Congestion-Aware Semi-Lossless Transport in Datacenter networks

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Abstract. RDMA (Remote Direct Memory Access) technology is widely deployed in modern data centers due to its advantages of high throughput, low latency and low CPU overhead. However, the traditional lossy RDMA network has high retransmission overhead due to packet loss, while the lossless RDMA network based on Priority Flow Control (PFC) is easy to cause head-of-line blocking, congestion diffusion and even deadlock. In order to solve the above problems, this paper proposes a novel and practical Congestion-Aware Semi-Lossless Transport called CASL. At its heart, CASL distinguishes the congested flow and non-congested flow accurately, and performs selective packet loss on the congested flows to alleviate network congestion. Meanwhile, the non-congested flows are protected to avoid packet loss. The NS-3 simulation results show that CASL reduces the average Flow Completion Time (FCT) by up to 31.7% compared to the state-of-the-art lossless and lossy RDMA protocols.

Keywords: Semi-lossless Mechanism, Congestion Flow, Non-Congestion Flow, Congestion Control.

1 Introduction

In recent years, as the hub of modern computing, data centers carry more and more computing-intensive and storage-intensive applications. These applications put forward increasingly stringent low-latency and high-throughput transmission performance requirements for Data Center Networks (DCN). For example, cloud services and big data analysis require data centers to quickly process and transmit large-scale data sets to support real-time data insights and decision-making; in order to improve the speed and accuracy of model training, the large model training task needs to perform complex algorithms and quickly update model parameters during the model iteration process. In order to solve the limitations of traditional network communication, RDMA technology came into being. By allowing user-mode applications to directly read and write to remote memory, high throughput, ultra-low latency and low CPU overhead are achieved.

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However, current RDMA solutions face many challenges in dealing with network congestion, especially in terms of lossless and lossy transmission mechanisms. Packet loss is a common problem in lossy networks. Although the RDMA protocol has a retransmission mechanism to ensure the reliability of data, the retransmission operation caused by packet loss will bring significant overhead. In addition, frequent retransmissions also take up a lot of network bandwidth and computing resources, further exacerbating network congestion and forming a vicious circle. Lossless network relies on Priority-based Flow Control (PFC [1]) to achieve zero packet loss by suspending data transmission, but it brings problems such as queue head congestion, congestion diffusion and even deadlock.

This paper proposes a semi-lossless transmission mechanism called CASL. The core idea of this semi-lossless transmission mechanism is to finely distinguish the traffic in the network, identify the congestion flow that really causes congestion and the non-congestion flow that does not contribute to congestion, and adopt different processing strategies. Specifically, it is necessary to ensure that non-congested flows do not lose packets during transmission to ensure their low latency and high reliability transmission requirements; for the congestion flow, it is allowed to lose packets when necessary, thereby reducing the pressure of network congestion.

We conducted NS-3 simulations in different scenarios. The experimental results show that compared with the traditional lossless and lossy schemes, the CASL mechanism reduces the FCT by up to 13.5% and 31.7%, and increased the throughput by up to 7.3% and 15.6%, respectively, which effectively improves the network performance.

2 Motivation

As an efficient memory-to-memory data transmission technology, RDMA achieves high throughput and low latency network communication through zero-copy, kernel bypass and low CPU overhead. However, the existing RDMA congestion control mechanism has obvious limitations in the face of network congestion: it cannot accurately distinguish between congested flows and non-congested flows, resulting in non-congested flows being affected by packet loss or suspension during congestion, reducing transmission quality and wasting network resources [2-5].

In lossy RDMA networks, because the RDMA protocol (such as RoCEv2) relies on reliable transmission mechanisms (such as Go-Back-N or selective retransmission), once a packet loss is detected, the sender must retransmit the lost packet. This process increases end-to-end delay, lowers effective throughput, and ultimately exacerbates network congestion. In addition, non-congested flows may be affected by sharing physical links or switch buffers, resulting in a decline in transmission quality.

In lossless RDMA networks, PFC-based congestion management prevents packet loss by suspending data transmission, but this method also brings a series of new problems. First, Head-of-Line (HoL) blocking occurs when stalled high-priority flows obstruct low-priority traffic, degrading network efficiency. Second, localized congestion triggers pause frames that cascade network-wide, risking deadlocks from multi-node resource dependencies. These pause storms exacerbate latency and degrade non-congested flows through global bandwidth contention [8-12].

In order to further illustrate the above problems, we perform NS-3 simulation experiments under a typical dumbbell-shaped topology with a link rate of 100Gbps and a propagation delay of 1us.We choose DCQCN [6] and IRN [7] as the typical mechanisms for lossless and lossy networks, respectively.

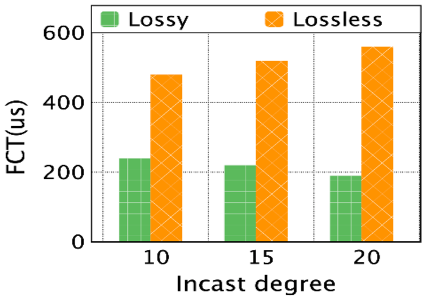

Fig. 1. FCT of victim flow

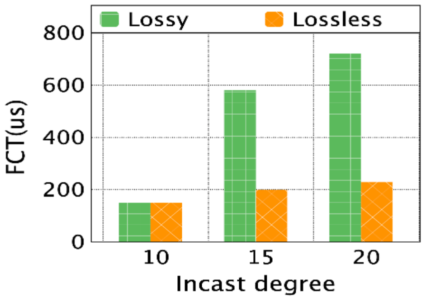

Fig. 2. FCT of burst flow

Figure 1 shows the flow completion time of victim flows in lossy and lossless networks at different levels of Incast.Due to Head-of-Line blocking and congestion diffusion, the performance of victim flows in lossless networks decreases significantly. In Figure 2, the burst stream has a large amount of packet loss in the lossy network, and has a high flow completion time. Based on the above experimental results, we consider distinguishing congestion flow and non-congestion flow and performing differential processing to improve network performance while combining the respective advantages of lossy and lossless networks.

3 Design

3.1 Design Overview

We propose a congestion-aware semi-lossless transmission mechanism, called CASL. The core mechanism of CASL is to accurately distinguish the congestion flow and non-congestion flow in the network through dynamic traffic identification technology, and implement differentiated control: take an active discarding strategy for the congestion flow to quickly release the network pressure, while the non-congestion flow realizes zero packet loss transmission through the priority guarantee mechanism. Figure 3 is an overview of CASL.

CASL is implemented on terminal hosts and switches, which is mainly composed of three parts: monitoring module, congestion isolation module and rate control module. The workflow is as follows: Firstly, the monitoring module collects key information such as switch queue length and Explicit Congestion Notification (ECN) tag in real time to classify the flows in the network. When the ECN label of a flow continues to accumulate and the queue length of the switch exceeds the preset threshold, the flow is determined to be a congested flow. On the contrary, if the ECN is less marked and the queue length is lower than the threshold, it is considered as a non-congested flow.

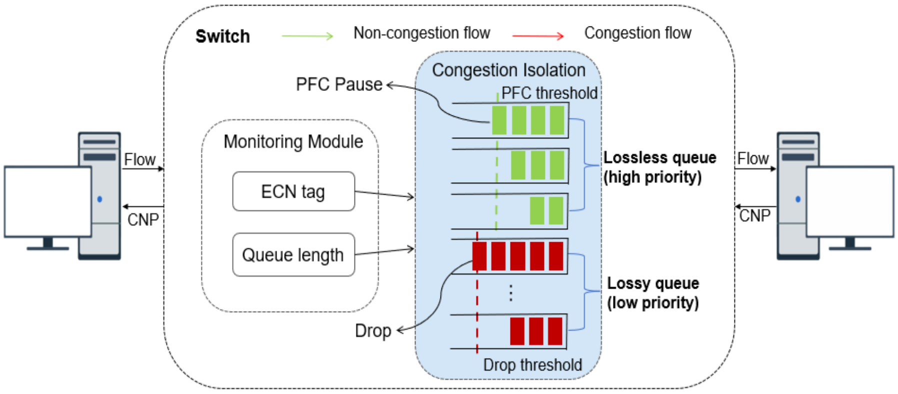

Fig. 3. CASL Overview

On the basis of the classification results, the switching opportunity queues the congestion into the lossy queue and adopts the selective packet loss strategy. For the non-congestion flow, the higher priority lossless queue is used for isolation protection to ensure that it is not affected by the congestion flow and achieve lossless transmission. Finally, the rate control module is responsible for the rate adjustment of the sending end, and adjusts the transmission rate according to the feedback information packet loss rate, Congestion Notification Packet (CNP), etc., to ensure that the network can achieve smooth recovery while alleviating congestion.

3.2 Design Details

Monitoring Module. Monitor the switch queue length and ECN tag information, maintain a status label for each flow and update it in real time according to the monitoring information. The specific decision logic is as follows: if the ECN tags of a flow continue to accumulate and cause the queue length to exceed the preset threshold Q_1, the flow is determined to be a congested flow; if the ECN tag is less and the queue length is lower than the preset threshold Q_1, it is judged as a non-congested flow. In this way, the accurate classification of different flows is realized. In the dynamic network environment, how to set the appropriate threshold to avoid misjudgment or misjudgment is still a difficult problem. CASL introduces an online learning algorithm to dynamically adjust Q_1, and combines historical traffic patterns to optimize the threshold in real time.
Congestion Isolation Module. The switch is configured with two priority queues, namely lossless queue and lossy queue, in which the priority of lossless queue is higher than that of lossy queue. When a flow is determined to be a congested flow, the switch queues the packets of the flow to the lossy queue, and uses an adaptive strategy based on historical data to dynamically adjust the packet loss ratio to avoid excessive packet loss. For non-congested flows, the switch puts its data packets into a lossless queue to ensure that it is not disturbed by the congested flow and achieves lossless transmission. This way of isolating different types of flows through priority queues effectively reduces the impact of congested flows on non-congested flows.
Rate Control Module. Based on the feedback information such as packet loss rate and CNP, the sender realizes the dynamic adjustment of the transmission rate. When the

packet loss rate of the congestion flow is detected to increase or the ECN flag is increased, this means that the network congestion is aggravated, and the sender reduces the transmission rate to avoid continuous congestion. On the contrary, if a flow returns to normal (ECN label reduction, queue length below the threshold Q_1), indicating that the flow is no longer a congested flow, it can be re-labeled as a non-congested flow to restore lossless transmission. Through this way of dynamically adjusting the sending rate, it can not only alleviate the network congestion, but also ensure that the network can recover smoothly after the congestion is alleviated.

4 Performance Evaluation and Analysis

In order to comprehensively evaluate the effectiveness and practical feasibility of the CASL semi-lossless mechanism, we use the NS-3 simulation platform for experiments. The typical 3×3 spine network topology is selected in the experiment, and each leaf switch is connected to 32 terminal hosts. The network traffic adopts a mixed traffic model, 80% of which is background traffic (short burst traffic) and 20% is elephant traffic (continuous high bandwidth). The network bandwidth of each link is set to 100Gbps, the round-trip time is 200ns, and the queue capacity is 200μs bandwidth capacity. We compare the CASL mechanism with the lossless network (RoCE with PFC) and the lossy network (IRN without PFC).

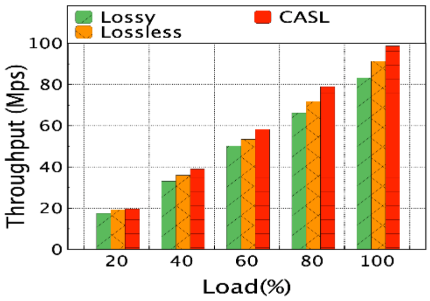

Fig. 4. Throughput

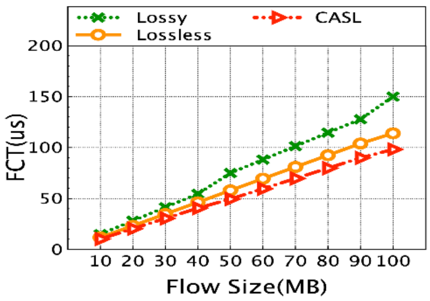

Fig. 5. Flow completion time

During the experiment, we change the packet generation rate to make the network load 20%, 40%, 60%, 80% and 100% respectively. As shown in Figure 4, the experimental results indicate that compared with lossless and lossy networks, the CASL mechanism improves throughput by up to 7.3% and 15.6% respectively. This is because the CASL mechanism can accurately distinguish between congested flows and non-congested flows, perform selective packet loss processing on congested flows, effectively alleviate network congestion, release network bandwidth, and thus improve overall throughput. In terms of Flow Completion Time, the CASL mechanism also performs well. Figure 5 shows the flow completion time of CASL compared with lossless network and lossy network under different flow sizes. CASL reduces FCT by up to 13.5% and 31.7% respectively. The isolation protection of CASL mechanism for non-congested flows avoids the unnecessary delay of non-congested flows due to network congestion, and ensures its low latency and high reliability transmission requirements.

In summary, CASL always shows excellent and stable performance, and its performance is always better than lossless networks and lossy networks. It dynamically distinguishes congested traffic and non-congested traffic according to the network state and applies differential processing, so that the congested flow loses packets in time to alleviate congestion. The non-congested flow is not affected by the congested flow, which reduces unnecessary packet loss and improves the overall network performance.

5 Conclusion

This paper introduces the congestion-aware semi-lossless transmission mechanism CASL in DCN. It achieves semi-lossless transmission through three ingenious designs: (i) Monitoring module, which can identify the traffic that really causes congestion; (ii) Isolation module, which can reduce the impact of congestion flow on non-congested flow; (iii) Rate control module, which can improve link utilization and reduce FCT. Extensive experiments and simulations show that the CASL mechanism reduces the average Flow Completion Time (FCT) by up to 31.7% compared with the traditional lossless and lossy schemes.

Acknowledgements

This work was supported in part by the National Natural Science Foundation of China under Grant 62472050 and Grant 62473146; in part by the Natural Science Foundation of Hunan Province under Grant 2025JJ20070 and Grant 2024JJ3017; and supported by the Science and Technology Project of Hunan Provincial Department of Water Resources under Grant XSKJ2024064-36.

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