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Time-Sensitive Networking Mechanism Aided by Multilevel Cyclic Queues in LEO Satellite Networks

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Abstract: With the proliferation of low-Earth-orbit (LEO) satellites, existing satellite networks need to be enhanced to better handle time-sensitive flows (TSFs). However, the migration of time-sensitive network (TSN) technology to satellite networks is challenged by the large space–time range and limited on-board resources, particularly in providing differentiated quality-of-service guarantees for multilevel TSFs. To address this issue, we propose a multilevel queue-based TSN technique that uses latency requirements as an indicator for traffic scheduling. This approach improves the time-sensitive transmission capability of services with different requirements in LEO satellite networks. We conducted a simulation evaluation under a Walker constellation, and the results demonstrate that our proposed method could significantly improve network throughput, and reduce the packet loss ratio by 90% and the time-out ratio by 14.5%. Additionally, our proposed mechanism could accommodate more TSFs with acceptable latency requirements.

Keywords: LEO satellite networks; time-sensitive network; time-sensitive flow; quality of service; traffic scheduling

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1. Introduction

Low-Earth-orbit satellite networking technology has developed tremendously in recent years. Like the Starlink, Kuiper, and OneWeb constellations, they comparable provide network service capabilities to those of terrestrial networks [1]. However, due to the initial stage, existing LEO satellite networks still need to improve in terms of quality-of-service (QoS) guarantee and differentiated service capability [2]. How to offer time-sensitive services is still an unsolved problem in LEO satellite networks. However, the satellite network faces multifaceted challenges when performing time-sensitive services. On the one hand, the satellite networks' spatial scale range is large, and dynamic changes in the network topology lead to the unstable channel quality of intersatellite links (ISLs) [3–5]. On the other hand, onboard resources such as computing, storage, and bandwidth are constrained [6–8]. Therefore, applying existing TSN technology directly to satellite networks takes time.

Traditional terrestrial TSN technologies, including time-trigger Ethernet (TTE), and cyclic queue and forwarding (CQF), distribute time-sensitive traffic to other queues, away from regular traffic for forwarding. According to IEEE 802.1 Qch, this mechanism of split forwarding gives deterministic capability to traditional Ethernet switches, but introduces some new problems. On the one hand, the size limitation of the queue constrains the bandwidth of both regular and time-sensitive traffic [9]. Burst traffic may cause network congestion or bandwidth waste. On the other hand, the existing CQF mechanism cannot provide differentiated services for multilevel time-sensitive traffic. Due to high-performance Ethernet devices, these two shortcomings are not apparent in terrestrial networks [10]. However, this is not tolerable in satellite networks, since the propagation delay of satellite networks is in the tens of milliseconds, resulting in a considerable time limitation scale for time-sensitive services. Therefore, a conventional time-sensitive forwarding strategy leads to the time-out of many flows for high-level time-sensitive services.

Many studies have been conducted to improve the reliability and delay characteristics of LEO satellite networks. Some researchers focused on routing computation and produced some exciting work [11–13]. Furthermore, queuing delay is an essential factor affecting time-sensitive services, which enhances the routing problem into a trade-off between the hop number and queuing delay of paths [14,15]. Some researchers focused on the joint routing and queuing scheduling for time-sensitive services [9,16]. However, most existing models focus on latency optimization, but neglect the transmission capacity of time-sensitive flows (TSFs) with limited onboard resources. Due to the limited resources for LEO satellites, terrestrial-traffic scheduling schemes do not fully use onboard resources for TSFs.

The motivation of this paper is to facilitate LEO satellite networks in offering differentiated forwarding actions for varied time-sensitive services. As satellite resources are limited, service latency requirements exhibit a high degree of differentiation. However, current network architectures and algorithms do not furnish differential forwarding capabilities for time-sensitive services, which hinders ensuring the determinism of numerous high-priority services. Therefore, this paper addresses the existing gap in a network's forwarding capabilities and enhances the efficiency of LEO satellite networks in providing differentiated forwarding actions for diverse time-sensitive services. This paper seeks to provide different forwarding mechanisms for multilevel TSF to improve the network throughput. First, departing from the priority-based forwarding mechanism of Ethernet, we propose a delay–urgency forwarding mechanism that assigns delay–urgency levels to traffic in satellite networks. This mechanism queues all traffic flows of different levels into different delay–urgency queues. At the same time, delay–urgency priorities are precisely forwarded according to the delay–urgency level of the service. The delay–urgency status of the queues changes periodically, ensuring that time-sensitive traffic of different levels is provided with differentiated forwarding services. The results show that the proposed mechanism could improve the service capability and reduce packet loss. The main contributions of this paper are as follows:

- An LEO satellite network management architecture for time-sensitive service is proposed, and a software-defined network-based (SDN-based) management mechanism is provided.
- A time-sensitive networking technique aided by multilevel cyclic queues (TSN-MCQ) is studied. The traffic scheduling process of TSN-MCQ is investigated for LEO satellite networks.
- We built a testbed for a 64-satellite constellation performing packet-level simulations by OMNET++. The result analysis for the proposed and existing TSN techniques is presented for comparison, which validated that the proposed algorithm could reduce the packet loss and time-out ratio.

This paper is organized as follows. The related work is shown in Section 2. We introduce the LEO network architecture and management mechanism in Section 3. The TSN-MCQ mechanism is proposed in Section 4. Sections 5 and 6 present the evaluation results and conclusions, respectively.

2. Related Work

We investigated traffic-scheduling techniques for LEO satellite networks. Traffic-scheduling approaches can be categorized into two types: routing- and latency-based schemes.

2.1. Routing-Based Schemes

In order to improve the time-sensitive transmission capability of services with different requirements in LEO satellite networks, various approaches have been proposed for traffic scheduling. For instance, Huang et al. proposed an AI-aided intelligent multipath traffic-scheduling approach for the autonomous and efficient communication of LEO satellite networks [17]. This approach formulated the multipath traffic scheduling problem into a pheromone-incentivized Markov decision process to derive an intelligent scheduling strategy. Yao et al. proposed a learning-based approach for intradomain QoS routing [18] that uses a learning-based scheduling algorithm to reduce the packet loss rate. Tao et al. presented an SDN-based LEO satellite networking architecture and proposed a load-balancing-based traffic scheduling scheme that transforms scheduling problems into modified maximal-flow problems [19]. Here, a deep reinforcement-learning model is utilized to make global optimal scheduling decisions. Additionally, other studies investigated routing-based schemes [11–13]. These studies improved network resource utilization, but lacked guarantees for high-priority services.

2.2. Latency-Based Schemes

Besides routing schemes, several approaches have been proposed in recent studies for optimizing latency. Wang et al. [20] proposed a latency-optimal scheduling algorithm that could achieve near-global-optimum solutions with a limited number of iterations and a constrained search space. Vasisht et al. [21] introduced L2D2, a geographically distributed ground station design that employs low-cost commodity hardware to provide low latency and robust downlink. Another approach, by Wang et al. [22], is the TOMRA algorithm, which minimizes the latency associated with task offloading and processing in GEO-LEO networks. Additionally, Soret et al. [9] investigated network delay and the age of information (AoI) in a multihop satellite network, and developed a model for latency patterns in satellite networks. However, these studies did not consider the different time delay requirements of various time-sensitive services. Therefore, further research is necessary to explore how to differentiate traffic management for varying time delay requirements.

3. LEO Satellite Network Management Architecture

3.1. Network Architecture

For the management, operation, and maintenance of existing ultralarge-scale LEO satellite networks, we designed an LEO satellite network management architecture as shown in Figure 1. The overall network adopts a multilayered SDN architecture that divides the network into data and control planes. The data plane includes the terrestrial network and the LEO satellite network. Moreover, the LEO satellite network divides the satellites into multiple orbit planes (OPs) according to their orbits, and each plane has a satellite controller. ISL resources within each plane are stable due to the relatively stable link state within the LEO satellite orbit. A terrestrial controller mainly manages the terrestrial network, which manages the terminal users and gateway stations associated with satellite services, and interacts with the terrestrial control center. In addition, the terrestrial network includes the traditional IP bearer network whose network management is carried out independently. However, the IP bearer network and the satellite network can be accessed through and interconnected with satellite terminal users and gateway stations.

To manage satellite resources, a robust control plane is required to interact with heterogeneous network nodes while satisfying the network state changes introduced by topological variation [23]. The control plane shown in Figure 1 contained two segments: the satellite controller and the terrestrial controller. The satellite controller needs to build an onboard cloud platform to manage heterogeneous virtual network elements to realize the network element management of large-scale dynamic topology. The fault manager, virtual network manager, and topology manager related to computing resources operate and maintain the satellite network characteristics through the onboard cloud platform. In addition, the satellite controller includes two main feature types, i.e., communication and computing features. Communication features include a protocol stack manager, routing manager, and time-sensitive manager, which can ensure traditional Ethernet service forwarding while effectively handling time-sensitive services. These features collaboratively control the communication resources of large-scale satellites. Computing features involve the computing-related management services of the onboard elements, which can manage and assign onboard tasks, and process the onboard computing services. At the same time, various resources of the satellite need to be managed to provide essential support for the onboard cloud platform. The terrestrial control is similar to the traditional SDN controller, with the difference that it needs to manage the access control of the satellite and the offload management of traffic flows. The control and data planes are interconnected through various southbound interfaces (SBIs). Different controllers collaborate with each other to manage a large-scale LEO satellite network.

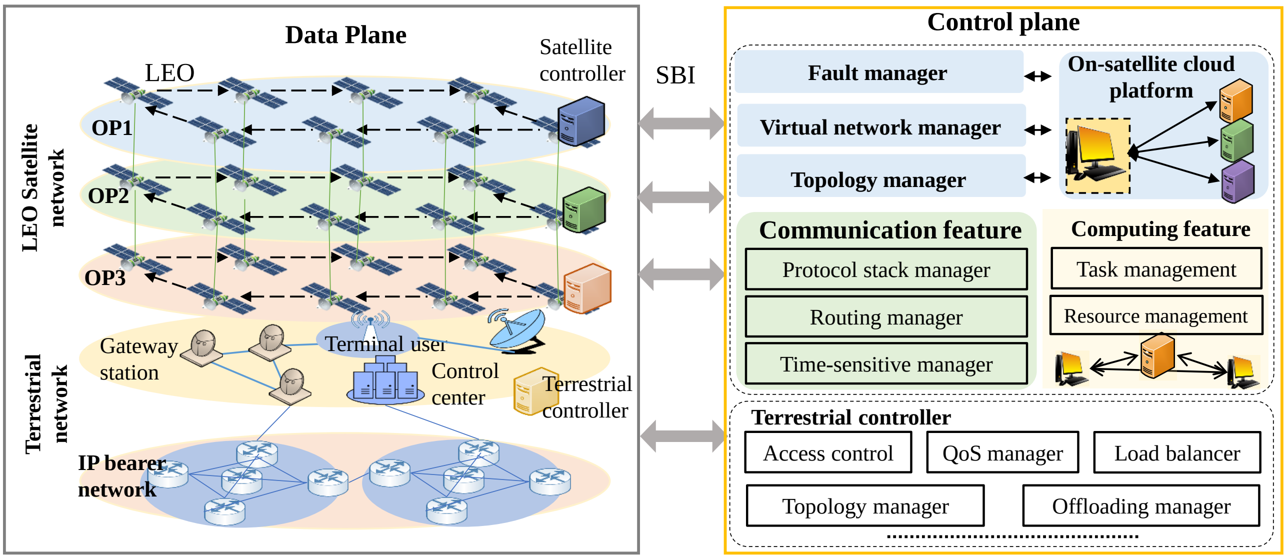


Figure 1. LEO satellite network management architecture.

3.2. System Model

An LEO satellite network model consists of N disjoint orbital planes. Each plane contains M satellites with an angle of $2\pi/M$. All of the planes are in inclined orbits with the same angle. ISLs are divided into two types, inter- and intraplane ISLs. Interplane ISLs operate in an unstable state with two planes moving, while intraplane ISLs maintain a steady state. In our system model, the satellites had four ISLs: two intraplane and two interplane ISLs.

We considered an LEO network undirected graph $\mathbb{G} = (\mathbb{V}, \mathbb{E})$, where $\mathbb{V}$ denotes the satellite nodes, and $\mathbb{E}$ is the ISLs. Then, we defined $e_{a,b} = [v_a, v_b] \in \mathbb{V}$ as the ISL connecting nodes v_a and v_b. The predictable and periodic trajectory of the satellite was considered in a temporal graph model (TGM) to improve the satellite routing performance. There are many studies on the topological description model using periodic characteristics in satellite networks [24,25]. The basic idea of a TGM is to divide the system period into discrete periods denoted by $\{t_1, t_2, ..., t_m\}$. Thus, all topological states in the system period can be represented as a set of static topology graphs; thus, $\{G_1, G_2, ...G_m\}$, with the subgraph at t_i denoted by $\{\mathbb{V}_i, \mathbb{E}_i\}$. The evolving topology comprises a series of static topological graphs that can be transferred periodically from one graph state to the following graph. The TGM accurately describes the topology at any point in the period. Therefore, we used this model to describe the satellite topology. In this model, we defaulted the routing policy for all traffic to the shortest path. If multiple shortest paths existed, a random path was selected.

For the CQF mechanism of LEO satellite networks, eight queues, Q_0 to Q_7, were adopted for each ISL or satellite–terrestrial link (STL). Moreover, Q_6 and Q_7 were used for the TSFs. The TSF is denoted by f^*, while regular traffic is denoted by f. The i-th TSF can be represented by

$$f_i^* = \{src, dst, ddl, period, band, \overline{path}, \overline{L_{prop}}\} \tag{1}$$

where src and dst are the source node and destination node, respectively; ddl is the deadline time for the service; $band$ and $\overline{path}$ represent the flow's average bandwidth requirement and path, respectively. The $\overline{path}$ includes many links denoted by $[v_i, v_j]$, namely, links between nodes v_i and v_j. The length of $\overline{path}$ is p. $period$ is the packet period of f^*. In this model, we defined each flow's degree of urgency denoted by U. U denotes the ratio of the flow deadline to the path length given by

$$U = (ddl)/p - L_{prop}, \tag{2}$$

where L_{prop} denotes the average propagation latency of ISLs. Due to the ISL's periodic mobility, the propagation delay of each ISL at a specific time can be predicted by ephemeris. However, multiple flows in a node could cause contention, since the time-sensitive bandwidth of a satellite is limited, which makes the flow run out of service time. Since satellite networks accommodate an increasing amount of IoT traffic and increasing number of industrial control scenarios, TSF is likely to become the leading service of LEO satellite networks.

4. Time-Sensitive Networking Technique Aided by Multilevel Cyclic Queues

In this section, we present a comprehensive analysis of the limitations of the current CQF technique. We then introduce a novel priority-based multilevel cyclic-queue mechanism aimed at delivering differentiated forwarding actions for a wide range of time-sensitive services. The proposed technique is centered on multiple queues that can cache TSFs with varying priorities, and a cycle priority mechanism that ensures all TSFs are forwarded within their respective deadlines.

4.1. Gating-Based TSN Scheduling Mechanism

We first introduce the CQF mechanism and its drawbacks in LEO networks. The CQF uses eight queues to meet different service requirements, as shown in Figure 2. Q_0 and Q_2 use best-effort forwarding to serve regular Ethernet traffic; Q_1 queues background traffic with the lowest priority. Q_5, Q_4, and Q_3 maintain the reservation bandwidth for non-time-sensitive traffic, including audio, video, and a bandwidth guaranteeing service called AVB traffic. Q_5 and Q_4 buffer delay-constrained audio and video traffic, respectively, and thus have higher scheduling priority than that of Q_3. Highest-priority queue Q_7 and second-highest-priority queue Q_6 are used for TSFs, and only these two queues require gating control mechanisms. As shown in Figure 2, CQF divides time into time slots, of which each allows for one queue to receive traffic (e.g., Q_6) and the other queue to only send traffic (e.g., Q_7). The next time slot opens another queue to accept traffic (Q_7), and queue Q_6 only sends traffic. Since different TSFs may have different sending periods, the incoming queue control requires a different gating logic. The output port of CQF switching is manageable, i.e., the user can manage the configuration of the priority level, inbound gating, outbound gating, queue measurement, and shaping logic.

The existing CQF mechanism forwards time-sensitive traffic separately from regular Ethernet traffic, and the SDN controller can manage the gating control list in real time in terrestrial networks. However, in the large-scale space of an LEO satellite network, it is difficult for the controller to real-time adjust TSFs in a short period. As a result, it is challenging to adapt CQF to burst traffic, and it causes packet loss. In addition, time-sensitive services possess different delay characteristics and have different demands on the forwarding mechanism. However, it is difficult for existing CQFs to differentiate delay demands to forwarding.

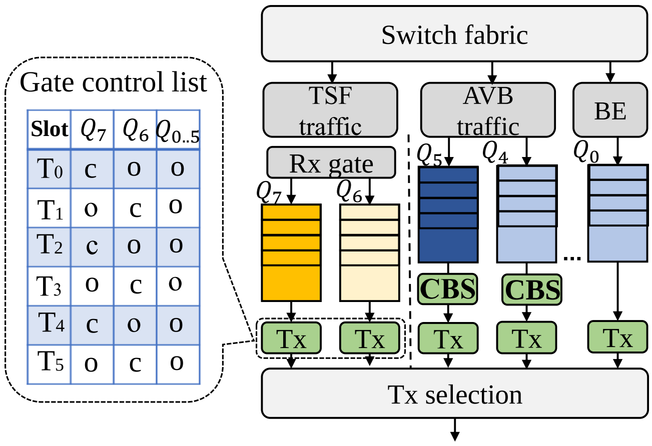


Figure 2. Priority-based queuing model for CQF (o: open, c: closed).

4.2. Priority-Based Multilevel Cyclic-Queue Mechanism

In order to enhance the forwarding capability of satellite nodes for TSF, we propose a multilevel cyclic-queue mechanism based on the CQF mechanism. As shown in Figure 3, this mechanism includes time-sensitive and non-time-sensitive queues. Non-time-sensitive queues use the same forwarding mechanism as that of the CQF. Time-sensitive queues are multiple, and we assumed that Q_4 to Q_7 were time-sensitive.Their priority is adjusted periodically. As shown in the figure, at time slot T_0, the priorities of Q_4 to Q_7 were 4, 5, 6, and 7, respectively. At the next time slot, the priorities of Q_4 to Q_7 changed into 5, 6, 7, and 4, respectively, i.e., the priority increased by 1. In contrast, the highest-priority queue became the lowest-priority queue (4 in the example). Therefore, the period of this priority change was four time slots. We assumed an ISL with n time-sensitive queues and m non-time-sensitive queues. The priority of each queue in time slot T can be expressed as follows:

$$P(q) = \begin{cases} q, & q \in [0, m-1] \\ (T+q)\%n + m, & q \in [m, m+n-1] \end{cases} \tag{3}$$

where q denotes the queue number. For LEO ISLs, the number of q can be dynamically configured according to the level of time-sensitive services. The entire orchestration of traffic flows is performed in the SDN controller of the LEO satellite network.

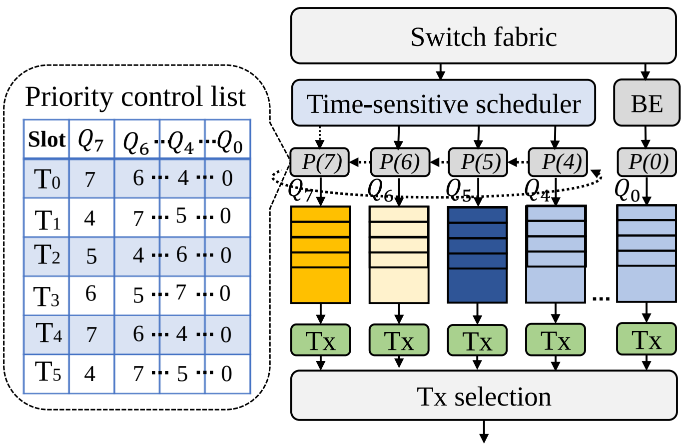


Figure 3. Multilevel cyclic-queue mechanism.

The core principle of the proposed technique is its utilization of a cycle priority mechanism that ensures that all TSFs are forwarded within the allotted time frame. This mechanism works by assigning a priority value to each TSF on the basis of its level of urgency. The cycle priority mechanism then ensures that TSFs are forwarded in the order of priority, with high-priority TSFs being forwarded before those with a lower priority. In summary, the proposed priority-based multilevel cyclic-queue mechanism represents a significant improvement over existing CQF techniques as it provides differentiated forwarding actions for diverse time-sensitive services. Multiqueue cache TSFs with different priorities use a cycle priority mechanism to guarantee that all TSFs are forwarded within their deadlines. This approach enhances system performance by dynamically allocating resources on the basis of the priority level of each service, thereby optimizing the handling of time-sensitive services.

In addition to priority scheduling, the inbound scheduling mechanism of services is entirely different from CQF. First, the SDN controller calculates the flow path and then the urgency degree on the basis of the deadline feature of the TSF flow. Traffic flows are mapped to different-priority queues of satellites according to the value of the urgency degree. As shown in Figure 4, if the value of urgency degree is low, meaning that the TSF should be forwarded immediately, the controller queues the flow to the queue corresponding to P(6). Then, it is guaranteed that the service is forwarded in the following two time slots. If the value of the urgency degree of the flow is high, the traffic flow can be inserted into the queue corresponding to P(4). The TSF can be guaranteed to be forwarded in four time slots. Therefore, the method can use different queuing mechanisms for different priority levels. Furthermore, the highest-priority queue, i.e., the queue corresponding to P(7), only sends a packet in a time slot and cannot queue the arrived packets. This gating mechanism can guarantee that, in each time slot, the traffic of the highest-priority queue can be completely forwarded. After completing the calculation, the SDN controller sends configuration messages to each satellite node to configure the look-up table for each satellite.

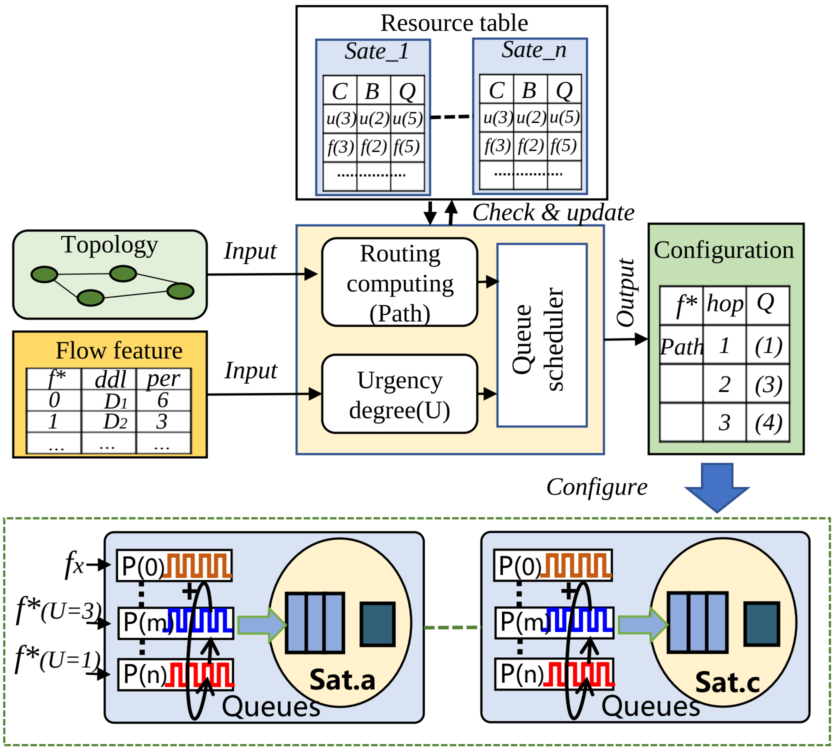


Figure 4. A control mechanism of TSN-MCQ.

In the traditional CQF mechanism, we cannot increase the time-sensitive forwarding capacity by increasing the size of the time-sensitive queue because the time-sensitive queue must guarantee that all packets are forwarded within that time slot. At the same time, it is difficult for the CQF to differentiate between services with different time-sensitive levels. Our proposed TSN-MCQ could remedy these shortcomings. We added multiple queues without increasing the latency of high-level TSFs. At the same time, we could perform differentiated forwarding for services with different time-sensitive levels and increase the forwarding capability for TSFs.

5. Performance Evaluation

We built a testbed for the LEO satellite network to validate the proposed TSN-MCQ mechanism. The testbed contained an LEO satellite network system where each satellite could randomly generate access user traffic. We controlled the bandwidth of the uplink traffic for each satellite, so that the load varied from 0.1 to 1. In addition, we compared this scheme with the CQF in IEEE 802.1 Qch [26] and the conventional Ethernet switch in terrestrial networks. The Ethernet switch handles time-sensitive traffic as regular traffic.

5.1. Simulation Setup

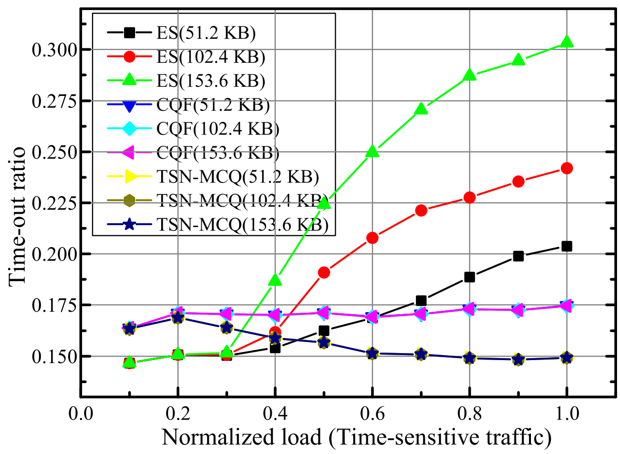
In the simulated scenario, we produced a Walker constellation of 64 satellites, each with an orbital inclination of 90 degrees. The constellation had eight orbits with eight satellites in each orbit. Each satellite had four intersatellite links, i.e., connecting two satellites in the same orbit and two satellites in adjacent orbits. The buffer size of each queue in the ISL was 16 KB. Considering the limited onboard resources, the scheduling time slot of TSN was set to 500 μs. The traffic flows were generated using the ON/OFF model, and adjusted by controlling the OFF period of the flows [27]. The packet size followed bimodal distribution, while the flow size followed Pareto distribution. The ratio of regular traffic to time-sensitive traffic was 3:1. We divided the time-sensitive traffic into four levels, and the deadline of TSFs was {2, 4, 6, 8} ms. This time-sensitivity requirement did not consider the propagation delay because the ISL's propagation delay was more significant than that of the terrestrial network.

5.2. Result Analysis

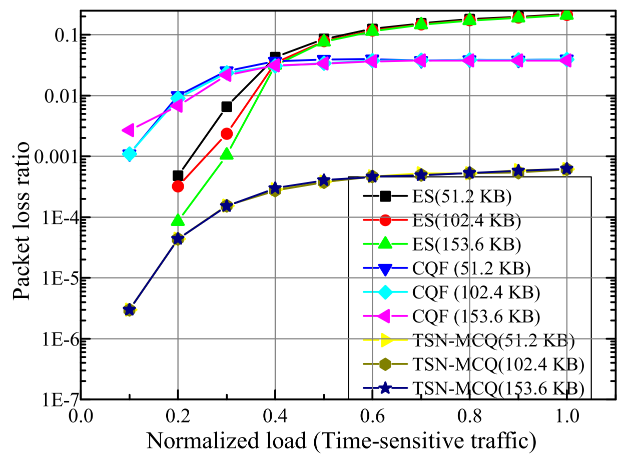
In order to observe the time-sensitive forwarding capability of different mechanisms, we calculated the service time-out ratio for different techniques. A service time-out occurs when the packet does not reach the destination node before the deadline. Figure 5a shows that TSN-MCQ could significantly reduce the time-out ratio. Moreover, as the load increased, the time-out ratio of time-sensitive traffic decreased. On the one hand, it benefited from the collaboration of multiple cyclic queues; on the other hand, removing the gating mechanism could improve the forwarding capacity of time-sensitive traffic. The figure shows that TSN-MCQ could reduce the time-out ratio by 14.5% compared to CQF in high-load cases.

Figure 5b shows the different mechanisms' packet loss ratio performance. TSN-MCQ maintained the lowest packet loss ratio with different loads. For TSFs, the packet loss ratio of TSN-MCQ was below 0.001, which was more than 90% lower than those of the Ethernet switch and CQF. Moreover, its performance remained relatively stable under different ISL buffer sizes. CQF could also reduce the packet loss ratio. However, its packet loss ratio performance was the worst under low-load cases due to the strict gating mechanism and limited time-sensitive forwarding capability.

We calculated the average latency performance of different mechanisms, including total and time-sensitive traffic, as shown in Figure 6. The latency in the figure does not include the propagation delay, because the propagation delay was large in the satellite network. Both CQF and TSN-MCQ could reduce the latency of time-sensitive traffic. However, CQF maintained the lowest average latency. Since TSN-MCQ had a lower packet loss ratio and forwarded more traffic at the same load case, its average latency was slightly higher than that of CQF.



(**a**)



(**b**)

Figure 5. Performance evaluation of different mechanisms under different load cases. (**a**) Time-out ratio with a cyclic period of 500 µs. (**b**) Packet loss with a cyclic period of 500 µs.

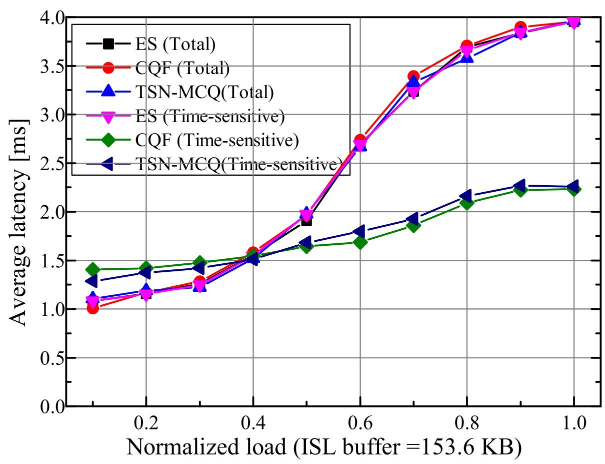


Figure 6. Average latency with a cyclic period of 500 µs and ISL buffer size of 153.6 KB.

We evaluated the throughput performance of CQF and TSN-MCQ, as shown in Figure 7. The throughput of time-sensitive traffic increased significantly with increasing load. This figure indicates that the TSN mechanism could increase the LEO satellite network's forwarding capacity for TSFs. At the same time, the overall throughput performance of TSN-MCQ increased significantly, which illustrates that the overall throughput of the network could be increased by using multiple cyclic queues in a LEO satellite network. The proposed mechanism could also guarantee that more than 99.9% of the time-sensitive flows were successfully scheduled, preventing the network throughput degradation caused by packet loss.

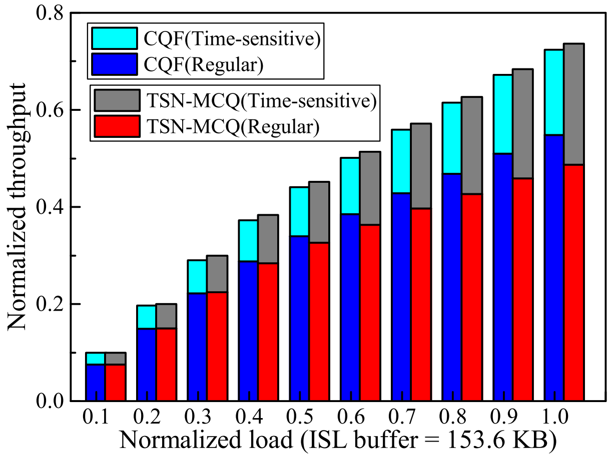


Figure 7. Normalized throughput with an cyclic period of 500 µs and a buffer size of 153.6 KB.

The results presented above show that the TSN-MCQ approach offered significant improvements in the time-out ratio and packet loss ratio performance of the network. However, the proposed algorithm demonstrated only a slight improvement in the average delay of the service. This marginal enhancement could be attributed to the relatively small proportion of queuing delay in the system, which was primarily caused by the large delay of the ISLs and the constrained queuing resources. The network size of the simulations used in this study was relatively small. If the number of satellites in the network increased to tens of thousands, the average hop count of the service significantly rose, leading to an increase in queuing delay. Furthermore, the method proposed in this paper requires additional queueing resources to support the distribution of multilevel services, which is a notable drawback of this approach. To address these limitations, future research will focus on optimizing the relationship between the number of queues and the overall network performance. Additionally, further investigation is required to determine the scalability of the TSN-MCQ approach for larger networks, including those with tens of thousands of satellites.

6. Conclusions

This paper presented an LEO satellite network management architecture for time-sensitive services. On the basis of the architecture, we proposed a time-sensitive network mechanism based on multilevel cyclic queueing (TSN-MCQ) for LEO satellite networks. This mechanism could differentiate the forwarding of different levels of time-sensitive services to maximize the protection of high-level TSFs. By eliminating the gating mechanism of CQF, TSN-MCQ reduced the time-out ratio of time-sensitive traffic in all load cases. Meanwhile, the proposed mechanism demonstrated an excellent packet loss ratio and throughput performance. The simulation results show that the proposed mechanism reduced the time-out ratio by 14.5% compared to CQF in high-load cases. Future research work will focus on the number and size of queues, and overall network performance to achieve better overall network performance with fewer queue resources.

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Conflicts of Interest: The authors declare no conflict of interest.

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