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Improving the Resilience of SD-WAN Networks Operating over GEO Satellite Links using Adaptive Tunneling*

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Abstract

This paper summarizes an adaptive SD-WAN tunneling mechanism designed for underlays based on geostationary (GEO) satellite links. The proposed solution operates entirely in IP-based tunneling and combines adaptive segmentation, controlled packet duplication, and receiver-side duplicate elimination to mitigate typical transmission impairments of GEO SATCOM links. Experimental results obtained in a prepared testbed show that our mechanism fully eliminates packet loss and unmanaged duplication under extreme latency and loss conditions, transforming an unstable satellite underlay into a predictable and deterministic transport channel suitable for SD-WAN deployments.

Keywords: SD-WAN, tunneling mechanism, satellite networks, packet loss mitigation

Introduction

Deploying SD-WAN over severely resource-constrained underlays such as GEO satellite links exposes fundamental limitations of mechanisms originally engineered for terrestrial networks. Prior analysis of SD─WAN architectures and traffic control techniques demonstrated that under high latency and unstable link conditions, approaches that rely mainly on path selection and reactive retransmissions do not provide deterministic behavior or predictable transmission efficiency (Dudczyk et al., 2025). These limitations become especially pronounced in satellite environments, where persistent propagation delays and nonzero loss amplify uncontrolled reactions of higher-layer protocols.

Recent studies focusing specifically on SD-WAN and satellite integration confirm these observations. Experimental evaluations of SD-WAN over satellite underlays indicate that telemetry-driven path adaptation alone is insufficient to stabilize overlay performance when impairments are localized and event-driven, leading to oscillatory routing decisions and reduced goodput (Wang et al., 2024). Similarly, recent work on constellation-aware SD-WAN routing highlights that even advanced satellite-aware control mechanisms cannot fully compensate for transmission impairments at the IP packet level without additional in-tunnel processing (Sguotti et al., 2025).

Building on these findings, the authors previously introduced a tunnel-level SD-WAN mechanism explicitly targeting transmission errors and unintended packet duplication, operating entirely at the IP layer and remaining

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transparent to transport protocols. Its effectiveness was experimentally validated in Wi-Fi and LTE scenarios, where active shaping of tunnel behavior significantly improved reliability at the cost of bounded and predictable overhead. This paper extends that line of research by summarizing the evaluation of the same tunneling mechanism that works with GEO satellite links. The objective of our research was to assess whether adaptive tunnel-level processing, rather than control plane or path-level optimization, can stabilize IP transmission and improve SD-WAN predictability in an environment characterized by extreme delay and persistent degradation. The results provide insight into the applicability of tunnel-centric resilience mechanisms as a complementary building block for SD-WAN deployments over satellite networks.

Related Work

Recent research on SD-WAN has largely focused on its role in hybrid cloud and distributed data center environments. Wang et al. (2025) analyze SD-WAN as a hybrid edge–cloud networking solution that interconnects multisite software-defined data centers. Their study demonstrates the benefits of centralized control and virtualization for scalability and traffic management. However, the analysis assumes relatively stable terrestrial underlay networks and does not consider the extreme latency and loss conditions characteristic of satellite links, nor does it address tunnel-level robustness.

The use of satellite networks as SD-WAN underlays has gained increasing attention, particularly in the context of rapidly changing link conditions. Sguotti et al. (2025) investigate SD-WAN operation over LEO satellite constellations and show that frequent topology changes lead to significant delay variation and packet reordering. To mitigate these effects, they propose constellation-aware edge routing based on predictive path selection. Although effective in improving routing decisions, its approach treats tunnels as passive transport channels and does not address packet corruption, loss recovery, or duplication control within the tunnel.

From a broader nonterrestrial networking perspective, Baena et al. (2025) introduce the Space-O-RAN architecture, extending Open RAN principles to satellite constellations through hierarchical control and telemetry-driven orchestration. Their work highlights autonomy and resilience in satellite systems, but focuses on control-plane and radio-level mechanisms rather than IP-layer overlays or SD-WAN tunneling behavior.

Additional recent studies examine the limitations of IP-based services over satellite links with severe delays and resource constraints. The work presented in Hu (2024) shows that high propagation delays significantly reduce the effectiveness of reactive retransmission mechanisms, while (Wu, 2024) emphasizes the role of telemetry and prediction in maintaining service continuity in nonterrestrial networks. However, both studies focus on adaptations at the path or transport layer and do not consider active mitigation at the tunnel level of transmission impairments.

In general, existing research demonstrates that SD-WAN operation over satellite links requires awareness of latency dynamics and link variability. At the same time, current approaches mainly rely on routing adaptation and treat tunnels as transparent conduits. None of the analyzed works directly enhance tunnel robustness by mitigating localized corruption, controlling redundancy, or eliminating duplicate packets at the IP layer. This observation motivates the tunnel-level approach evaluated in this paper for GEO satellite environments.

Adaptive SD-WAN Tunneling for Lossy Underlay Networks

SD-WAN overlays are increasingly deployed on networks with lossy links, where bit errors, packet losses, and reliability enhancement mechanisms such as IP packet duplication significantly reduce effective throughput (Liu et al., 2024). This paper summarizes the proposed mechanism for automatic configuration and adaptive control of transmission channels (IP tunnels) between SD─WAN edge nodes, designed for overlay networks operating in resource-constrained environments, with particular emphasis on GEO satellite links.

This solution is based on the experience gained during the design and deployment of the ROSe system, an industrial platform for programmable overlay networks based on automatically established IP tunnels (Sergiel & Bednarczyk, 2024). Observations of tunnel behavior in high-latency and lossy networks directly motivated the development of a mechanism that operates exclusively at the tunnel level.

The core component of the proposed approach is adaptive segmentation of encapsulated datagrams within SD-WAN tunnels to increase the efficiency of data transmission over lossy links. Since bit errors occur as discrete point-like events in digital communication systems (Chitre et al., 2013), reducing segment size limits the impact of localized impairments on a small portion of transmitted data. The segmentation intensity level and its characteristics are dynamically adjusted based on the applied signalization between the SD-WAN edges, reacting on the quality of underlay links. Native IP fragmentation is deliberately avoided, as it lacks adaptive control and fragment-level recovery mechanisms (Zhou & Van Mieghem, 2004).

To further improve packets delivery probability under lossy links, the mechanism incorporates controlled packet duplication combined with receiver-side duplicate elimination based on extended sequence numbering. This approach increases robustness in highly variable transmission environments while preventing redundancy from propagating to upper-layer protocols (Liu et al., 2024). All processing is performed within the tunnel and remains fully transparent to transport layer protocols. Lightweight telemetry mechanisms complement the solution by enabling continuous observation of tunnel behavior and validation of packet loss and packet duplication rate.

Validation of the Adaptive Tunneling Mechanism

To verify the proposed mechanism, a testbed was prepared in a virtualized KVM-based environment, ensuring full control over network topology, links quality parameters, and SD-WAN edge node configuration, while ensuring high repeatability of experiments. The testbed consists of three network nodes, as shown in Figure 1.

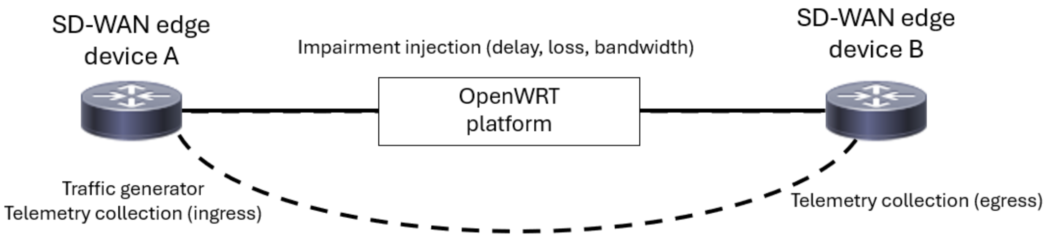

Fig 1. The SD-WAN testbed

Two nodes operate as SD-WAN edge devices representing the functionality of the tactical router (TRR–8M 5G/W platform) deployed in the Polish Armed Forces and act as tunnel endpoints that implement the proposed mechanism, including segmentation of adaptive datagrams, intentional redundancy, elimination of duplicate datagrams and telemetry. The third node, based on OpenWrt, serves as an intermediate element used to introduce controlled transmission impairments, latency, packet loss, and bandwidth limitations, emulating GEO satellite link characteristics.

Adaptive SD-WAN tunnel performance evaluation was based on selected ITU-defined transmission quality metrics (ITU-T, 2019), including Mean IPTD, IPLR and IPDR, complemented by throughput and goodput measurements. All experiments were carried out using TCP traffic generated by the iperf3 tool, which operates with the default Linux TCP congestion control algorithm (CUBIC). The traffic represented a continuous bulk data transfer, allowing the assessment of tunnel behavior under sustained load conditions typical for SD-WAN overlay deployments All data were collected in a repeatable manner using traffic generation tools and tunnel-level telemetry counters.

Our mechanisms validation was conducted using 10 predefined measurement scenarios representing the characteristics of the GEO satellite links, with throughput ranging from 0.3 to 6 Mb/s, latency from 550 to 800 ms, and packet loss rates between 1% and 10%. Scenario 1 assumes the use of the worst SATCOM links, while Scenario 10 assumes the use of the best links. The research was based on evaluating the quality of data transmission through SD-WAN tunnels when using our mechanisms and comparing the results obtained during tests of the network that used standard tunneling mechanisms. The test results are summarized in Figures 2 to 6.

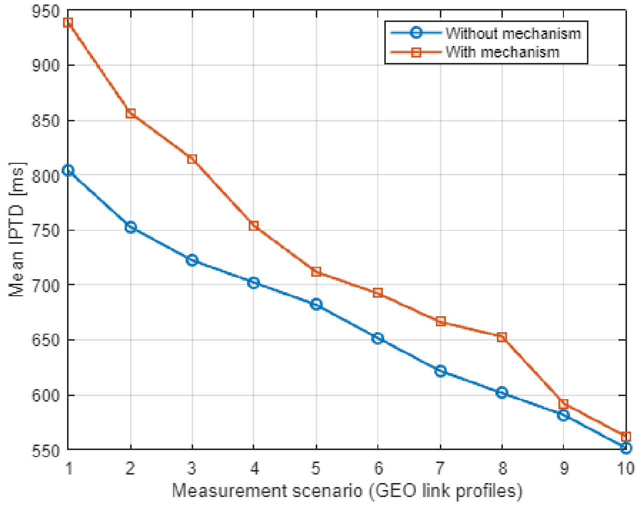

Fig. 2. Mean IP Packet Transfer Delay (Mean IPTD) measured for successive GEO satellite link scenarios.

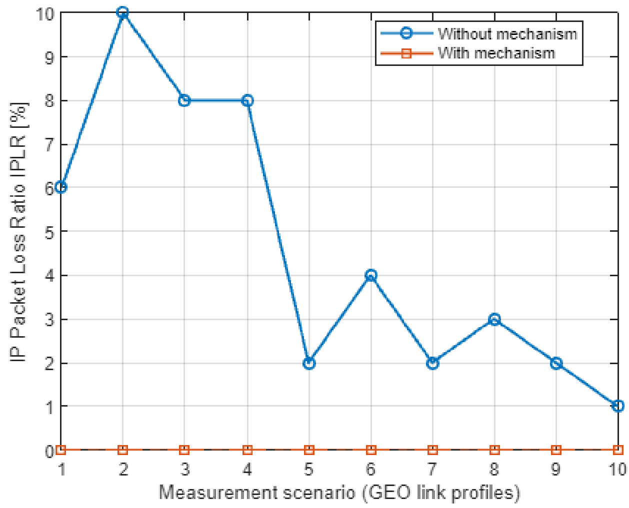

Fig. 3. IP Packet Loss Ratio (IPLR) measured for successive GEO satellite link scenarios.

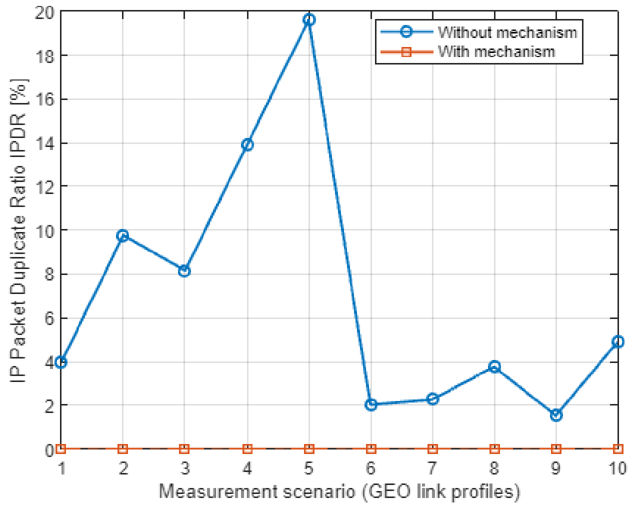

Fig. 4. IP Packet Duplicate Ratio (IPDR) observed for successive GEO satellite link scenarios.

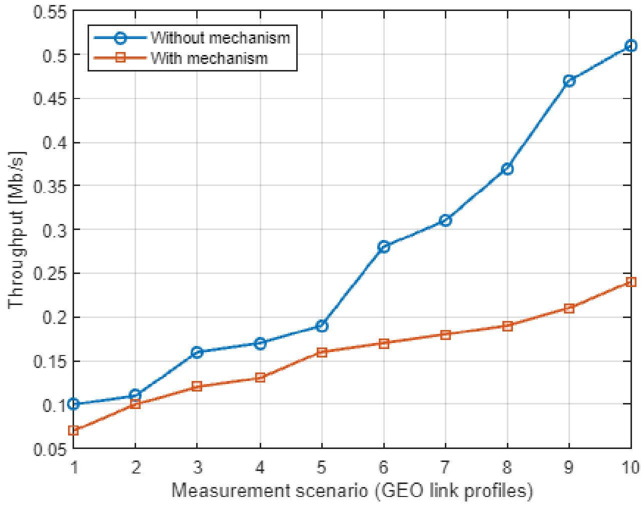

Fig. 5. Throughput for successive GEO satellite link scenarios.

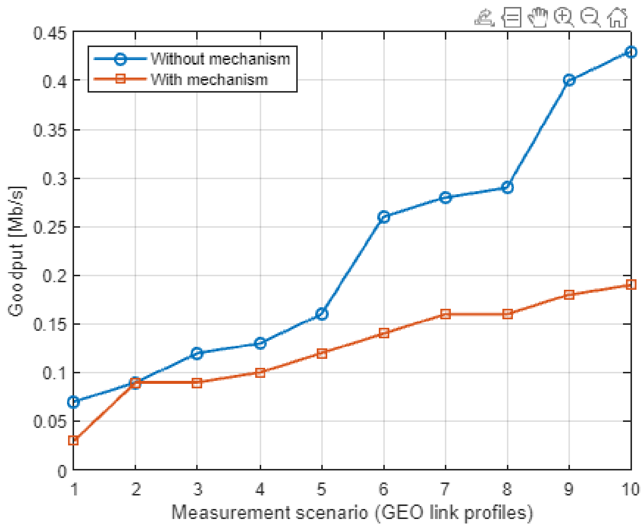

Fig. 6. Goodput for successive GEO satellite link scenarios.

The results presented in all the figures above, highlight significant differences in IP transmission behavior depending on the use of the adaptive tunneling. In the baseline scenario, very high propagation delays (550–800 ms) combined with packet loss lead to unstable transmission, reflected by variable IPLR values and the presence of packet duplication (Figure 3 and Figure 4), indicating nondeterministic behavior under GEO conditions. This observation is further supported by the mean IPTD results shown in Figure 2, where the packet transfer delay remains consistently high and only weakly affected by increasing nominal throughput, confirming the dominant influence of the GEO propagation delay. The results also show that, without adaptive tunneling, increasing nominal throughput does not produce proportional improvements in effective data delivery (Figure 5). Goodput remains limited despite the higher bandwidth (Figure 6), confirming the inability of standard mechanisms to cope with long-delay satellite links. When the adaptive tunneling mechanism is enabled, the transmission behavior becomes fully stabilized. Packet loss and duplication are eliminated at tunnel exit across all tested scenarios, which is particularly important for GEO links, where end-to-end retransmissions incur excessive delay penalties. This reliability improvement is achieved at the cost of a longer mean packet transfer delay, especially under the most constrained conditions. However, the delay increase remains predictable and decreases as link conditions improve, demonstrating adaptive rather than static overhead. In general, adaptive tunneling converts an unstable GEO underlay into a controlled and deterministic transport channel suitable for SD-WAN operation over high-latency satellite networks.

Conclusions

The experiments carried out confirm that the geostationary satellite–like (GEO) transmission conditions significantly challenge conventional SD-WAN operation due to extreme latency, limited bandwidth, and persistent packet loss. Measurements without the proposed adaptive tunneling mechanism reveal unstable transmission behavior, noticeable packet losses, and uncontrolled duplication.

The introduction of the proposed mechanism fundamentally alters this behavior. Across all tested GEO operating points, packet loss and unmanaged duplication are fully eliminated at the tunnel egress, yielding a stable and deterministic transmission model. Although adaptive fragmentation and intentional redundancy introduce additional delay and reduce raw throughput, these effects remain bounded and consistent, providing predictable performance under severely constrained conditions. In GEO environments, the achieved determinism and reliability prove more valuable than maximizing peak throughput.

Future research will focus on optimizing redundancy levels and segmentation strategies specifically for satellite links, where long round-trip times strongly influence feedback dynamics. Additional work is also required to integrate the mechanism with SD-WAN control planes to enable cross-tunnel coordination and policy-driven adaptation. Validation over real GEO satellite systems and hybrid GEO/terrestrial scenarios constitutes a natural next step toward fully functional deployment of our solutions.

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