

DEVELOPMENT AND INVESTIGATION OF AN SDN MODEL FOR MULTISERVICE TRAFFIC TRANSMISSION IN LEO SATELLITE COMMUNICATION NETWORKS

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ABSTRACT

This article focuses on the development and simulation-based study of a model for multiservice traffic transmission in low Earth orbit (LEO) satellite communication networks. The relevance of this work stems from the rapid expansion of LEO satellite constellations and the need to ensure guaranteed Quality of Service (QoS) for latency-sensitive applications. The objective is to construct a model that accounts for the dynamic topology of LEO networks – specifically, frequent handovers – and provides differentiated service for four traffic classes: real-time traffic with strict (RT1) and relaxed (RT2) requirements, interactive (INT) traffic, and best-effort (BE) traffic. The model is based on Software-Defined Networking (SDN) principles, employing priority-based scheduling disciplines and queue management mechanisms. The effectiveness of the proposed solutions was evaluated through discrete-event simulation using the ns-3 simulator, with subsequent data analysis performed in MATLAB. The results demonstrate that, compared to a standard FIFO (First-In, First-Out) scheme, the proposed approach significantly reduces both latency and packet loss for real-time traffic across various LEO network load levels.

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KEYWORDS: *low-Earth orbit (LEO) satellite network, multiservice traffic, QoS, SDN, handover, NS-3, FlowMonitor.*

Introduction

Modern multiservice network traffic – including voice, real-time video, streaming services, cloud applications, and IoT – requires communication networks to provide a guaranteed quality of service (QoS), even under uneven load distribution. Low Earth orbit (LEO) satellite systems [1] are considered a promising platform for global broadband coverage that can be integrated into 5G/6G infrastructure, primarily due to their significantly lower signal propagation latency compared to geostationary (GEO) satellites. For instance, the one-way signal propagation latency in LEO systems is on the order of a few milliseconds – an order of magnitude lower than the ~120 ms latency associated with GEO systems – making LEO networks well-suited for interactive services and cloud applications. However, this reduction in orbital altitude comes at the cost of a highly dynamic topology: each LEO satellite remains within a ground user's field of view for only a few minutes, after which the connection must be handed over to the next satellite. In LEO networks, handovers occur regularly (every few minutes) and affect numerous active sessions, placing stringent demands on the robustness of protocols, routing algorithms, and QoS mechanisms. While existing solutions for ensuring QoS in satellite networks and their integration with terrestrial infrastructure – such as the use of multi-channel queuing, traffic prioritization, and traffic duplication – have been extensively studied, the dynamic nature of LEO constellations necessitates new approaches [2].

One promising avenue for the development of satellite networks is the transition toward centralized software-defined networking (SDN) architectures. Software-defined networking enables the separation of the control plane from the data plane, allowing a central controller to maintain a global view of the network state, including its topology, link loads, and queue status. This enables the dynamic adaptation of routing and the allocation of resources in response to current conditions – a capability particularly crucial given the frequent handovers and variable environment characteristic of LEO (Low Earth Orbit) satellite networks. When combined with Differentiated Services (DiffServ) mechanisms, centralized SDN (Software-Defined Networking) control provides a flexible means of maintaining required Quality of Service (QoS) parameters for various traffic classes, even within a rapidly changing network topology. This paper proposes an SDN-based model for LEO networks that implements traffic classification and prioritization, QoS-aware dynamic routing, and handover management. The modeling methods, the architecture, and the core components of the model are described below, followed by the results of simulation experiments conducted to evaluate the effectiveness of these approaches [4].

Methods

Model architecture. The LEO network model under development comprises two planes: a data plane, which includes user nodes and forwarding nodes, and a control plane, represented by a centralized SDN controller. The model's topology consists of key nodes: a user equipment (UE) terminal, two low-Earth orbit (LEO) satellites (Sat1, Sat2), a ground gateway (GW), and an application server (Server). Each node in the data plane

functions as a switch that supports IP routing and multi-queue traffic processing. The SDN controller is connected to these nodes via a dedicated logical control channel and maintains global knowledge of the network state – such as satellite positions, link utilization, and queue status – enabling it to calculate optimal routes and allocate resources to maintain Quality of Service (QoS). Specifically, the controller updates routing rules during hand-over events by proactively rerouting traffic flows and adjusting priorities, thereby minimizing the impact of satellite switching on critical services. The logical topology of the network segment and the interactions between its components are illustrated in Figure 1.

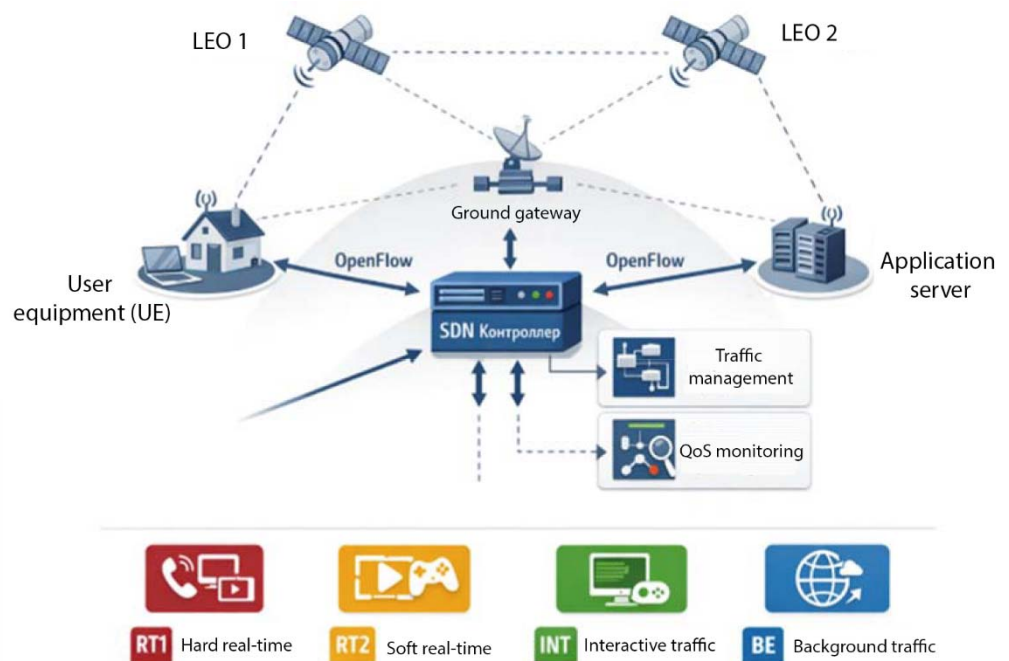


Fig. 1. Logical topology of a LEO network fragment with an SDN controller and four traffic classes (RT1, RT2, INT, BE)

QoS mechanisms. To ensure differentiated service, traffic is divided into four classes: RT1 – real-time services with strict latency requirements (e.g., voice); RT2 – real-time services with moderate requirements (e.g., video); INT – interactive services (web, transactions); and BE – background traffic with no guarantees ("best effort"). At satellite nodes and the gateway, a separate queue is allocated for each class (a multi-queue system). The RT1 class queue is serviced using strict priority with minimal latency (Low Latency Queue); the RT2 and INT queues are allocated a guaranteed share of bandwidth (using a method such as Weighted Round Robin); and the BE queue is serviced on a residual basis and equipped with an active buffer management mechanism (RED/WRED).

All queues are connected to a central scheduler that selects packets based on their assigned priorities and weights. This combination of disciplines aligns with the DiffServ model and aims to reduce latency and packet loss for sensitive traffic classes by limiting background traffic [3]. Such an approach has previously proven effective in both terrestrial and satellite networks for improving the quality of TCP traffic through the use of Differentiated Services. In our model, an SDN controller centrally configures the queue and scheduler parameters – such as priorities, weights, and buffer limits – at each node in accordance with the established QoS policy. This enables the dynamic reallocation of resources among traffic classes as load conditions change, while also preventing congestion in high-priority queues [5].

Simulation modeling. To evaluate the effectiveness of the proposed solutions, a software suite based on the ns-3 network simulator was developed. This discrete-event simulator supports a realistic model of IP protocols, routing, queuing, and traffic scheduling, as well as the FlowMonitor module for collecting QoS statistics. The model implements the aforementioned LEO network topology (UE – Sat1/Sat2 – GW – Server) with channel parameters approximating real-world conditions: the UE–Sat radio link accounts for propagation delay (tens of milliseconds) and limited bandwidth; the Sat–GW links reflect typical Earth-to-space satellite channel characteristics; and the GW–Server segment represents a high-speed, low-latency terrestrial connection. An SDN controller is incorporated as a distinct logical entity that manages traffic routing between nodes via control interfaces.

Traffic generation is handled by built-in ns-3 applications: for each traffic class (RT1, RT2, INT, BE), flows are created with specified intensities and packet distributions (using Poisson and self-similar ON/OFF processes to model different types of traffic). During the simulation, QoS metrics – such as average end-to-end delay, packet loss ratio, and average throughput – are recorded for each traffic flow using FlowMonitor. Data processing is performed using Python scripts (which parse the XML logs generated by FlowMonitor and aggregate statistics by class into CSV files) and the MATLAB software package; during the post-processing stage, average performance indicators for each scenario are calculated, and plots illustrating the distributions of delay, packet loss, and throughput are generated [6].

The sequence for configuring, building, and running the simulation model is shown in Figure 2. The procedure for generating FlowMonitor reports and preparing data for subsequent post-processing is illustrated in Figure 3.



```
wallys@wallys-VMware-Virtual-Platform:~/ns-3-dev$ ./ns3 run "scratch/leo_qos_sim --scenario=S1"
=== LEO QoS simulation START ===
Scenario: S1
Attribute 'RemoteAddress' is deprecated: Replaced by Remote in ns-3.44.
Attribute 'RemotePort' is deprecated: Replaced by Remote in ns-3.44.
Attribute 'RemoteAddress' is deprecated: Replaced by Remote in ns-3.44.
Attribute 'RemotePort' is deprecated: Replaced by Remote in ns-3.44.
Attribute 'RemoteAddress' is deprecated: Replaced by Remote in ns-3.44.
Attribute 'RemotePort' is deprecated: Replaced by Remote in ns-3.44.
Attribute 'RemoteAddress' is deprecated: Replaced by Remote in ns-3.44.
Attribute 'RemotePort' is deprecated: Replaced by Remote in ns-3.44.
CSV saved: results_S1.csv
FlowMonitor saved: leo_qos_flowmon_S1.xml
=== LEO QoS simulation END ===
```

Fig. 2. Compiling and running a simulation model in ns-3

```
wallys@wallys-Vmware-Virtual-Platform:~/ns-3-dev$ ls -lh leo_qos_flowmon_*.xml
-rw-rw-r-- 1 wallys wallys 6.7K Jan 25 17:51 leo_qos_flowmon_S1.xml
-rw-rw-r-- 1 wallys wallys 107K Jan 24 22:40 leo_qos_flowmon_S2.xml
-rw-rw-r-- 1 wallys wallys 821K Jan 24 22:41 leo_qos_flowmon_S3.xml
wallys@wallys-Vmware-Virtual-Platform:~/ns-3-dev$ ls -lh results_*.csv
-rw-rw-r-- 1 wallys wallys 455 Jan 25 17:51 results_S1.csv
-rw-rw-r-- 1 wallys wallys 711 Jan 24 22:40 results_S2.csv
-rw-rw-r-- 1 wallys wallys 1.2K Jan 24 22:41 results_S3.csv
```

Fig. 3. Generating FlowMonitor reports and preparing data for post-processing

Scenarios and experiments. A series of experiments was conducted across three distinct load scenarios. Scenario S1 represents a moderate network load, where the aggregate bitrate of all traffic flows does not exceed ~50% of the bottleneck link capacity, and handover events are infrequent. This mode simulates a relatively favorable environment for evaluating the baseline resource allocation among different traffic classes. Scenario S2 involves an increased load: the intensity of interactive and background traffic rises, with total channel utilization reaching 60-80% of its capacity. This scenario tests the model's ability to maintain an acceptable Quality of Service (QoS) for real-time (RT) traffic as the background load intensifies. Scenario S3 represents a stress condition: the network operates near saturation, the UE–Sat (user equipment-to-satellite) link is nearly 100% utilized, and handovers occur frequently.

This scenario reveals the stability limits of the proposed mechanism under congestion. Each experiment was run for a specified duration (tens of seconds of simulated time); for S3, multiple handover events were scheduled at intervals of several seconds, whereas for S1, no more than one handover occurred throughout the entire duration. Upon completion of each run, the average QoS metric values for each traffic class and scenario were recorded. Furthermore, to demonstrate the advantages of the proposed model, a comparison with a First-In-First-Out (FIFO) scheduling discipline was performed. Specifically, for the stress scenario S3, the network was simulated using a simple FIFO approach (a single, non-prioritized queue) to benchmark real-time latency performance against the proposed QoS scheme [7, 8].

Results

Simulation results confirm the effectiveness of the proposed differentiated service model for LEO networks. Under moderate load (S1), all traffic classes achieve low latency and negligible packet loss. Critical classes RT1 and RT2 exhibit minimal average latency (<20-30 ms), while interactive traffic (INT) shows slightly higher, yet still acceptable, latency; background traffic (BE) utilizes the remaining bandwidth without significantly impacting high-priority flows. Under increased load (S2), latency and packet loss rise for the INT and BE classes; however, real-time classes maintain an acceptable level of quality, with the average latency for RT1 remaining well below 100 ms and packet loss being virtually non-existent. In a stress scenario (S3) – where total traffic approaches the channel

capacity – the developed model demonstrates robust performance. Any degradation in Quality of Service (QoS) primarily affects the lowest-priority traffic: latency and packet loss rates for the BE class increase sharply, and the INT class also experiences some degradation, whereas the performance metrics for RT1/RT2 traffic remain within acceptable limits. Thus, during periods of congestion, the network automatically sacrifices the performance of background services to ensure that critical real-time flows continue to be handled at an acceptable level, consistent with the established prioritization policy. A comparison of average latency across traffic classes for scenarios S1-S3 is provided in Figure 4, while the estimated packet loss probability for each traffic class under the same scenarios is presented in Figure 5.

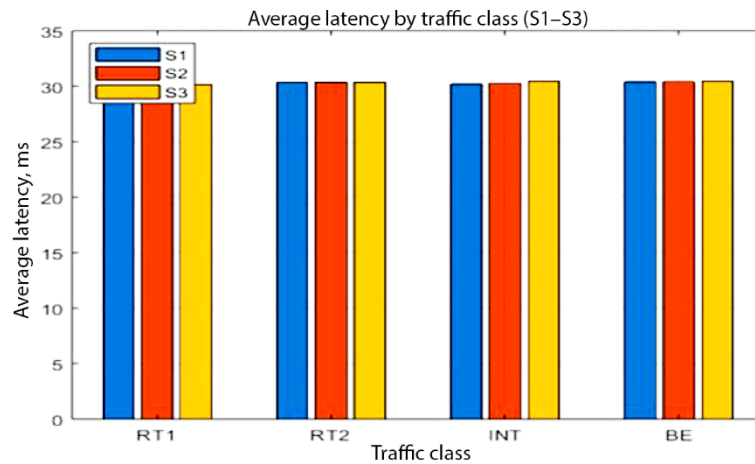


Fig. 4. Average latency by traffic class in scenarios S1-S3

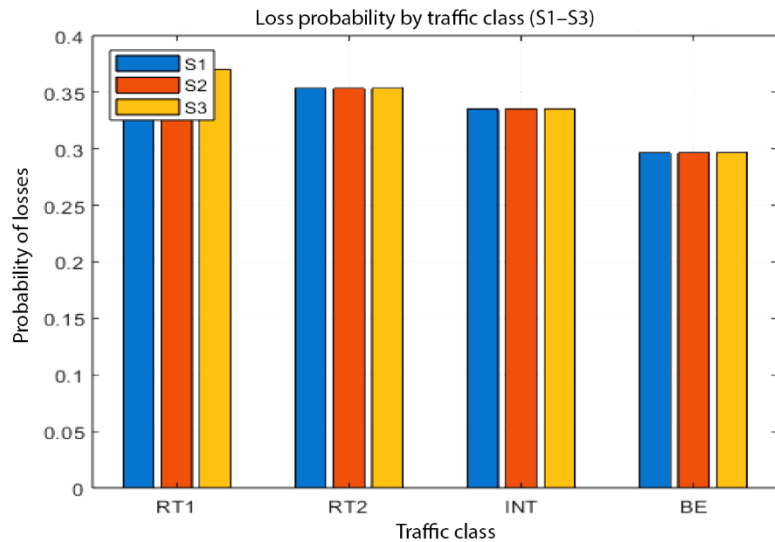


Fig. 5. Loss probability by traffic class in scenarios S1-S3

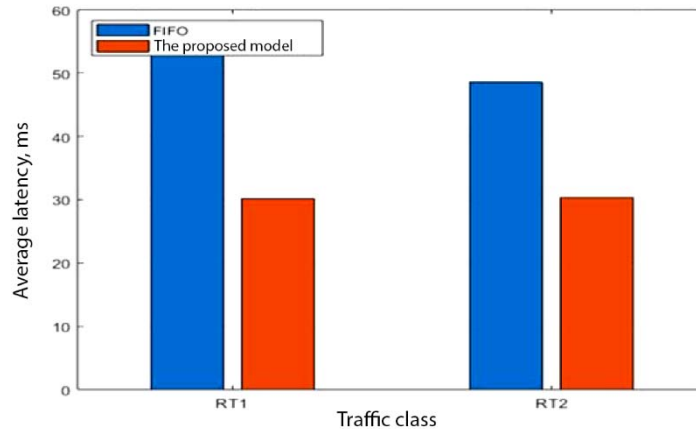


Fig. 6. Comparison of average latency (RT1/RT2) for FIFO and the proposed model (scenario S3)

A key result is the notable improvement in RT (real-time) traffic performance compared to a scenario without differentiation (FIFO). In comparative experiments for scenario S3, the average packet latency for the RT1 class in our model was significantly lower than under FIFO scheduling – with an improvement of tens of milliseconds – while the RT2 class also showed a reduction in latency, albeit less pronounced. This is clearly illustrated in Figure 6: transitioning from FIFO to the proposed model leads to a substantial decrease in latency for high-priority traffic, achieved through the implementation of a priority queue and a guaranteed share of resources. The packet loss probability for RT1/RT2 traffic is also lower with the QoS model than in the FIFO scheme, as the priority-based queuing mechanism prevents critical packets from being displaced from the buffer during periods of congestion. Furthermore, overall channel capacity is utilized more efficiently; high-priority traffic does not lead to resource underutilization, as any unused bandwidth is made available to lower-priority classes. Taken together, these data demonstrate that SDN-based management with differentiated queues enables the achievement of required QoS levels for critical services without the need for excessive bandwidth provisioning.

Additional experiments examined the impact of handovers on traffic parameters. During the switching of the serving satellite, brief spikes in latency were observed for the affected flows – primarily in the RT2 class, due to route reconfiguration – along with a reduction in throughput for some BE (best-effort) packets. However, thanks to proactive management at the controller level, these effects subsided quickly and did not result in any prolonged degradation of service quality. Time-series charts showed that, following a handover event, latency returns to a stable level within a few tens of milliseconds, confirming the validity of the implemented flow-reassignment mechanism. Thus, even with frequent handovers (scenario S3), the proposed architecture maintains the benefits of differentiated service.

Conclusion

This paper presents an SDN-oriented model for multiservice traffic transmission in low Earth orbit (LEO) satellite networks, featuring centralized routing and Quality of Service (QoS) management with traffic classified into four distinct categories. A simulation framework, developed using ns-3 and MATLAB, implements the proposed architecture and enables a series of experiments under reproducible load scenarios. The simulation study confirms that combining differentiated queuing mechanisms (LLQ, WRR/CBWFQ, and RED) with global SDN-based control effectively addresses QoS challenges in LEO networks characterized by dynamic topologies. Compared to a traditional FIFO scheme, this model offers a clear advantage for real-time traffic: as network load increases and frequent handovers occur, latency and packet loss for the RT1/RT2 traffic classes remain significantly lower than those for the INT/BE classes, while the total channel bandwidth is utilized more efficiently.

Congestion primarily affects background services, whereas critical traffic flows maintain an acceptable level of service quality—a result that aligns with prioritization objectives and validates the effectiveness of the chosen algorithms. Consequently, the proposed model provides an accurate representation of multiservice traffic transmission in LEO networks, ensuring the required QoS through a combination of differentiated packet processing and awareness of the satellite infrastructure's dynamics. These findings can inform the design of next-generation satellite systems integrated with terrestrial networks and serve as a foundation for further model development. Specifically, future work will focus on an in-depth investigation of multi-criteria QoS routing algorithms and adaptive resource management in LEO networks, building upon the proposed approach.

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