Fast Deadlock-free Routing Reconfiguration for Arbitrary Datacenter Networks

July 7, 2016 9:22 AM

ABSTRACT

to be added.

1. INTRODUCTION

The growing demand for online services and cloud computing has driven today's datacenter networks (DCNs) to a large scale with hundreds of thousands of servers and thousands of switches. With this enormous number of network devices, network failure and device upgrade become the norm rather than the exception.

Network reconfiguration will be needed when there is failure or upgrade of links/nodes, new switch onboarding, load balancer reconfiguration, etc. To support this, the network's routing function, which includes all the paths packets can take in the network, are often needed to be reconfigured for the purpose of either maintaining the connectivity of the network or better serving the current network traffic.

On the other hand, as DCNs enter the 40/100Gbps era, RDMA is currently being deployed for achieving ultra-low latency, high throughput and low CPU overhead. To enable efficient operation, RDMA usually runs over a lossless L2 network. The using of a lossless L2 network introduces the deadlock problem into the DCNs, which refers to a standstill situation where a set of switch buffers form a permanent cyclic waiting dependency and no packet can get drained at any of these buffers. Once deadlock occurs, no packet can be delivered through a part of or even the whole DCN.

Under static circumstances (i.e., when both of the network topology and the routing function are fixed), deadlock can be avoided by using a routing function that contains no cycle in the corresponding buffer dependency graph.

Under dynamic circumstances, however, deadlock may occur during reconfiguration process when transitioning from an old deadlock-free routing function R_s to a new deadlock-free routing function R_t. This is because during the routing reconfiguration process, due to the asynchronous updates of switch rules, any paths included in $R_s \cup R_t$ may take effect at the same time. When $R_s \cup R_t$ contains a cycle in the corresponding buffer dependency graph, deadlock may occur if the routing reconfiguration process is not well planed. We refer to this kind of deadlock as *reconfiguration-induced deadlock*.

Reconfiguration-induced deadlock can be avoided by imposing some constraints on the ordering of configuration actions during the reconfiguration process. For example, deadlock-free can be guaranteed by removing all the paths included in R_s first before adding any new path included in R_t. Alternatively, we can remove some paths in R_s to reduce the routing function into $R_s \cap R_t$ at first, and then add the new paths included in R_t to finish the reconfiguration procss.

The speed of routing reconfiguration is important as it determines the response time to a network failure. Although both of the above approaches can ensure deadlock-free, they will lead to a slow routing reconfiguration process as multiple staitc intermediate stages are needed.

In this paper, we develop an approach for achieving fast deadlock-free routing reconfiguration. It is based on two observations: 1) there exist multiple valid orderings that is deadlock-free; and 2) choosing an ordering with minimum order dependencies among configuration actions can lead to fast reconfiguration. Our approach is general and can be applied to arbitrary DCNs, including Fat-tree, VL2, HyperX, Jellyfish, etc.

2. BACKGROUND AND MOTIVATION

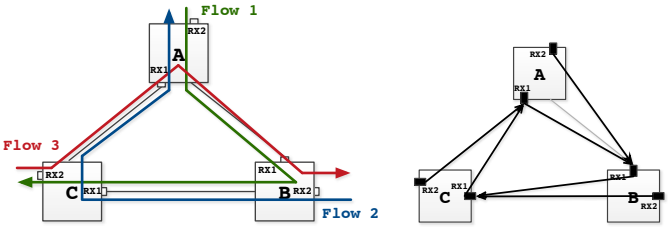
2.1 PFC deadlock problem

Priority-based Flow Control (PFC): The deployment of RDMA over Ethernet requires PFC to provide a lossless L2 network. PFC is a mechanism for ensuring zero packet loss under congestion in data center bridging (DCB) networks. PFC allows an overwhelmed network device to send a PAUSE frame to its immediate upstream device, which halts the transmission of the sender for a specified period of time.

PFC works in a per ingress queue fashion. When PFC is enabled, the switch will maintain a counter to track the virtual queue length of each ingress queue. Once the queue length exceeds a pre-configured PFC threshold, a PAUSE frame will be generated.

PFC deadlock problem: The using of PFC can cause deadlock problem. In Fig. 1, we use a simple example to show how deadlock can be created when there is a cyclic buffer dependency among a set of switch buffers.

As shown in Fig. 1(a), three flows are runing over three



(a) Topology and flows. (b) Buffer dependency graph.

Figure 1: Flows 1, 2 and 3 forms a cycle in the buffer dependency graph that can create a routing deadlock. In both figures, RX represents an ingress switch queue.

switches A, B and C. Flow 1 starts at a host (not shown) attached to A, passes through B, and ends at a host attached to C. Flow 2 and flow 3 are two symmetric flows of flow 1. Buffer dependencies among active ingress queues are drawn in Fig. 1(b). The path flow 1 takes introduces two dependency links, one from RX2 of A to RX1 of B, the other from RX1 of B to RX1 of C. Similarly, paths taken by flow 2 and flow 3 introduce the other four dependency links in Fig. 1(b).

As we can find in Fig. 1(b), the paths taken by the 3 flows introduce a cyclic buffer dependency among switches A, B and C. When network congestion occurs, it is possible that all the three RX1 queues become full of the packets destined for the next-hop switch and trigger PFC PAUSE simultaneously. Then a PFC deadlock is created as links A-B, B-C and C-A will be permanently paused and no packet in the three RX1 queues can ever get drained.

PFC deadlock problem can be avoided by leveraging a routing function that introduces no cycle in the buffer dependency graph. However, this approach cannot eliminate the cyclic buffer dependency during routing reconfiguration, as we are going to show in the next.

2.2 Reconfiguration-induced deadlock

In this part, we use an example to show 1) cyclic buffer dependency can be generated if the routing reconfiguration is not well planed; 2) a bad deadlock-free reconfiguration plan will lead to a slow reconfiguration process.

As shown in Fig. 2(a), in this example we consider a 4-node network **N**. Fig. 2(b)-(c),(e)-(f) are four spanning trees **T1**-**T4** which specify the routing paths that can be used in **N**. For example, path p1 is a legal routing path specified in T1.

Let $\mathbf{R}_i$ be the set of paths specified in tree **Ti**. Let $\mathbf{R}_s = \mathbf{R}_1 \cup \mathbf{R}_2$, and $\mathbf{R}_t = \mathbf{R}_3 \cup \mathbf{R}_4$. It is easy to check both $\mathbf{R}_s$ and $\mathbf{R}_t$ are deadlock-free routing functions. Initially, $\mathbf{R}_s$ are used as the routing function of **N**. Due to the failure of link S2-S3, switch S3 becomes unreachable. To maintain the connectivity of **N**, we can perform a routing reconfiguration to transition from $\mathbf{R}_s$ to $\mathbf{R}_t$.

During the reconfiguration process, if path p2 in **T3** and path p3 in **T4** are added to the routing function before path p1 in **T1** is removed, a cyclic buffer dependency will be generated. This may cause a PFC deadlock as we explained in Sec. 2.1.

In Fig. 2(d), we present three possible deadlock-free reconfiguration schmes. The first scheme is to remove all the paths in **T1** and **T2** before adding any new paths in **T3** and **T4**. This scheme will lead to a slow reconfiguration process as all the operations of adding new paths are delayed by the operations of removing old paths.

The second scheme only requires path p1 is removed before paths p2 and p3 are added. All the other paths not mentioned can be updated freely without any order constraint. Hence the speed of routing reconfiguration can be improved. The third scheme is an optimized reconfiguration scheme in terms of imposing minimum order constraints on the update actions. The intuition here is that as long as paths p1, p2 and p3 do not take effect at the same, deadlock-free can be well guaranteed.

While for this example it may seem easy to find a deadlock-free reconfiguration scheme that requires minimum order constraints, in general it is difficult as there are combinatorial such schemes to be checked.

2.3 Measurement of Rule Update Time

In this part, we demonstrate that adding order constraints to the update of switch rules will significantly prolong the reconfiguration process.

3. SOLUTION

In this part, we present our preliminary solution for achieving fast deadlock-free network update.

Enumerating all the possible orders of path updates would be computationally impossible as there are combinatorial such options. Hence we seek to find an efficient heuristic solution for minimizing the number of order constraints on update actions.

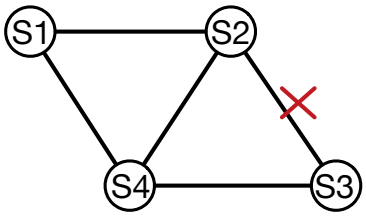
The intuition behind our solution is that *For each possible cycle in the buffer dependency graph, as long as we ensure that one old dependency link is removed before one new dependency link is added, the reconfiguration process is deadlock-free.*

The idea of our heuristic solution is as follows: First, for each cycle in the buffer dependency graph, we enumerate all the sets of update actions that can exactly add or remove one dependency link from the graph. Then we pick up two minimum action sets A and B, where A can remove one dependency link for a given cycle while B can add an dependency link for the same cycle. The deadlock-free reconfiguration scheme our solution produces will ensure that A is finished before B starts to be configured.

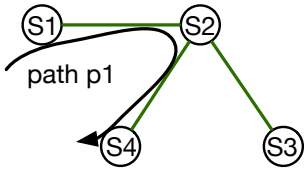
4. EVALUATION

to be added. In this part, we evaluate the performance of our solution via simulations.

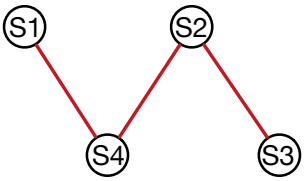
Topology: 4-level Fat-tree, HyperX, Jellyfish, etc.



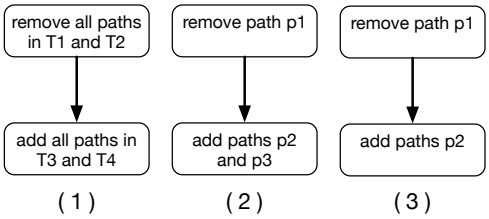
(a) A 4-node network **N**.



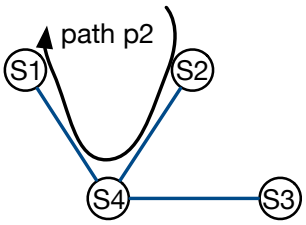
(b) Routing spanning tree **T1**.



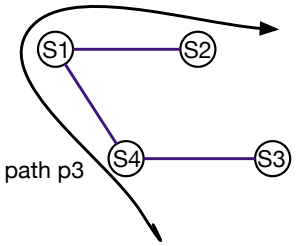
(c) Routing spanning tree **T2**.



(d) Three deadlock-free reconfiguration schmes.



(e) Routing spanning tree **T3**.



(f) Routing spanning tree **T4**.

Figure 2: Reconfiguration-induced deadlock case.

Model of switch rule update: parallel update, sequential update, etc. We also need to model the delay of control messages in our simulator.

5. RELATED WORKS

to be added.

6. REFERENCES

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