Load balancing challenges in AI fabric

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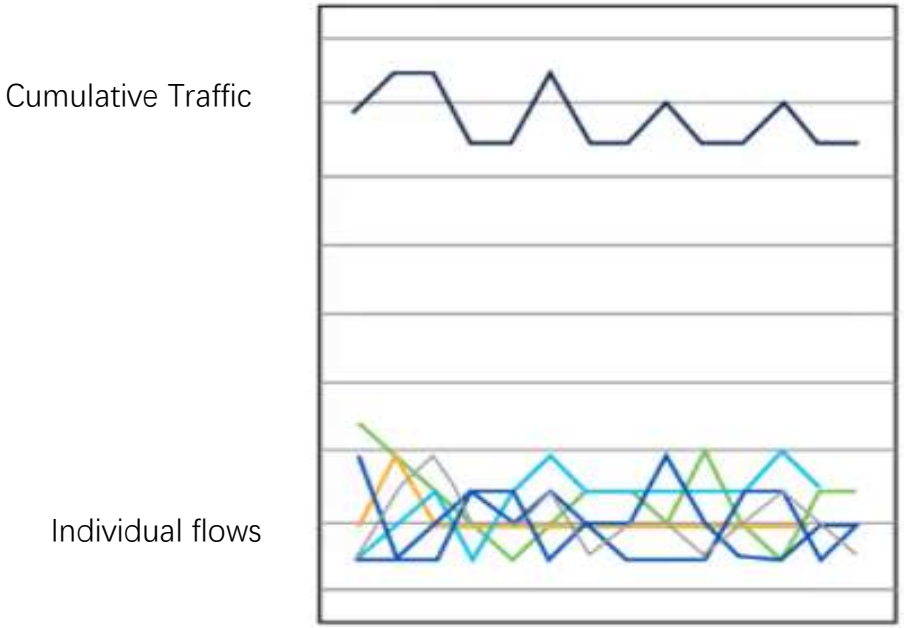
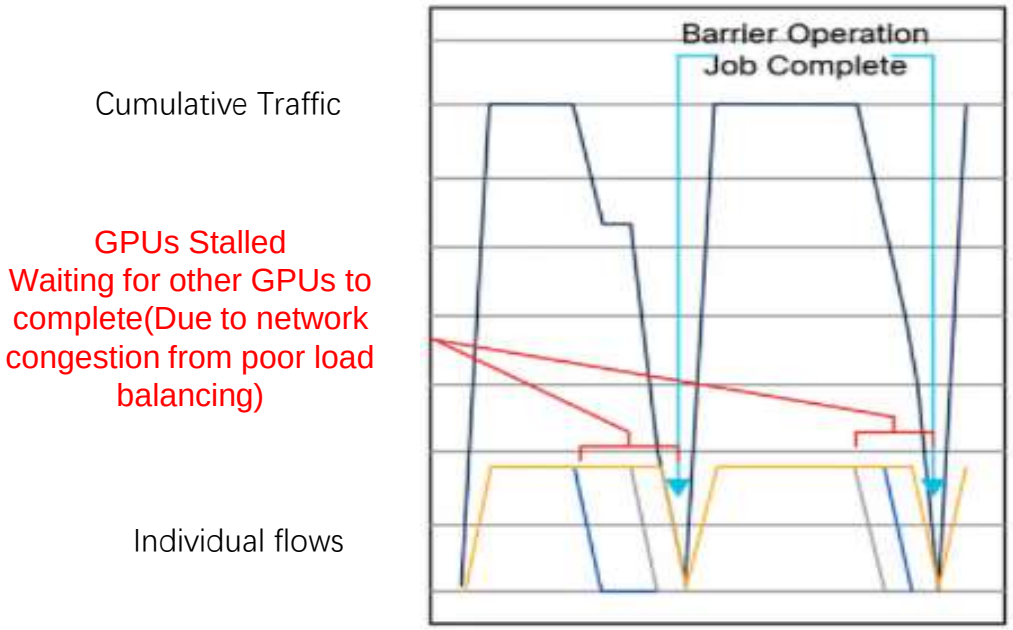
AI Traffic pattern challenge

Traditional DC Traffic pattern



- Many asynchronous small BW flows.
- Chaotic pattern averages out to consistent load.

AI (All-to-all Collective) Traffic Pattern



- Few synchronous high BW flows.
- Synchronization magnifies long tail latency and bad load balancing decisions.

Data from Cisco's public whitepaper.

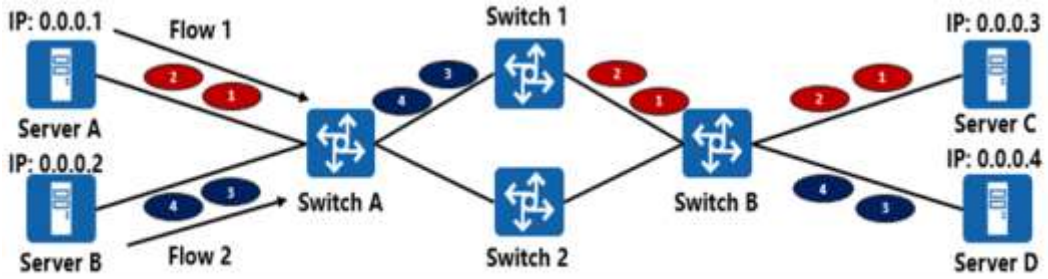
Traditional flow-based ECMP perform poorly

- **Flow-based load balancing means switches distribute packets to multiple paths in the flow granularity, and Packets within a flow take the same forwarding path.**

Limitations

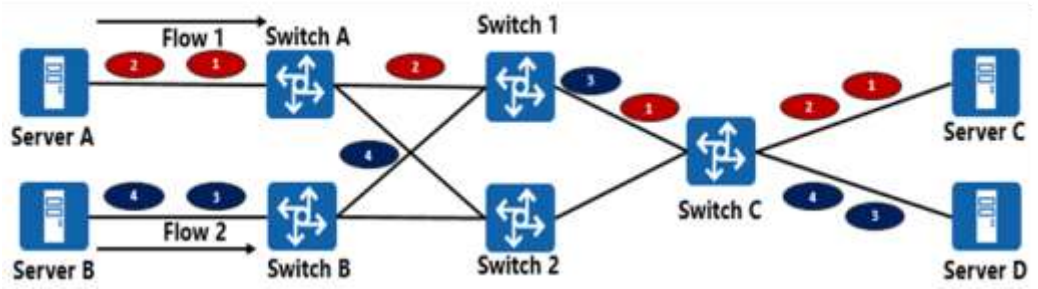
Coarse granularity:

The flow-based LB's granularity is coarse, It does not take into account the size of different flows and hard to balance the few high bandwidth flows well in AI fabric.



Local collision:

5 tuple based hash algorithm may output the same hash-key for different flows, resulting multiple flows to be forwarded to the same path causing local collision.

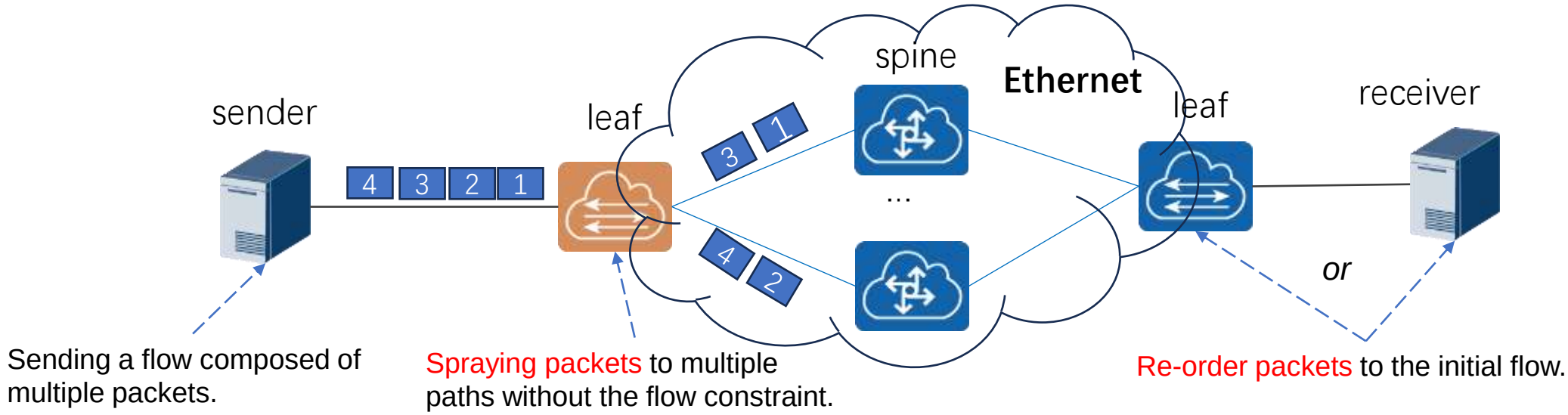


Downstream collision:

The local decision-making mechanism lacks of global view of the fabric (e.g. downstream nodes status) which may select multiple flows forwarded to the same downstream path, causing downstream collision.

Packet-based LB become the trend for AI fabric (1)

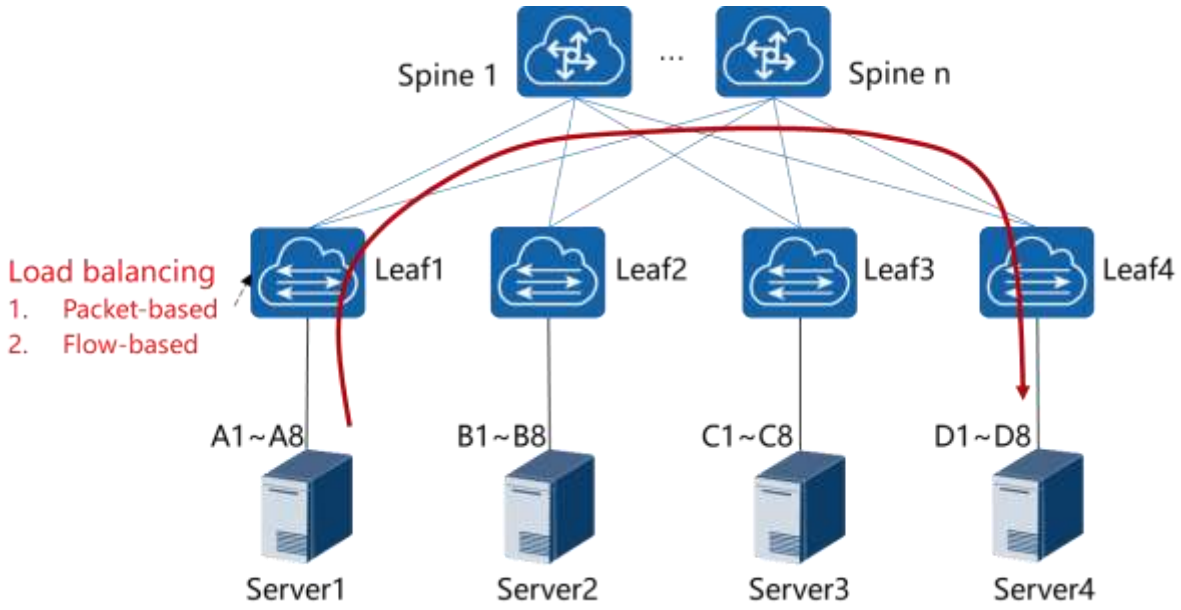
- **Packet-based load balancing means switches distribute each packet to multiple paths independently, making the load on the network more balanced than flow-based.**
- **There are several routes supporting packet-based LB:**
  - Cell-based in dedicated network or ethernet-based: Standardization → ✓ **Ethernet-based.**
  - NIC-driven or Network-driven: Applicable to different scenarios. → Focus on **network-driven** solution in this document.
- **Basic Architecture of network-driven packet-based LB in ethernet:**



Packet-based LB become the trend for AI fabric (2)

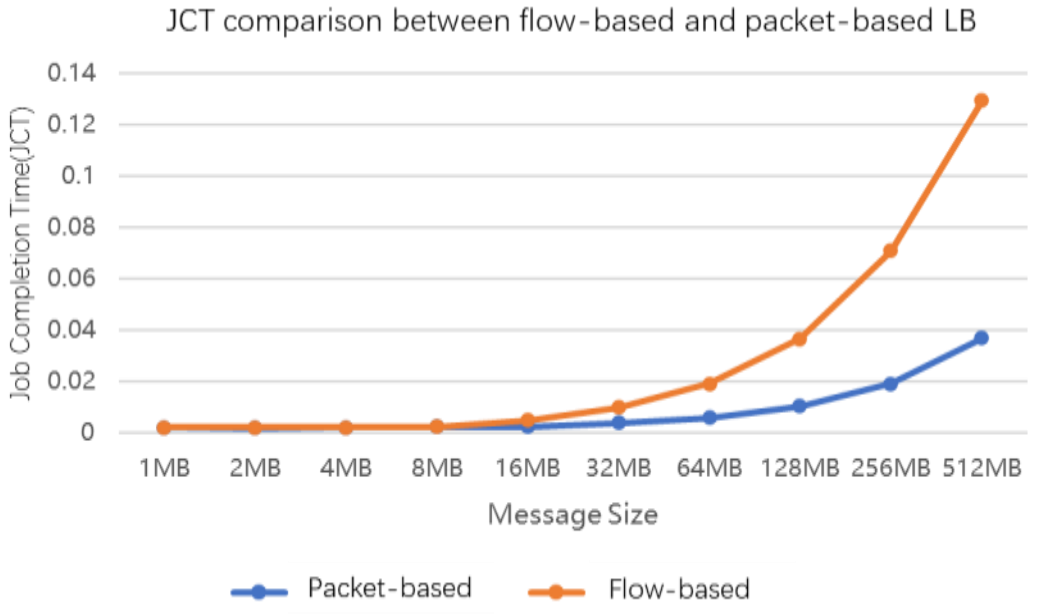
- **We conduct an experiment to evaluate the performance of flow-based and packet based LB.**

Experiment settings



- The topology is the classic two-layer clos network, 4 servers, 8GPU with 8 NICs in a server.
- There are 8 jobs running: A1~D1、A2~D2….A8~D8.

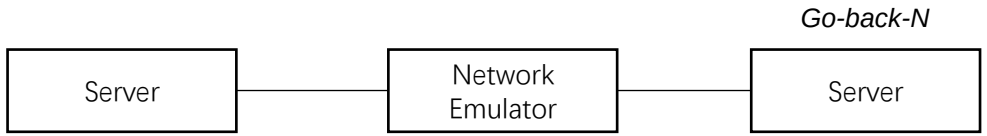
Results



- Testing the task completion time (JCT) of flow-based and packet-based load balancing under different message size.
- In a 512MB scenario, JCT of packet-based LB is reduced to about one-third compared to flow-based.

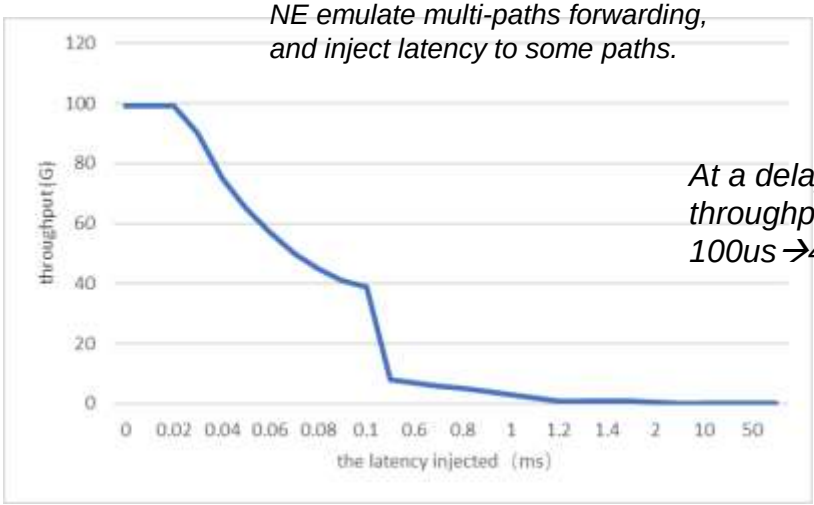
Challenges in Packet-based LB

- **The main side-effect of packet-based LB is causing packets of a flow arriving at receiver out of order:**
  - Re-order problem.
  - **Reliability problem: Loss-detection and retransmission;**



NE emulate multi-paths forwarding, and inject latency to some paths.

- **Out-of-order cause performance degradation significantly under Go-back-N mechanism.**
  - The mainstream RNIC adopt Go-back-N mechanism to provide reliability.
  - A lot of out-of-order packets may trigger frequently Go-back-N, resulting in a precipitous decline in throughput, as shown in the right emulation.



At a delay of about 20us, throughput begins to decline. 100us→40%, 500us→10%

- **RNIC can adopt Selective ACK to improve GO-back-N, but still existing problems hindering performance.**
  - The receiver can not directly determine whether the packet is lost or just out of order through the PSN,
  - relying on the timeout mechanism to detect packet loss reduces the sending rate.
  - Accurate fast-retransmit is necessary, but only by receiver is often not possible.

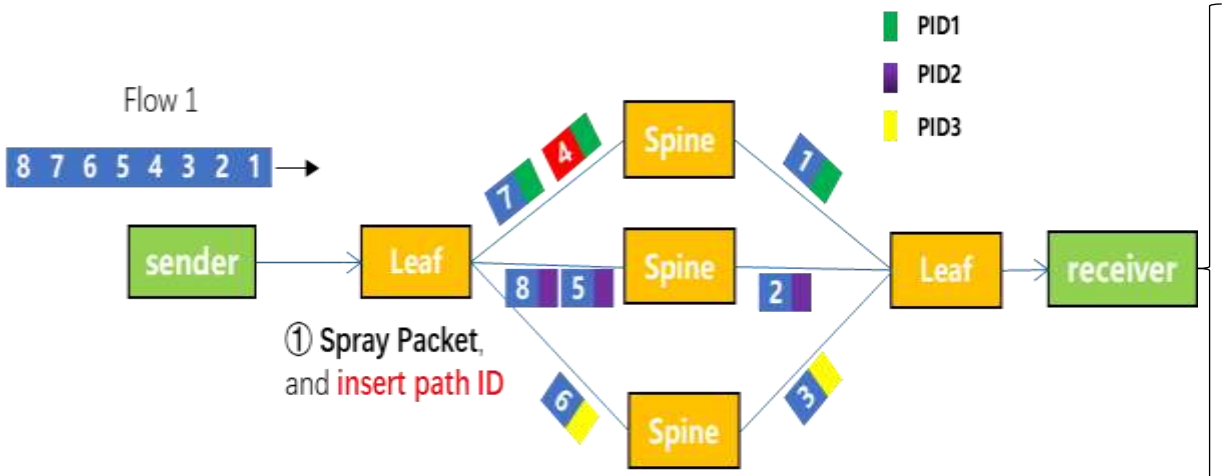
- **A preliminary conclusion is that processing out-of-order packets exclusively on the receiver NIC can hardly achieve optimal performance.**

Network can do more…

- **In packet-based LB, the root difficulty of receiver dealing with out of order packets is that it does not know the forwarding path and state of each packet.**
- **An intuitive solution is that network provide receiver the path information of packet forwarding to help loss detection and fast retransmission.**

Key idea: network device insert the path information(e.g. Path ID) into packet header, so that the receiver can detect the loss more quickly and execute fast retransmission.

Example



② Update the receiving window of flow 1, *assume the 'hole' is packet 4*:

PSN	1	2	3	4	5	6	7	8
state	1	1	1	0	1	1	1	0

③ Update the max receiving PSN of each path of flow 1:

- Path 1: maxRcvPSN[1]:7
- Path 2: maxRcvPSN[2]:5
- Path 3: maxRcvPSN[3]:6

④ Compare the hole number with maxRcvPSN of each path:

- If hole number < maxRcvPSN of all paths → Packet 4 loss

Current industrial support for packet-based LB

① Cisco：Silicon one

Figure 1: Cognitive routing features

Global load balancing

Prior generations of Tomahawk and Trident switches support Adaptive Routing via the Dynamic Load Balancing (DLB) feature. DLB is a quality-aware load distribution scheme that selects the next hop for a packet based on the local switch's port quality. It supports both per-packet spray and flowlet modes of operation and can be enabled selectively for different traffic types with ineligible flows falling back to hash-based ECMP. DLB is successfully deployed in multiple networks today.

② Broadcom：Tomahawk 5

Table 3. Ethernet ECMP vs. scheduled fabric

Characteristic	Unscheduled Ethernet fabric	Fully scheduled fabric
Distribution method	ECMP hash	Spray and re-order
Link utilization	Low	High

③ Nvidia spectrum x

Spectrum-X Technology Innovations

Spectrum-4 switches and BlueField-3 SuperNICs work in tight coordination to form a **NCCL-optimized network fabric** built to optimize AI cluster performance using a suite of end-to-end innovations:

- **RoCE adaptive routing** avoids congestion by dynamically routing large AI flows away from congestion points. This approach improves network resource utilization, leaf/spine efficiency, and performance. The Spectrum-4 switch employs fine-grained load balancing, re-routing active flows to eliminate congestion. Additionally, the BlueField-3 SuperNICs work in tandem to handle out-of-order packets, placing packets in the correct order in the destination memory. RoCE adaptive routing supports profiles for efficient provisioning and automation.

- **The mainstream chip venders have supported the packet-based load balancing, but their solutions are different. → standardization of packet-based load balancing on ethernet is needed.**

Summary

- **Introduce the drawbacks of traditional flow-based ECMP for AI fabric, and packet-based load balancing become the trend.**
- **Analyze the challenges bring to receiver in packet-based load balancing.**
- **Network can assist receiver to solve the challenges.**
- **Potential Standard Requirements：** Need to standardize path information in L2 for network-assisted fast retransmission, such as path ID.

Thank You !