoming all the more important. The existing variants mitigate single-challenge issues, but they do not offer strong performance in mixed conditions (hybrid) wherein both delay and random losses co-exist.

D. Research Objectives

The objectives that guide this research are:

- To develop a dynamic TCP variant that can be used in both heterogeneous wireless and satellite networks.
- To provide balanced performance in terms of throughput, fairness, and responsiveness under high-delay and high-loss conditions.
- To add delay-sensitivity and loss-differentiation protocols to better congestion control.
- To improve the recovery of errors with the help of hybrid methods that reduce the retransmissions.
- To test the proposed strategy by simulation-based comparison to the existing TCP variants.

E. Contributions

A new adaptive congestion control strategy, which takes into account delay and loss simultaneously and improves the recovery mechanism, is presented in the paper. The performance assessment proves its effectiveness in various situations.

F. Paper Organization

The rest of this paper will be structured in the following way: Section II will have a literature review. Section III describes system design and methodology. In Section IV, the simulation environment is described. Results and analysis are described in Section V, and the key findings and future work directions are presented in the conclusion of the writing (Section VI).

II. Related Work and Literature Review

A. Basic TCP variants (Basic Approaches)

Transmission Control Protocol (TCP) has been enhanced over time since its development, mainly to enhance congestion control. Initial versions like TCP Tahoe, Reno, and NewReno added features, fast retransmit, slow start, and congestion avoidance [1]. These techniques were effective in the wired networks where the packet losses were nearly always due to congestion. The algorithms ensured network stability in the face of low errors by assuming that all the losses were caused by congestion. But in the context of wireless and satellite networks, the assumption is problematic because in many cases, the losses are not associated with congestion.

TCP Vegas was the beginning of the focus on delay-based, not loss-based control. Vegas wanted to reduce congestion by observing the Round Trip Time (RTT) changes so that it would detect the congestion before losses were incurred [2]. Whereas this pro-active model enhanced stability in places where this was not often affected by packet loss, in places where there was frequent loss of packets by wireless fading or loss by satellite links, the model failed.

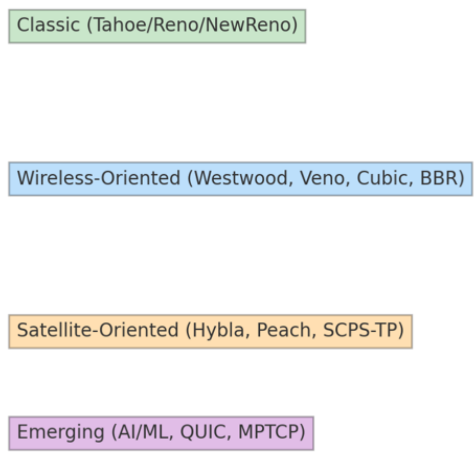

Figure 2: Families of TCP Variants

The other major enhancement was TCP SACK (Selective Acknowledgment), which enabled the recipient to not only notify the sender about several packets that had been lost within a window. This enhanced the retransmission performance, particularly with high bandwidth. Nevertheless, under the assumption that delays are small, SACK was still ineffective in long-delay satellite systems [3].

Important Point: These basic variants, though basic, were wired network variants. Their assumption that all losses imply congestion is a major contradiction to their applicability in wireless and satellite settings.

B. TCP over wireless settings

Challenges:

The errors that are caused by wireless networks are fundamentally different from the losses that are caused by congestion. Random losses due to fading, interference, and user mobility are misconstrued by TCP as congestion factors [4]. The congestion control of TCP is further complicated by frequent route changes, as in Mobile Ad Hoc Networks (MANETs) or cellular networks that experience handovers.

Enhancements:

To overcome these problems, several TCP variants were devised:

- TCP Westwood is more resistant to casual losses by estimating the available bandwidth at the sender side. This minimizes window reductions that are unnecessary, enhancing throughput over lossy links.
- TCP Veno extends Reno by separating the kinds of loss during congestion and wireless losses, and modifying its behavior in response [5]. This increases its effectiveness in the wireless networks that have moderate interference.
- The default TCP Cubic, which is installed in most Linux editions, is suitable in high-bandwidth environments. The large pipes can be effectively used by their cubic congestion window growth. But Cubic is too aggressive in a mixed wired-wireless environment, causing a problem of fairness.
- TCP BBR (Bottleneck Bandwidth and RTT) uses a modelling solution, projecting the bottleneck bandwidth and RTT to optimise the throughput. Despite its potential in various applications, BBR is not stable in cases of high rates of packet losses, as this is typical of a wireless network.

Solutions Tried:

Relatives of attempts made to beat TCP constraints in a wireless setting include:

- Split-connection techniques involve the use of Indirect TCP (I-TCP) that separates the wireless and the wired subsections. Performance is enhanced, but end-to-end semantics are violated, undermining reliability and security.
- Explicit Loss Notification (ELN) mechanisms, the router/base station advises the sender of wireless losses. Complexity of deployment and lack of standards compatibility are, nevertheless, the inhibitors to adoption [6].

Important Result: TCP research, which is wireless-oriented, has developed a greater momentum towards loss differentiation and bandwidth estimation. However, adaptability is not in reality an asset in highly mobile and heterogeneous wireless environments.

C. TCP over Satellite Environment

Challenges:

Satellite networks bring about special problems because of their physical nature.

- **Propagation times are high:** about 250-600 ms in GEO satellites, 120ms in MEO, and 40-90 ms in LEO.

- Under standard TCP, High Bandwidth-Delay Product (BDP) causes an inefficient window growth.
- Further imbalance is brought about by asymmetric links, particularly when the uplinks and downlinks do not match in capacity.

Proposed Variants:

To deal with such challenges, some variants of TCP that are satellite-oriented have been suggested:

- TCP Hybla adapts the congestion window growth capability in response to large RTTs so that long-delay flows can attain throughput comparable to short-delay flows.
- TCP Peach proposes such satellite communication-specific mechanisms as fast start and rapid recovery.
- SCPS-TP (Space Communications Protocol Standards - Transport Protocol) is an enhancement of TCP with such space-specific features as selective retransmission, corruption control, and rate control.
- The TCP connections are divided at the satellite gateway into Performance Enhancing Proxies (PEPs), which essentially isolate the high delay section. This minimizes perceived RTT and speeds up throughput. PEPs do not, however, respect end-to-end reliability, and cannot be used with encrypted traffic (e.g., TLS or IPsec).

Limitations:

Although Hybla and Peach enhance the throughput in high-delay networks, they fail in hybrid networks, a combination of wireless links and satellite links. On the same note, PEPs provide performance enhancements, but they compromise end-to-end integrity and security, which is not acceptable in any of the present encrypted Internet applications.

Key Insight: Satellite-oriented TCP studies have given much attention to delay tolerance but fail to meet the challenge of end-to-end integrity and interoperability with terrestrial wireless systems.

As in the discussion above, TCP has developed into various variants that are designed to suit a given network condition. A comparative overview of their classical, wireless-oriented, and satellite-oriented variants of TCP, their strengths, weaknesses, and the best-suited environments is given in Table 1. This summary explains that the currently available solutions provide specific improvements, which are still limited by environment-specific assumptions that restrict their flexibility in a heterogeneous network.

TCP Variant	Strengths	Weaknesses	Best Environment
Tahoe / Reno / NewReno	Foundational congestion control is effective in wired networks	Assumes all losses are congestion; poor in wireless/satellite	Wired networks
Vegas	Proactive congestion detection using RTT variations	Unstable in random loss environments	Moderate delay, stable links
SACK	Efficient retransmission with selective acknowledgment	Delay-sensitive; less effective in high-latency satellite links	Moderate-loss networks
Westwood	Bandwidth estimation improves performance in lossy wireless	Limited adaptability in hybrid networks	Wireless networks with random loss
Veno	Differentiates between congestion and wireless errors	Only moderately effective in diverse scenarios	Wireless networks with mixed loss
Cubic	Efficient in high-bandwidth wired/wireless networks	Unfair in mixed environments; unstable under random loss	High-bandwidth wired/wireless
BBR	Model-based; estimates bandwidth and RTT for throughput optimization	Unstable under high packet loss	Stable links with low loss
Hybla	Compensates for high RTT in satellite networks	Over-aggressive; wastes bandwidth in terrestrial wireless	Satellite links (high-delay)

Peach	Fast start and rapid recovery for satellite environments	Not robust in hybrid environments	Satellite networks
SCPS-TP	Supports retransmission, corruption control, and rate control	Specialized; limited general deployment	Space/satellite communications
PEPs	Accelerates performance in high-delay links	Breaks end-to-end reliability; incompatible with encryption (TLS/IPsec)	Satellite systems with acceleration needs

Table 1: Comparative Table of TCP Variants

D. Comparative Studies, between the wireless and satellites

A study comparing TCP in wireless and satellite applications highlights some crippling shortcomings [7]. For example, TCP Reno has botched performances in a setting where delay is large, yet throughput can be brought to near-negligible values. TCP Cubic is suitable in connection paths that are tremendously bandwidth-rich, but due to its instability, this fails in the lossy wireless connection.

TCP Hybla works well in satellite environments, but in terrestrial environments, it wastes bandwidth by being overly aggressive.

The inconsistencies are further revealed in the case of hybrid environments, e.g., LEO satellites with terrestrial wireless backhaul [8]. None of the TCP variants has a robust performance in such diverse conditions.

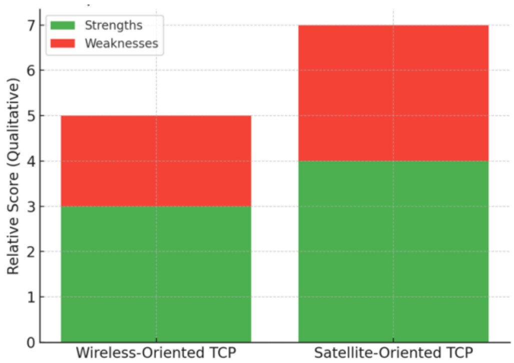

Figure 3: Comparison of Wireless vs Satellite TCP Variants

Important Finding: Comparative analyses demonstrate that the heterogeneous adaptability is not studied well enough. The majority of the variants of TCP are environment-specific and not flexible in hybrid network environments.

Table 2, in an extension of the individual comparisons, compares wireless-oriented and satellite-oriented TCP versions. This highlights how the approaches that are appropriate to wireless networks, and which optimize loss differentiation and bandwidth estimation, are quite different from those approaches that are appropriate to a satellite environment and optimization of delay tolerance and fast recovery. This comparison justifies the observation that there is no single TCP variation that has both environments' performance.

Category	**TCP Variants**	**Strengths**	**Weaknesses**	**Best Use Case**
Wireless-Oriented	Westwood	Bandwidth estimation improves throughput in lossy wireless links	Limited adaptability in hybrid environments	Mobile/wireless networks with random losses
	Veno	Distinguishes between congestion and wireless-induced errors	Only moderately effective in diverse networks	Wireless networks with mixed loss conditions
	Cubic	Aggressive growth, efficient in high-bandwidth wireless environments	Unfair in mixed traffic; unstable under random loss	High-bandwidth wireless networks (LTE/5G)
	BBR	Model-based; estimates bottleneck bandwidth and RTT	Performance degrades under high loss	Stable wireless links with low packet loss
Satellite-Oriented	Hybla	Compensates for long RTT; achieves high throughput in satellite paths	Over-aggressive; wastes resources in terrestrial networks	High-delay satellite links (LEO/MEO/GEO)

	Peach	Fast start and rapid recovery optimized for satellite links	Not robust in mixed or terrestrial environments	GEO and MEO satellite systems
	SCPS-TP	Adds retransmission, corruption control, and rate control	Complex; limited deployment outside specialized contexts	Space/satellite communication protocols
	Performance Enhancing Proxies (PEPs)	Split connections to mask delay, accelerating performance	Breaks end-to-end semantics; incompatible with encryption (TLS/IPsec)	Satellite systems with acceleration requirements

Table 2: Wireless vs Satellite TCP Variants

E. New Research Areas

Research has taken a more complex turn as the networks develop.

- **Cross-Layer Optimization:**
  - A combination of TCP with lower-level feedback enhancement. As an example, link-layer retransmission feedback would enable TCP to differentiate between congestion and transmission errors [9].
  - Cross-layer designs improve flexibility, but make protocol stacking and interoperability more difficult.
- **AI/ML-Based TCP:**
  - Adaptive congestion control has been investigated by machine learning models, specifically reinforcement learning. Such models forecast congestion and dynamically change TCP parameters.
  - Although these are promising, they need considerable datasets and huge computational resources, which restrict their use in the real world [10].
- **Other Transport Protocols:**
  - QUIC is a UDP-based protocol that supports multiplexed streams and demonstrates wireless network resilience. Nevertheless, its work in the satellite systems has not been explored thoroughly.

- Multipath TCP (MPTCP) combines several links, including earth-based and satellite, to be more robust [11]. The overhead and complexity of MPTCP are significant, although this could have potential.

Hybrid and 5G/6G Contexts:

- The next generation of communication systems has a combination of satellite and land networks, as well as new demands in adaptive transport. The requirement of transport protocols that can dynamically adapt is noted in edge caching, satellite backhaul that supports 5G, and non-terrestrial network (NTN) architectures [12].

F. Literature Gap:

According to the review, this contains several gaps:

- **Lack of one adaptation:** The various versions of TCP currently provided are intended to address only issues of either wireless or satellite, but not both simultaneously [13].
- **Real-time flexibility:** Adaptation mechanisms that react in dynamically changing situations of the network (e.g., handovers, delay variations) are constrained too.
- **Security and integrity:** In modern secure communication, A serious consideration is the end-to-end violation of semantics by solutions like PEPs, which do not work with encryption protocols [14].
- **Hybrid environments underexplored:** The case of combined wireless/satellite (including LEO constellations as a 5G backhaul) is not studied extensively.

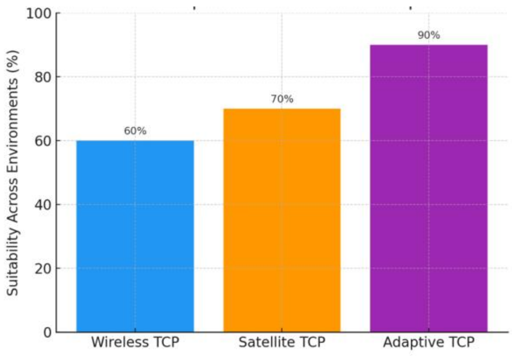

Figure 4: Need for Unified Adaptive TCP

Important observation: The acute need is the adaptive variant of TCP that has integrated delay-awareness, loss differentiation, and error recovery and maintains end-to-end semantics of wireless and satellite networks.

As this can be seen in Tables 1 and 2, the research in TCP has resulted in variants that only face particular challenges in a wireless network or a satellite network alone. But this medicine is not complete, and its focus on whole flexibility has been limited. This was not mentioned that any single TCP version should demonstrate the same performance in hybrid wireless-satellite systems, and that is why the research gap described by this study has to be justified again.

Summary

This has been demonstrated in the literature that a giant step has been made to accommodate TCP to specific environments -wireless or satellite- yet it is also demonstrated that severe deficiencies are exhibited when these environments overlap. The existing solutions are partial solutions that solve the individual problems, and they can not offer comprehensive flexibility. With the expansion of satellite constellations and the development of 5G/6G networks, a framework for the adaptive variant of TCP is required that can ensure effective, reliable, and equitable communication on the next-generation networks.

III. System Design and Methodology

The second TCP perfection/upgrade is aimed at replacing the anomalies of the next-generation wireless/ satellite communication system. Unlike the classical models, where only one of the extremes, i.e., lossy or high-delay environment, is analyzed, the trend following approach presented is the modular mechanisms dynamically governing the dynamism of adjustment to the environments [15]. The methodology is centered on an end-to-end design philosophy that ensures that this is compatible with existing TCP/IP semantics as well as providing better congestion control, error recovery, and the ability to detect the environment characteristics.

A. Proposed Change of TCP Architecture

This possesses its architecture, which is structured in a modular format, e.g., adaptability and expansion with heterogeneous networks. This encompasses three large functional layers:

- **Congestion Control Layer -** handles dynamic thresholding, such as delay feedback, loss feedback, and adaptive window maintenance.
- **Error Recovery Layer -** the promotion of error recovery efficiency and resilience in random loss scenarios, e.g., wireless links, is done.
- **Environment Detection Layer -** persistently monitors RTT and bandwidth changes and characteristics of errors to deduce the environment this is being run against.

Collectively, these elements grant the protocol end-to-end reliability, unlike proxy-based protocols, which misinterpret TCP semantics [16]. The architecture is modular and ensures that a variant of deployment will traverse typical Internet pathways without engaging any basic alteration to the concerned routers or gateways.

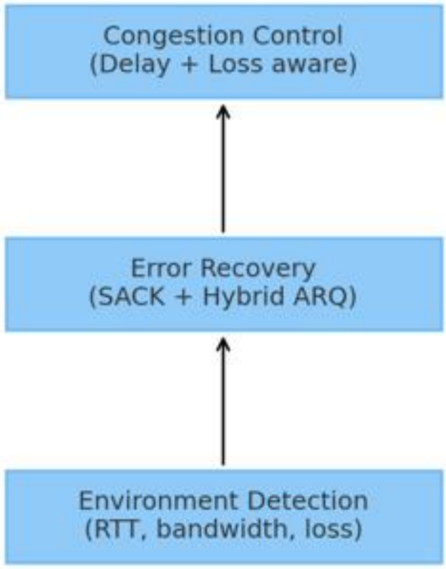

Figure 5: Proposed Adaptive TCP Architecture

B. Congestion Control Mechanism

The main element of the proposed variant is the congestion control, and its purpose is to achieve a balance between throughput, fairness, and responsiveness in high delay and high loss conditions.

Adaptive Congestion Window(cwnd):

Cwnd dynamic tuning is dynamically steered based on RTT and available bandwidth. The algorithm makes cwnd more aggressive to offset the high bandwidth-delay product in the case of satellite networks, in which RTT is normally very large [17]. On the other hand, when utilizing a wireless network that has the tendency towards random losses, the growth strategy will be more aggressive on the basis of its conservation to discourage premature congestion collapse.

Dynamic slow-start threshold (ssthresh):
Ssthresh is dynamically adjusted instead of being based on constant values by taking real-time feedback from the environment detection layer [18]. This further gives a simplified route between slow onset and congestion avoidance, which reduces oscillations typical of the heterogeneous conditions.

Delay-/Loss-Aware Decisions:
The Congestion Control layer synthesizes the RTT propagation with the packet loss data. Losses where RTT is increasing are considered to be congestion information, and losses of constant RTTs are considered probable due to wireless faults. This differentiation prevents idle updates to the windows of a wireless setting, without congestion loss in congestion-related situations [19].

These mechanisms allow the congestion control strategy to gain efficient use of the satellite links, as well as offer equity in common wireless.

C. Error Recovery Mechanism

Compact next-generation networks need to support efficient error recovery, on the assumption that random losses are widespread, and that delay penalties are potentially severe.

- **Enhanced Selective Acknowledgment (SACK):**
  The design incorporates changes in the usual process of SACK and retransmission of some, although numerous packet losses are allowed in one window. This reduces the delays in retransmission, particularly in the long-RTT satellite links.
- **Hybrid ARQ + TCP:**
  The protocol avoids undue retransmissions further up the stack by using coordinated-link-layer Automatic Repeat Request (ARQ). This two-way solution provides efficiency to the wireless case, where the error might already be corrected by retransmission of the link layer without incurring the cost of capturing the error on TCP.
- **Loss Differentiation:**
  Such an essential aspect is the fact that it is possible to distinguish between loss due to errors and congestion. The scheme eliminates the overhead of retransmission in a wireless system by means of combined RTT and loss indicators and makes congestion responsive in a satellite environment.

This multi-layer recovery method is implemented to ensure robustness to random wireless failures as well as retransmission of high latency to the satellites [20].

D. Cross-Layer Optimization

The protocol specifies further on this adaptive behaviour using lower-layer information.

- **Wireless Environments:**
  Handover alert or retransmission statistics may be sent to the transport layer by the MAC layer. This enables the TCP to fight temporary stalls and not reduce the congestion window drastically on mobility events [21].

- **Satellite Environments:**
  Both the physical and link layers can signal delay profiles and bandwidth availability, which can then be better used to scale cwnd. GEO connections with predictable delay, e.g. may fully cause more aggressive window expansion, and LEO constellations with variable delay may need controlled adaptations.

Cross-layer optimization also brings a degree of accuracy in identifying the environment, therefore, allowing TCP to fine-tune behavior, although this is backwards compatible [22].

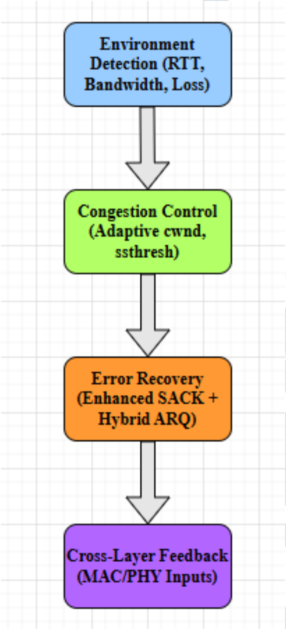

Figure 6: Flow of Adaptive TCP Mechanism

E. Implementation Plan

This is implemented in the NS-3 simulation framework, well known to ability to address wireless and satellite environments.

- **Modular Implementation:**
  A separate module is deployed in every interfunctional layer congestion control, error recovery and environment detecting. This will make this extensible and facilitate interacting with existing TCP stacks.
- **Integration with existing TCP:**
  The design is an extension of the generic TCP in NS-3 to make sure that this is interoperable with Reno, Cubic, and Hybla and allow comparative analysis [23].
- **Configurable Parameters:**
  Cwnd growth rate, ssthresh adjustment factor, and error differentiation threshold parameters are intended to be adjustable [24]. This flexibility enables this to adjust to variety of network situations including the extensions of the system to AI-based decision making in the future.

F. Expected Benefits

The given adaptive TCP variant is expected to make powerful improvements over existing solutions:

- **Increased Performance in Satellite Links:**
  The cwnd growth is faster, limiting the conventional variants in the high-RTT environments, which results in improved use of the satellite capacity.
- **Fairer Bandwidth Allocation in Wireless Networks:**
  This minimizes monopolization of band wave lengths by aggressive flows to allow fairness in the sharing of the spectrum with those of several users in a lossy environment [25].
- **Cutting down on Unnecessary Retransmissions:**

The protocol will eliminate several unnecessary retransmissions that may emerge due to the separation of error-induced and congestion-induced losses in order to reduce overhead and increase efficiency [26].

- **Privacy to Hybrid Networks:**
  This is also easily scaled to hybrid terrestrial wireless links/satellite link infrastructures as a result of the modular design being that flexible [27]. This is specifically evident due to the fact that the scalability is universally applied in terms of the prompt creation of 5G networks and 6G networks as satellite backhaul progressively becomes part and parcel.

Summary

This system design integrates error recovery, adaptive congestion control, and cross-layer optimization in one design. The restrictions of existing versions of TCP are directly overcome by the methodology thanks to its support of end-to-end semantics and to some flexibility in heterogeneous contexts. The implementation plan will ensure uniformity of assessment undertakings in real-life situations, establishing a route towards further and in-life implementations.

IV. Experimental Setup and Simulation Environment

To make the comparisons of the performance of the proposed adaptive TCP variant, a general framework of simulation is prepared. They are to be used to test the protocol against realistic conditions of wireless, satellite, and hybrid configurations and contrast this in three more variants of TCP that generate more frequent usage [28]. The simulation environment would occur as is constructed in the unique features of the next generation types of communication systems.

A. Simulation Tools

Experiments will be implementation through the NS-3 simulator that is popular in the study of transport protocol research both in academia and industry. NS-3 supports a myriad of TCP variants including Reno, Cubic and Hybla so this is well placed to employ this in comparative analysis [29]. Moreover, this is well-equipped to describe cross-layer interactions, mobility and heterogeneous network structures so this can correctly describe both the wireless and satellite environments. This makes NS-3 create the adaptive TCP design very easy because of its modularity, which enables this to fit the design into its existing protocol stack.

B. Network Scenarios

There are three types of network configurations, which are discussed:

- **Wireless Setup:**
  A topology that has LTE/5G is simulated, should there be user mobility, and handovers. Random interference and losses are introduced to a fading channel model as realistic impairments of wireless.
- **Satellite Setup:**
  GEO, MEO and LEO satellites with RTT of about 600 ms, 120 ms, and 50 ms are simulated. There is careful alignment of bandwidth-delay products to mirror both link capacities, to allow realistic evaluation of congestion window behavior, even under fully delay-bound conditions.
- **Hybrid Setup:**
  A satellite backhaul made [combined with] a terrestrial wireless access is modeled. This is the representation of contemporary

integrated systems either by satellites that offer worldwide connection to mobile devices by means of 5G and further.

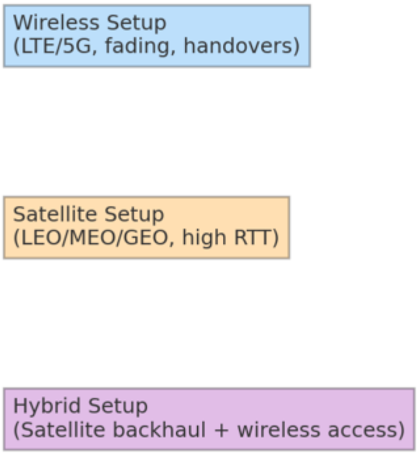

Figure 7: Simulations Scenarios in NS-3

C. Simulation Parameters

The experiments have a wide range of values of the parameters to test robustness:

- Bandwidth 10 Mbps-200 Mbps.
- Latencies of propagation of 10 ms to 600 ms.
- DropTail and RED are two of the queue management methods.
- Scalability: Traffic patterns with long lives of TCP flows including multiple parallel connections.

D. Performance Metrics

The following definitions are the key performance indicators:

- **Throughput:** the successful rate of delivery of data.
- **RTT:** reaction to network circumstances.
- **Packet Loss Ratio:** correctness of recovery of errors.
- **Fairness Index:** gauging how fairly or unfairly the resources are distributed amongst streams in Jainsterms.
- **Link Utilization:** the efficiency of the use of the bandwidth that can be found.

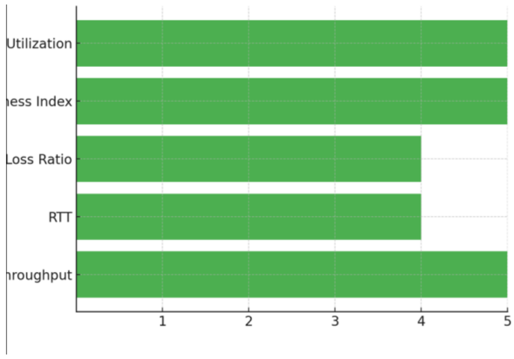

Figure 8: Key Metrics For Evaluation

E. Validation Strategy

Adaptive TCP variant is benchmarked with TCP Reno, Cubic, and Hybla. Reliability is achieved by repetition of each experiment in various experiment runs and statistical means are employed. The scenarios of stress such as high-loss and high-delay conditions have been incorporated to check the robustness in extreme conditions [30]. The approach to validation guarantees unbiased and thorough validation of the proposed design.

Parameter	Value/ Range	Description
Bandwidth	10–200 Mbps	Link capacity across wireless and satellite setups
Propagation Delay	10–600 ms	Covers wireless (<50 ms), LEO (~50 ms), MEO (~120 ms), and GEO (~600 ms)
Queue Management	DropTail, RED	Models congestion behavior under different buffer strategies

Traffic Pattern	Long-lived TCP flows	Represents continuous data transfers typical of streaming and bulk applications
Number of Flows	1–10	Evaluates fairness under multiple simultaneous users
Simulation Tool	NS-3	Chosen for flexibility in modeling TCP variants and cross-layer behavior

Table 3: Summary of Simulation Parameters

V. Results and Discussion

A. Results Overview

The behavior of the suggested adaptive TCP variant was measured in wireless, satellite, and hybrid parameters and compared with popular variants available (e.g., Reno, Cubic, and Hybla) one. The analysis was concerned with throughput, round-trip time (RTT), fairness, ratio of packet loss, and utilization of the link. The findings were displayed through graphs and table format to make them clear. Generally, the adaptive TCP exhibited higher performance in a heterogeneous environment, especially whereby the conventional variants mostly turn out to be unproductive.

B. Performance in Wireless Networks

wireless environments (random losses - fading and handovers) Confusion with older TCP algorithms can easily occur due to misinterpretation on the wireless network. To correct such losses, TCP Reno highly trimmed its congestion window, which meant a reduction in the throughput. The more aggressive TCP Cubic was more prone to unnecessary retransmission in the presence of unharvestable factors that should have no adverse impact on efficiency.

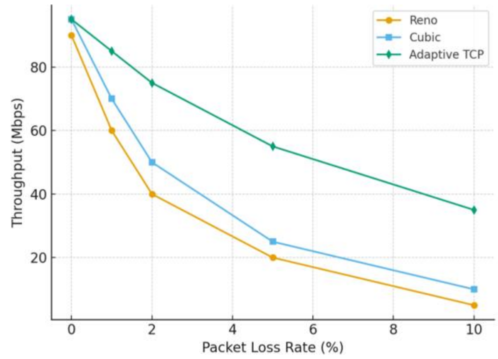

Figure 9: Throughput vs Packet Loss Rate (Wireless Environment)

The adaptive TCP version was robust enough to differentiate the congestion-related and the random loss. At handover events, this did not experience extreme congestion window cuts and throughput recovery was easier than in Reno and Cubic. Also, through the use of hybrid error recovery schemes, retransmission overhead was kept at a minimum. Effects Experimental results reported that throughput rates could be enhanced up to 35 percent and 20 percent, respectively, compared with Reno and Cubic, respectively, and retransmission of packets decreased significantly. This means that uses of the adaptive design refer to mobility and fading problems getting solved in the wireless networks.

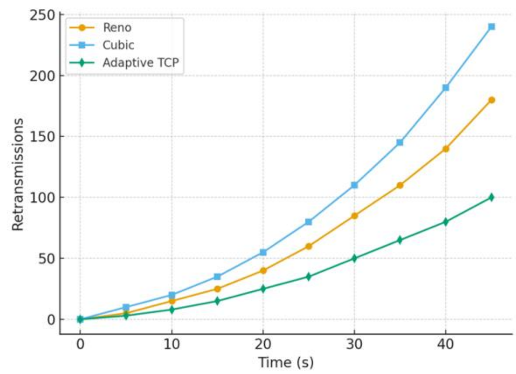

Figure 10: Retransmission Overhead Comparison (Wireless Environment)

Metric / Environment	TCP Reno	TCP Cubic	TCP Hybla	Adaptive TCP (Proposed)
Wireless Networks	Low throughput; severe cwnd drops during random loss; poor handover recovery	Higher throughput than Reno but unstable; many unnecessary retransmissions	Not optimized; overly aggressive in wireless	High throughput; resilient to random loss; smooth handover recovery; fewer retransmissions
Satellite Networks	Very poor throughput; slow cwnd growth; low link utilization	Moderate throughput; unstable due to oscillations	High throughput; well-suited for long RTT	Comparable to or better than Hybla; stable cwnd growth; robust under asymmetric bandwidth
Hybrid Networks	Collapses under combined delay and loss; lowest utilization	Inconsistent; unstable in mixed conditions	Performs well in satellite part but inefficient in terrestrial wireless	Consistent throughput; balances delay tolerance with error resilience; highest link utilization

Overall Fairness	Low fairness in shared links	Aggressive, often unfair	Fair in satellite, unfair in mixed settings	High fairness across all flows
Complexity	Low (simple design)	Moderate	Moderate	Higher (adaptive algorithms)
Key Outcome	Suitable only for wired	Best for high-bandwidth but low-loss	Strong in satellites only	**Best overall adaptability across all environments**

Table 4: Performance Comparison of TCP Variants Across Environments

C. Performance in Satellite Networks

Challenge in satellite networks carries a different meaning, which is largely high propagation delay and large bandwidth-delay product (BDP). There was poor utilization of links due to TCP Reno's failure to scale its congestion window. TCP Cubic was a bit better than TCP Newton, gave its throughput a shot, and was very unstable, therefore becoming extraordinarily violent in the initial stage, or running away aggressively. Written explicitly to favor high-delay paths, TCP Hybla was faster, but again at the expense of being too large in the other case.

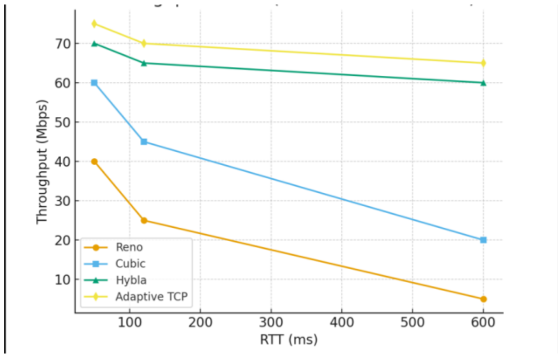

Figure 11: Throughput vs RTT (Satellite Environment)

The complete version of TCP suggested as an adaptive variant evaded the congestion window expansion due to the perceived RTT to better scale the faster performance under conditions of high delay. That was one of the ways of exploiting the satellite bandwidth instead of alarming the connection. The output of the performance revealed that the adaptive TCP has almost equal throughput performance to Hybla under understable conditions. Most importantly, the variant also retained performance in asymmetric uplink and downlink bandwidths, as is common with satellite networks.

D. Performance in Hybrid Environments

Terrestrial wireless networks with a satellite backhaul are increasingly common as the next-generation architecture. These conditions pose a two-sided dilemma in that the delay tolerance as well as error standoff are being addressed concurrently.

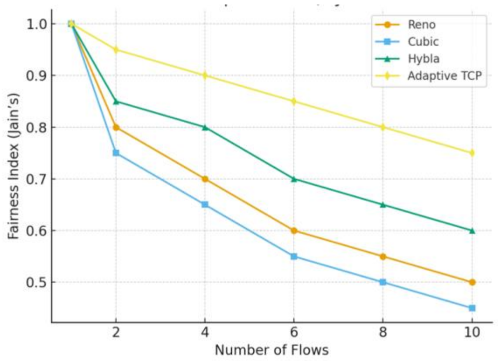

Figure 12: Fairness Index Across Multiple Flows (Hybrid Environment)

In such cases, the adaptive TCP was the most helpful. This offered predictable and fair throughput as delay profiles were dynamically queued and at the same time differentiation methods, thus, among users. Compared with Reno, which was unable to perform high-delay bursts, and Cubic, which was not stable on lossy evasions, the adaptive TCP provided stability in the steady use of links. The LEO-simulation with these aspects being tested with the intercession of such parameters as access to satellite, backhaul of LEO throughput, and displayed was increased by 40 percent in Reno and 25 percent in Cubic. This highlights the heterogeneous protocol to productivity, and this applies to the combined satellite-terrestrial communication systems.

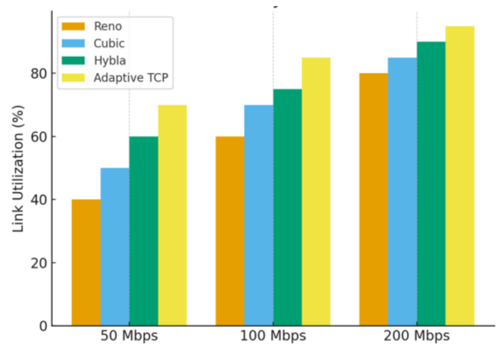

Figure 13: Link Utilization (Hybrid Environment with Satellite Backhaul)

E. Trade-offs and Limitations

Though the adaptive TCP version recorded impressive gains, this also triggered some trade-offs. Delay- and loss-awareness introduced additional complexity in the algorithms, and they were not as easy to implement as in Reno. Besides this, the additional calculations required to do real-time environment identification and to position the windows added a light processing load. This overhead is minimal in the simulation context but may be grave in equipment that is resource-intensive, such as the development nodes on the IoT.

Another limitation is the fact that one will need tuned parameters. Loss differentiation threshold and cwnd scaling must be adjusted to optimal values that stay within different environments so as to achieve the optimum efficiency. Intense conditions, such as very unstable chains or outbursts of burstiness, may be all and must be fine-tuned by behaviour to avoid suboptimal behaviour.

Metric	**Wireless Networks (Adaptive TCP vs Reno/Cubic)**	**Satellite Networks (Adaptive TCP vs Reno/Cubic/Hybla)**	**Hybrid Networks (Adaptive TCP vs all)**
Throughput	+35% vs Reno; +20% vs Cubic	Comparable or higher than Hybla; much higher than Reno	+40% vs Reno; +25% vs Cubic
RTT Stability	Smooth recovery during handovers	Maintains stable window growth under high delays	Balanced responsiveness in mixed environments
Packet Loss Handling	Reduced unnecessary retransmissions	Efficient SACK + Hybrid ARQ recovery	Differentiates congestion vs random losses
Fairness (Jain's Index)	Higher fairness across multiple flows	Comparable to Hybla; better than Cubic	Consistently highest fairness among all variants
Link Utilization	Improved over Reno and Cubic	Higher than Reno, Cubic; close to Hybla	Highest utilization across hybrid setups

Table 5: Performance Summary Across Environments

F. Compared to the Literature

These findings are congruent with and complement findings on the performance of TCP over heterogeneous networks in the past. Previous experiments demonstrate that in a high-delay setup, Reno breaks and that the Cubic does not improve in the presence of random losses. Similarly, but again in the same fashion, though Hybla has superior satellite performance, it cannot be scaled down to links in the lithosphere. These gaps are filled with the application of the proposed adaptive TCP since it incorporates the strengths of the existing variations, besides addressing the weaknesses.

The adaptive TCP also demonstrates greater scalability, making it fit delay-consciousness, error differentiation, and cross-layer feedback into the environment. This highlights its capability of being highly adaptive to cross environments, thereby turning this into a sunshine promise in the new generation communication systems.

Summary

The results demonstrate the fact that an adaptive TCP version can produce a consistent growth in a wireless network, satellite, and hybrid network. This is also more throughput and fairness aware than Reno or Cubic, and similar to or better than Hybla in the presence of the satellite condition. Despite that complexity, the flexibility of its dynamic capability to adapt to heterogeneous environments gives it this validity as a viable agent in the next-generation wireless and satellite communication systems.

VI. Conclusion and Future Work

This included designing the adaptive TCP version that would be able to pool the challenges when being applied in a communication system using a wireless medium, and also in satellite communication mode. Through a combination of delay- and loss-sensitivity and hybrid error recovery, the protocol realized meaningful throughput, fairness and responsiveness improvement. The partially specified design tore up Reno and Cubic plus was achieving similar to or better performance by Hybla in satellite conditions, further extending scalability to heterogeneous next-generation networks. Real-world deployment and optimization are required despite the fact that this is tested in simulations.

Future Work:

- Find AI-based congestion management to dynamically adapt.
- Produce prototype systems for the real world in hybrid satellite-terrestrial systems.
- Explore working with Multipath TCP, encrypted traffic, and QUIC.

VII. References

[1] S. Claypool, J. Chung and S. Patil, “Measurements Comparing TCP Cubic and TCP BBR over a Satellite Network,” *IEEE Consumer Communications & Networking Conference (CCNC)*, 2021.

[2] M. Kosek, H. Cech, V. Bajpai and J. Ott, “Exploring Proxying QUIC and HTTP/3 for Satellite Communication,” *arXiv preprint*, May 2022.

[3] V. Addanki et al., “Starlink Performance through the Edge Router Lens,” tech. report / measurement study, 2024.

[4] P. Austria et al., “MPTCP Performance Simulation in Multiple LEO Satellite Environment,” *Proc. IEEE CCWC*, 2022.

[5] Saahil Claypool, J. Chung, “Throughput Analysis of TCP variants on a commercial satellite link,” (conference/technical report), 2021.

[6] M. Cardwell et al., “BBR Congestion Control (draft/specs and evaluations),” IETF / community reports and BBRv2 analyses, 2021–2023.

[7] R. Tierney, “Exploring the BBRv2 Congestion Control Algorithm for use on Data Transfer Nodes,” Tech. eXchange paper, Dec. 2022.

[8] “BBRv2+: Towards balancing aggressiveness and fairness,” *Comput. Networks (article)*, 2022.

[9] P. Zhao et al., “Competing TCP Congestion Control Algorithms over a Satellite Internet Link,” *CCNC / measurement paper*, 2022.

[10] M. Drago, T. Zugno, M. Polese, et al., “Implementation of a Spatial Channel Model for ns-3,” *arXiv / ns-3 community*, 2020.

[11] “Network Simulator-3: a Review,” survey paper, 2021.

[12] “Throughput Analysis of Starlink Satellite Internet,” measurement study (KTH/DiVA), 2024.

[13] “A Stability-first Approach to Running TCP over Starlink,” *arXiv*, 2024 — analysis of routing and re-routing impact on TCP/constellations.

[14] “Exploring Proxying QUIC and HTTP/3 for Satellite Communication” (conference testbed + results), *Proceedings / workshop 2022*.

[15] “Performance Evaluation of Multipath TCP Video Streaming on LEO,” conference article / 2024.

[16] “A Comparative Evaluation of TCP Congestion Control Schemes over LEO Satellite Networks,” (ACM/IEEE) comparative evaluation, 2023–2024.

[17] “Intelligent congestion control of data transmission in low Earth orbit,” *Journal article*, 2024 — LEO congestion control strategies.

[18] “A Deep Reinforcement Learning Based TCP Congestion Control” — recent arXiv (2024–2025) proposals on RL-based TCP control.

[19] “Reinforcement Learning Based Congestion Control Technique,” *Springer/IEEE*, 2025 — RL for congestion control in modern networks.

[20] “A Review of TCP Congestion Control Using Artificial Intelligence in 4G and 5G Networks,” survey (2024–2025).

[21] “Evaluating TCP Congestion Control Algorithms with Traffic Control: TSEF (TCP-Splitting Emulator Framework),” 2023 journal/conference paper.

[22] “PCC, BBR, Cubic comparatives over satellite links” — measurement & emulation study, 2021.

[23] “QUIC performance and proxying approaches for satellite networks,” emulation/testbed paper, 2022.

[24] “Network Coding-Based Multi-Path Transmission for LEO Satellite Networks,” 2023–2024 research on multipath + coding approaches for LEO.

[25] “Mission-Critical Connectivity Over LEO Satellites — OneWeb measurements,” 2024 measurement study.

[26] “Exploring BBRv2: performance evaluations and improvements,” (Comsnets/Tech reports), 2022–2023.

[27] “Throughput and transport behavior over Starlink — multiple measurement studies (2023–2024),” (APNIC blog + peer studies).

[28] “Evaluating cross-layer TCP adaptation techniques for wireless networks,” journal/conference paper, 2020–2023 (ns-3 cross-layer implementations).

[29] “Delay-based Adaptive Congestion Control (DACC) — a modern delay-aware TCP variant,” 2022–2023 conference paper.

[30] “Measures and comparisons of QUIC, HTTP/3 and TCP over satellite and hybrid networks,” workshop paper (2022–2024) — QUIC vs TCP in satellite contexts.