# Hostmesh: Monitor and Diagnose Networks in Rail-optimized RoCE Clusters

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# Background

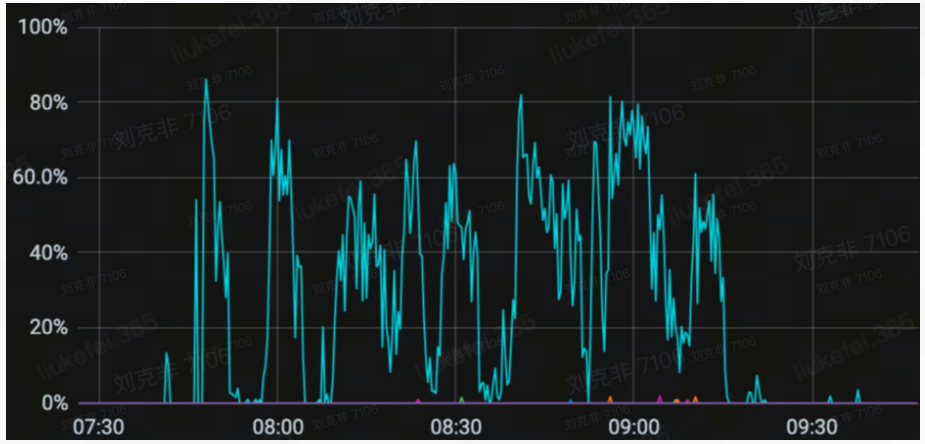
## ■ Characteristics of RoCE Network Problems

- **RDMA throughput is sensitive to packet drops**
  - **Commodity RDMA NICs (RNICs) use go-back-n as the retransmission mechanism.**
- **Frequent network misconfigurations**
  - **RoCE (RDMA over Converged Ethernet) networks typically require a variety of configurations, such as enabling PFC and configuring PFC headroom, leading to a high probability of misconfigurations, which can cause packet drops and throughput degradation.**
- **Frequent RNIC problems**
  - **Such as RNIC flapping, which can lead to packet drops and throughput degradation.**

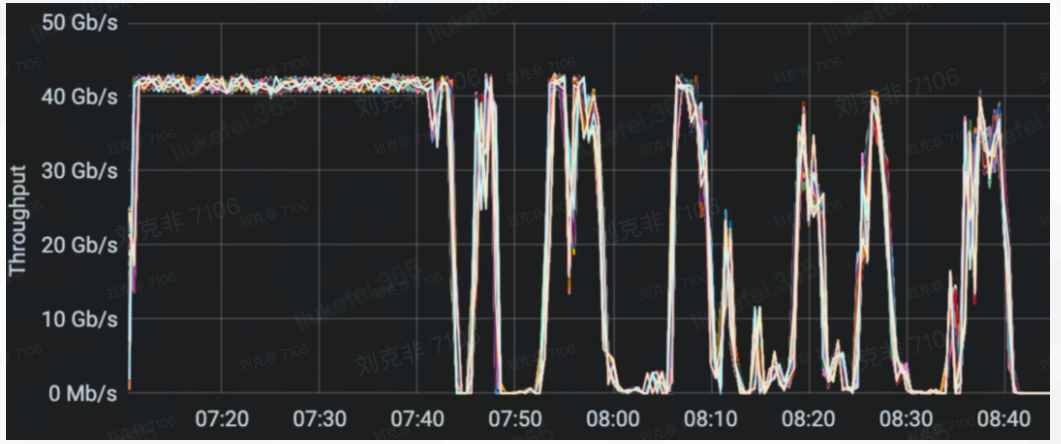
# Background

## ■ Characteristics of RoCE Network Problems

- **Distributed Machine Learning (DML) has a barrel effect.**
  - **In DML, all participating GPUs periodically synchronize their local gradients over the network. The completion time of this process is determined by the slowest GPU.**
  - **Either RNIC or in-network packet drops can cause throughput degradation of multiple flows, further degrading the average throughput of the *ENTIRE* DML cluster.**




One RNIC's drop rate

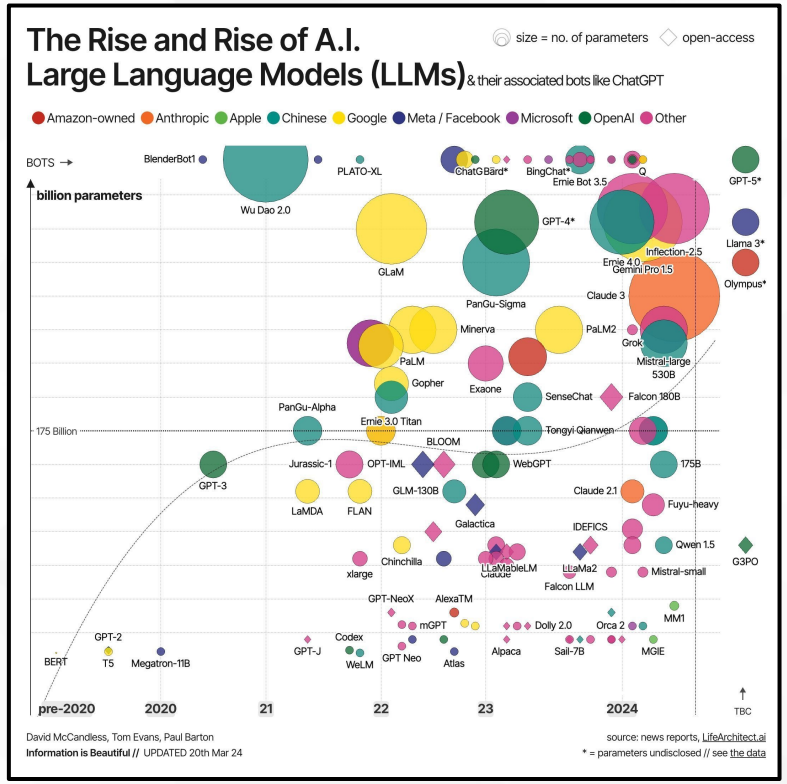


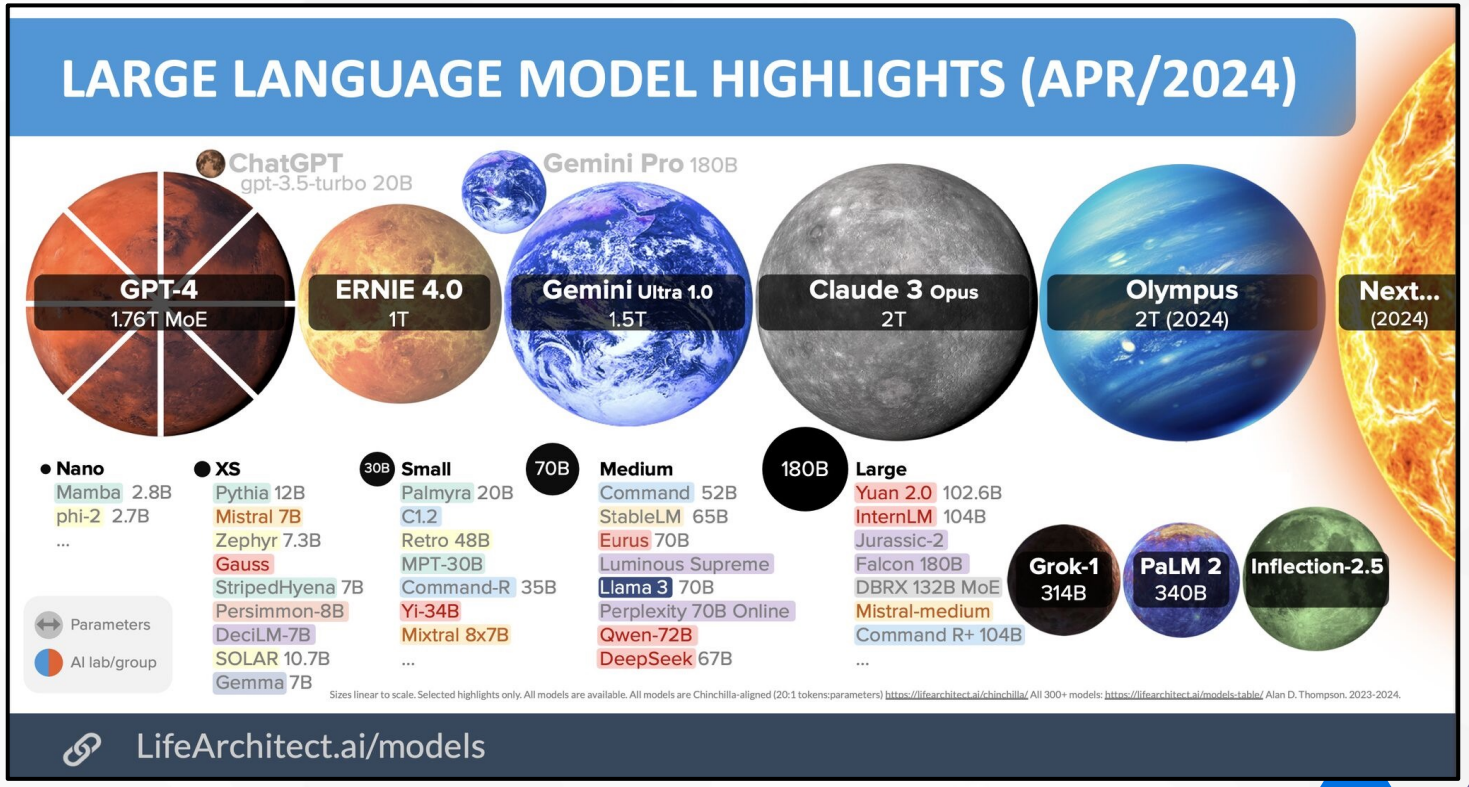

Average throughput of the DML cluster

# Background

## ■ RoCE Clusters are Growing in Size

- **The size of large language models (LLMs) is increasing, and typical LLM model parameters have now reached 100B or even >1000B.**

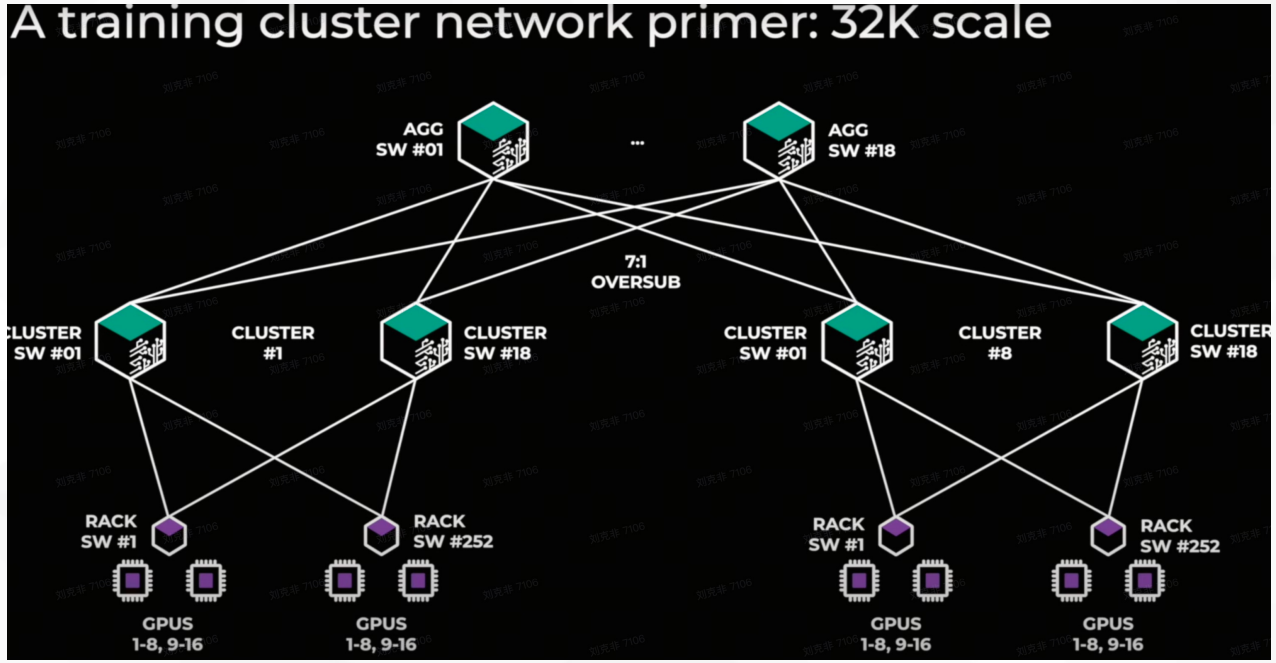


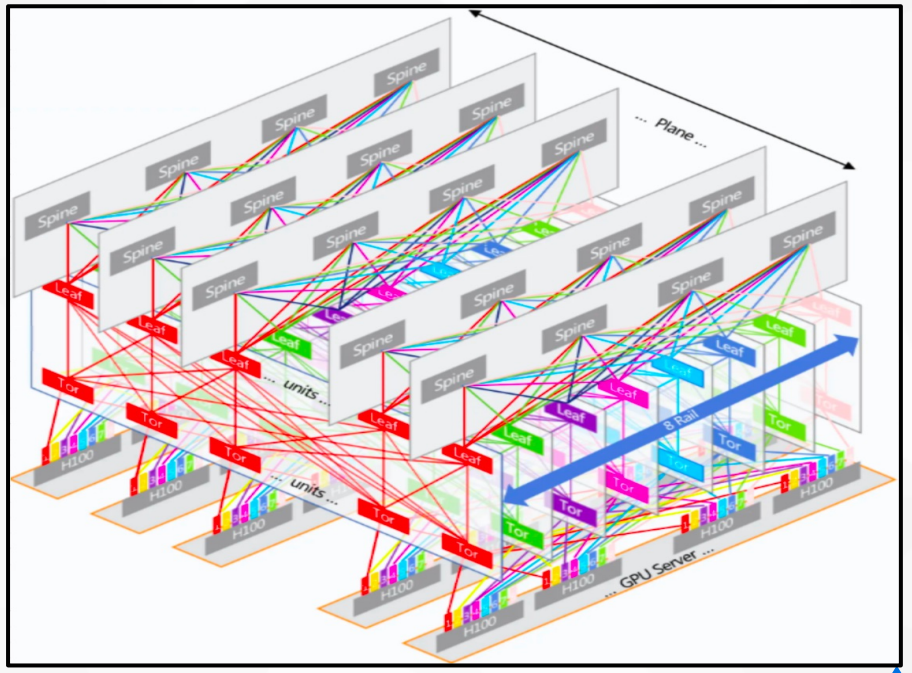
# Background

## ■ RoCE Clusters are Growing in Size

- To increase the training rate, the DML cluster uses more GPUs for training as well as more RNICs and switches to connect these GPUs.
- As a result, both the frequency and impact of network problems are increasing.




LLM training cluster in Meta (32K GPUs and RNICs)

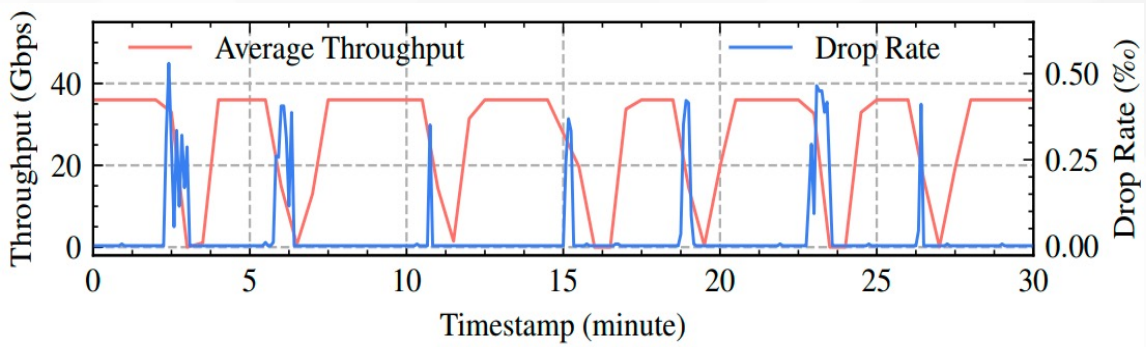


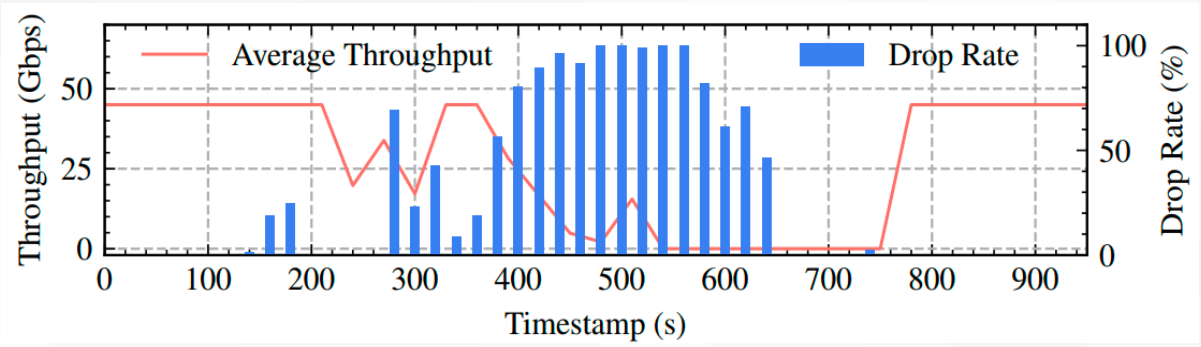

A rail-optimized cluster for 32K GPUs

# Background

## ■ Efficient Troubleshooting is Critical for Optimal Training Performance

- When training **fails** or training **performance degrades**, the problem needs to be quickly located to **restart the training task** or **restore optimal training performance**.
- Large clusters that are **idle for troubleshooting** or running in **a suboptimal state** can result in **significant financial losses**.



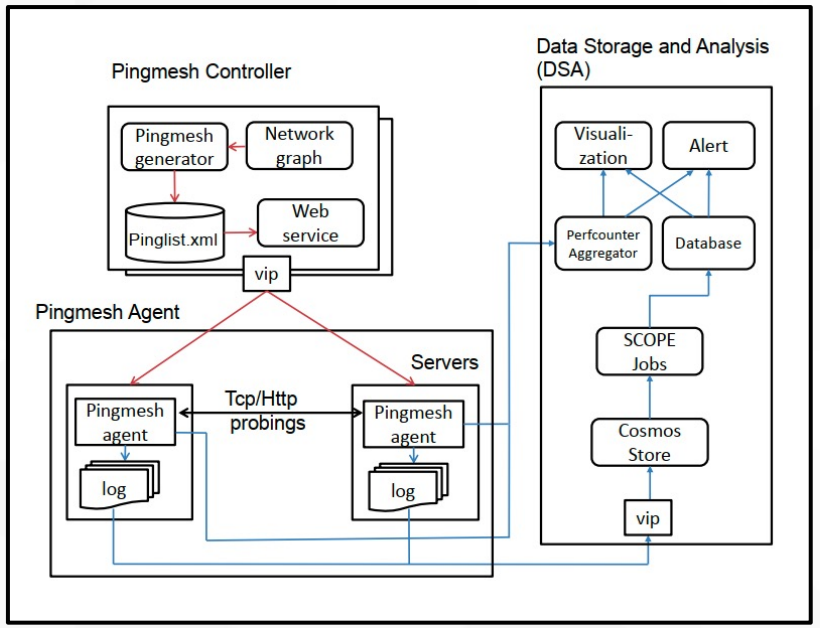




One **single** flapping switch link (left) or RNIC (right) results in **severe cluster throughput degradation**

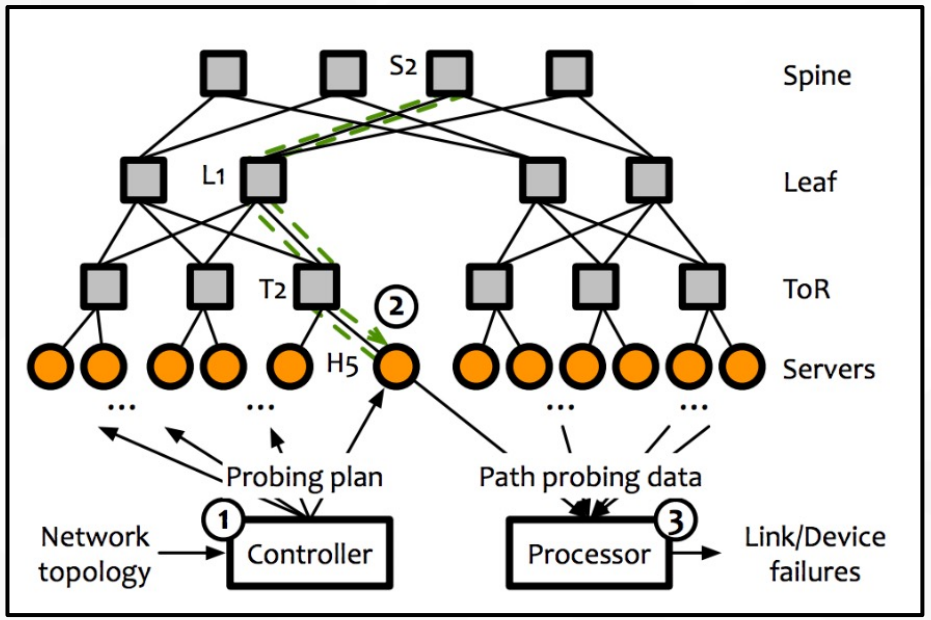
# Motivation

## ■ Need an Efficient Network Monitoring and Diagnostic System

- Detect and locate RoCE network **failures** and **performance bottlenecks**.
- The system should be based on **active probing**.
  - Ensure that network problems can be detected **independent of service traffic**.




Pingmesh Framework

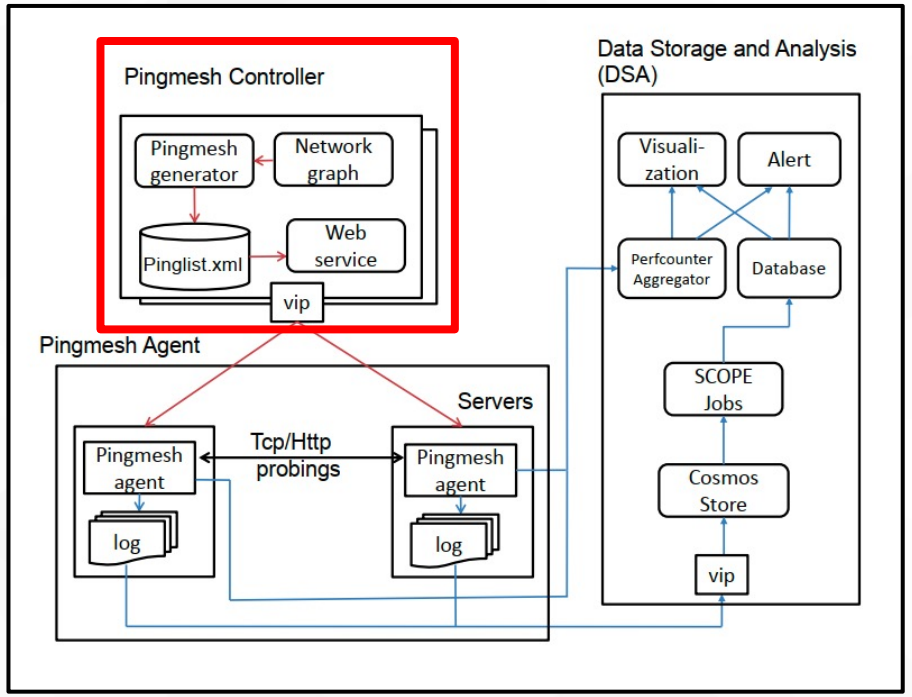


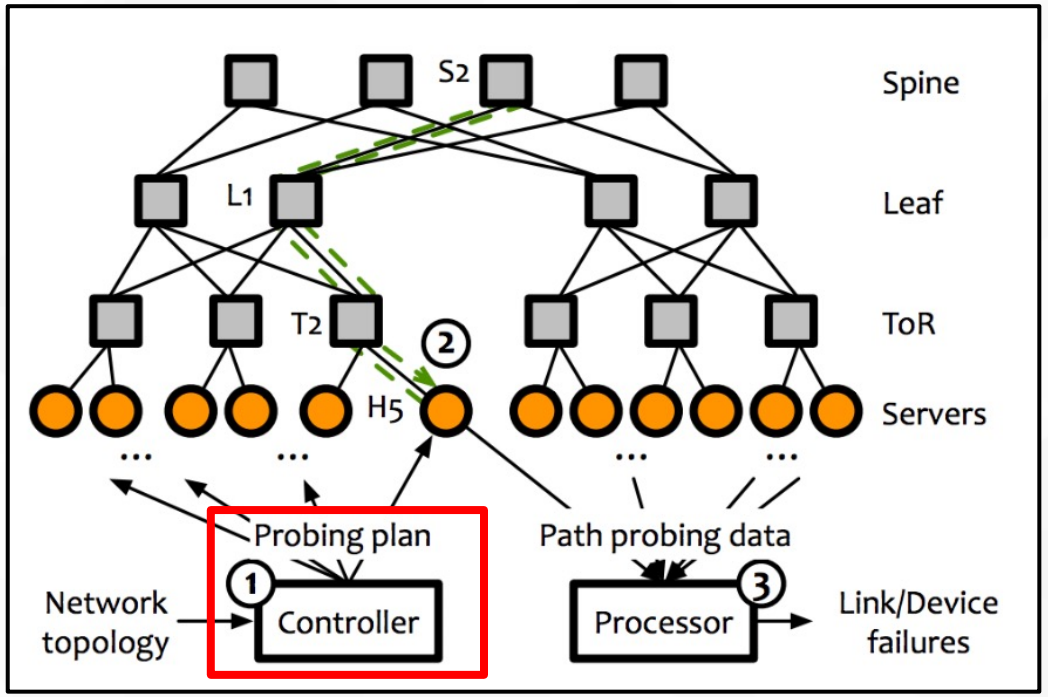

Netbouncer Framework

# Motivation

## ■ Limitations of Existing Active Probing Mechanisms

- Rely on a **centralized controller** to generate pinglists (probing plan).
- The need for a **controller** has limitations in **multi-tenant clusters**.




**Pingmesh Framework**

**Netbouncer Framework**

# Motivation

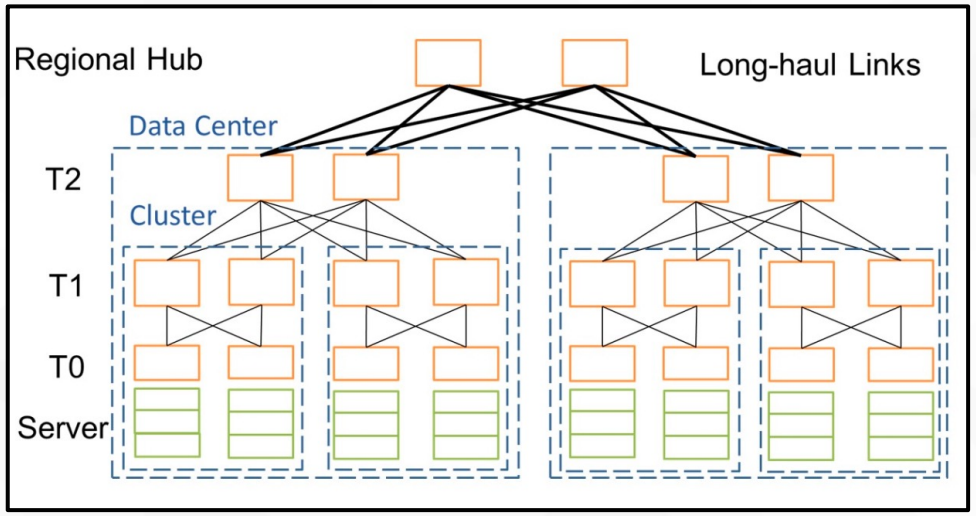
## ■ Limitations of Existing Active Probing Mechanisms

- Deploying a controller in multi-tenant clusters is difficult.
  - A centralized controller may not be accepted due to security concerns.
  - A server within each tenant cluster as the controller consumes additional tenant resources and is difficult to ensure stable operation of the controller.
- Controllers in multi-tenant clusters have high synchronization overhead.
  - Controllers must maintain the latest server information of each tenant cluster and frequently update the pinglist for each server to avoid probing noise.

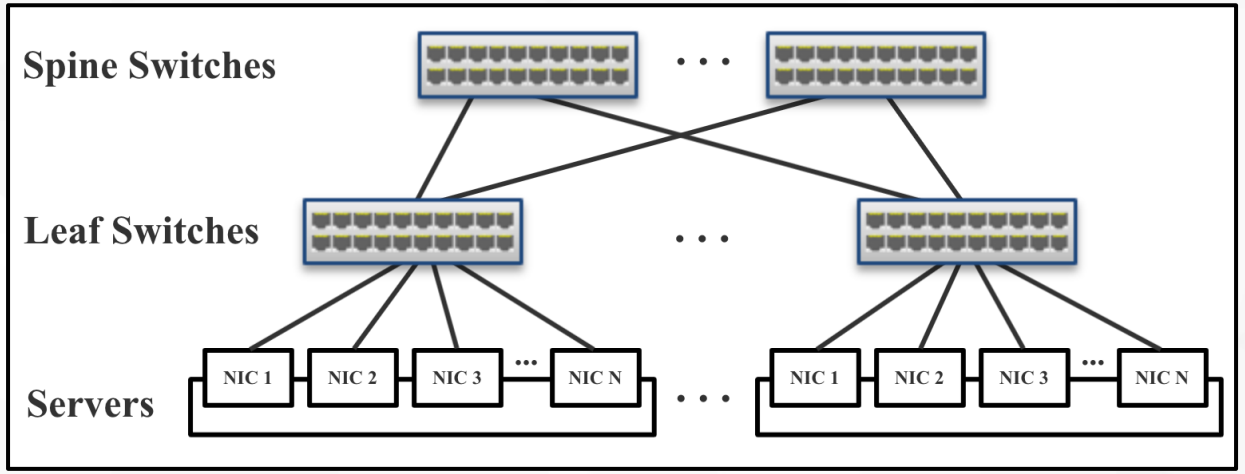
# Motivation

## ■ Our System Design Targets

- An active probing system for RoCE clusters without relying on a controller.
- However, in some topologies, inter-server probing is necessary, and a controller is essential to provide the communication address of the target servers.




CLOS topology in Azure

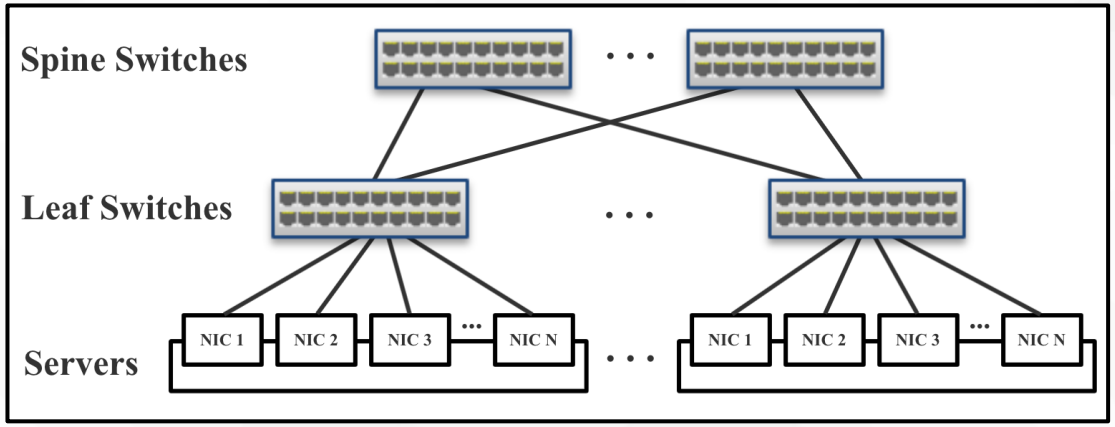



CLOS topology for hosts with mulitple NICs

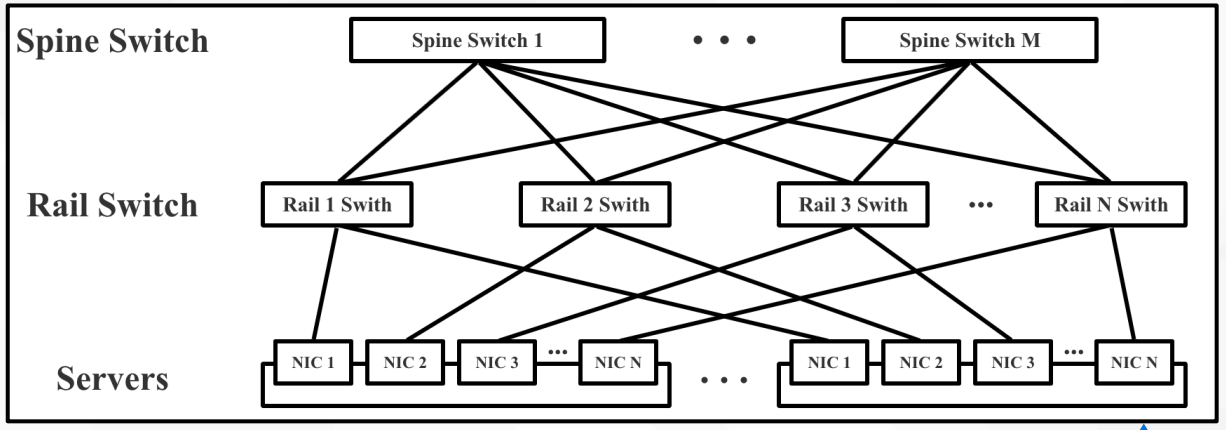
# Motivation

## ■ Opportunity: Rail-optimized Network

- For multi-NIC hosts, the rail-optimized topology improves network performance.
  - In Clos networks, all NICs on a host are connected to the same ToR switch.
  - In rail-optimized networks, NICs on a host connect to different ToR switches (rail switches).
- Rail-optimized topology allows more hosts to be under the same ToR switch.




CLOS topology for hosts with mulitple NICs

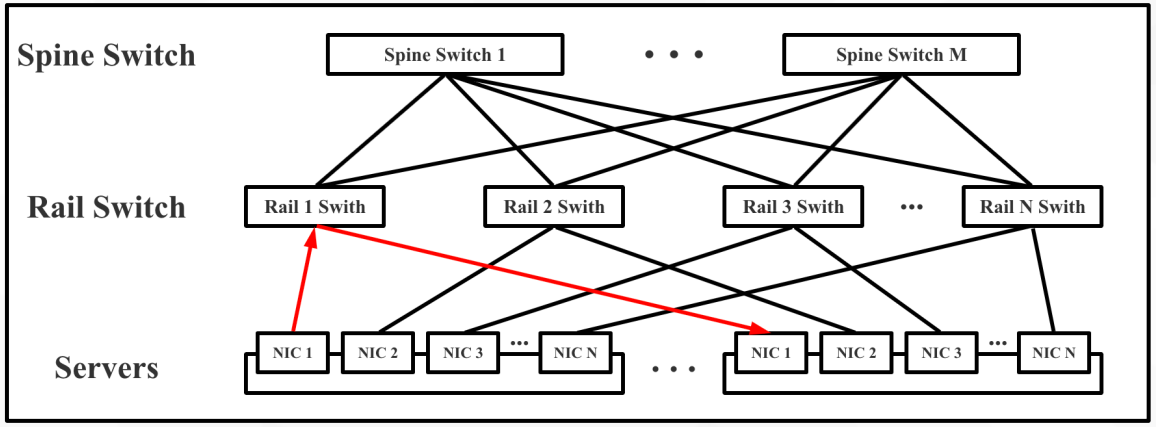



Rail-optimized topology for hosts with mulitple NICs

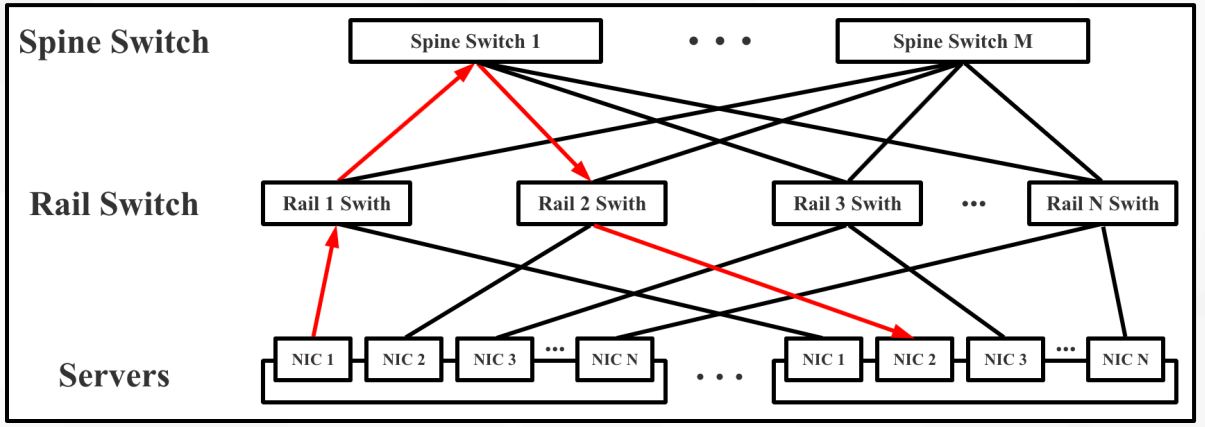
# Motivation

## ■ Opportunity: Rail-optimized Network

- Traffic paths in rail-optimized clusters
  - Intra-rail communication is **below the rail switch**.
  - Inter-rail communication must **pass through the top-tier switches** in the cluster.




Intra-rail traffic



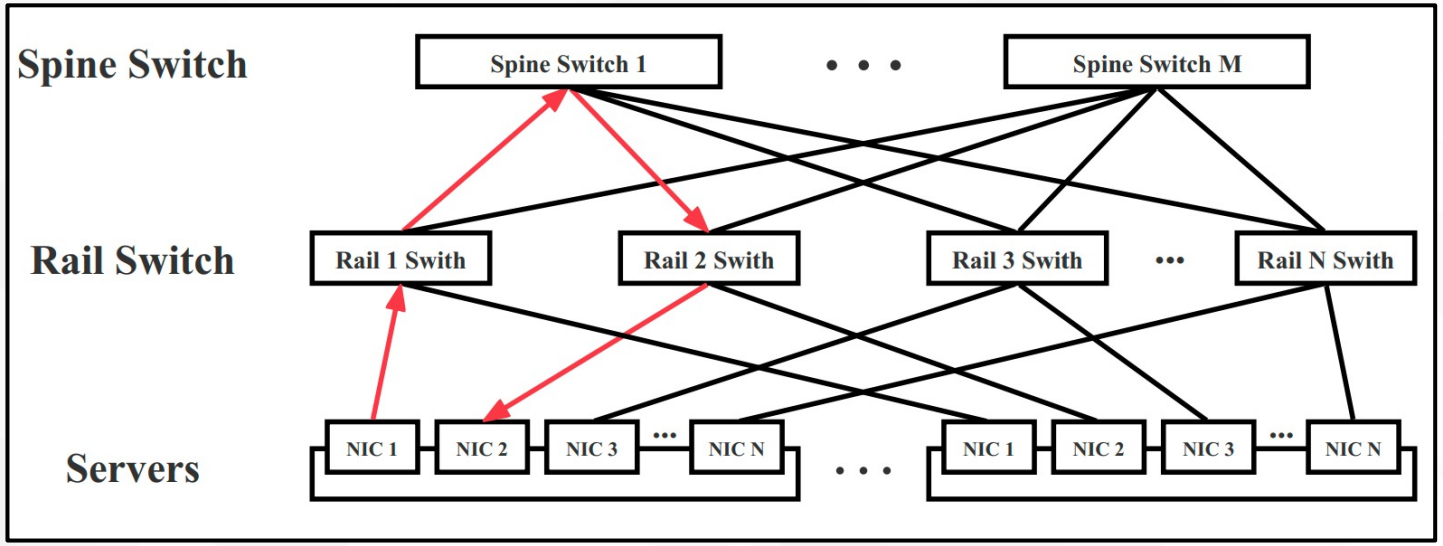

Inter-rail traffic

# Motivation

## ■ Opportunity: Rail-optimized Network

- **Key insights:** Each host has **multiple NICs**, and traffic between different NICs on the same host must **go through top-tier switches** in the cluster.
- We can use **different NICs on each host to probe each other**, and keep changing the probe's 5-tuple. Then these probe packets can cover all the links in the cluster.

**Need No Controller!**



# Motivation

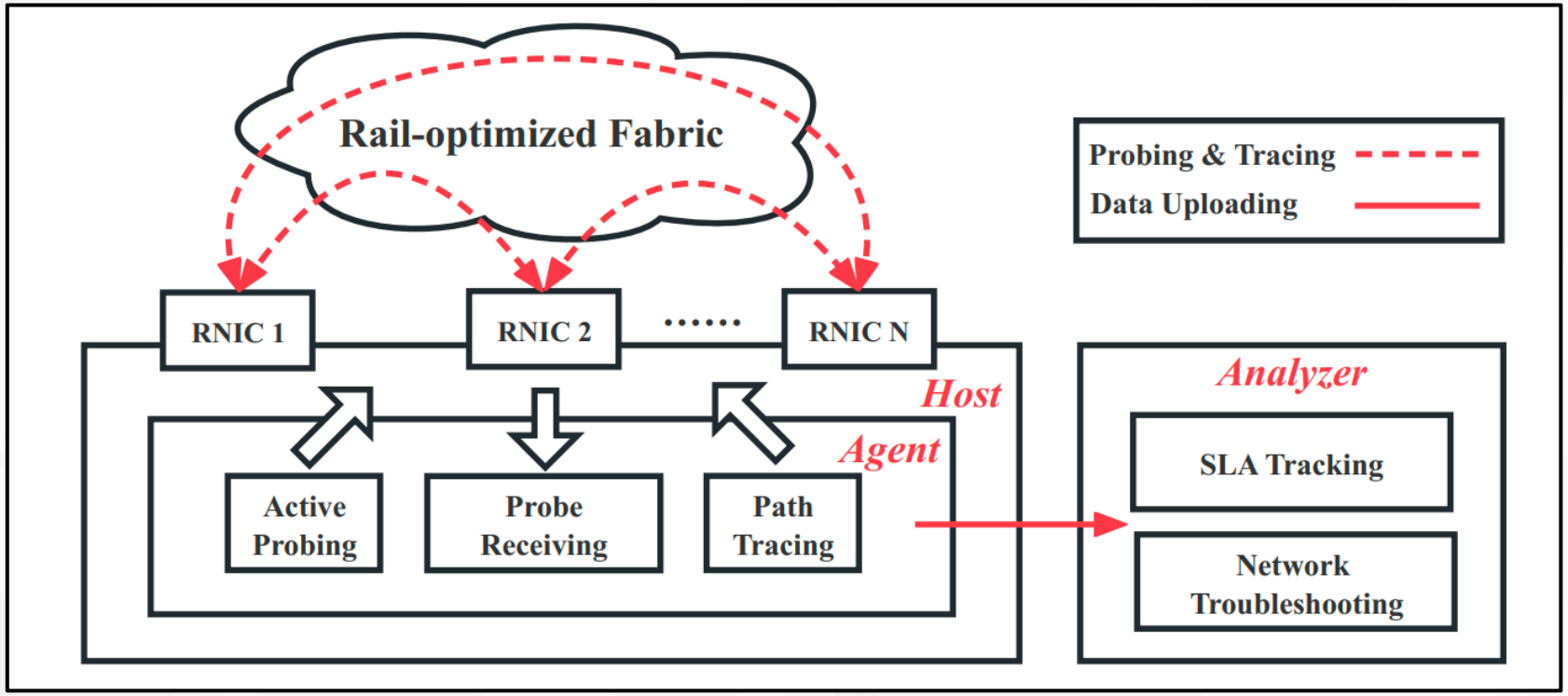
## ■ Benefits of Probing Between RNICs on the Same Host

- Get one-way latency and detect one-way packet drops with low overhead.
  - Probing between different servers typically involves both the probe and ACK paths. The problem with anomalous probes can be in either the probe path or the ACK path.
  - One-way probe data helps to locate network problems more accurately.
- No probe noise caused by high processing delay in the responder server.
  - In inter-server probing, if the responder has a high CPU load, it will spend more processing time responding with ACKs. In some severe cases, this will result in a probe timeout.

# Hostmesh Design

## ■ Hostmesh Framework

- **Agent**: Active probing and probe path tracing.
- **Analyzer**: SLA tracking and network troubleshooting.

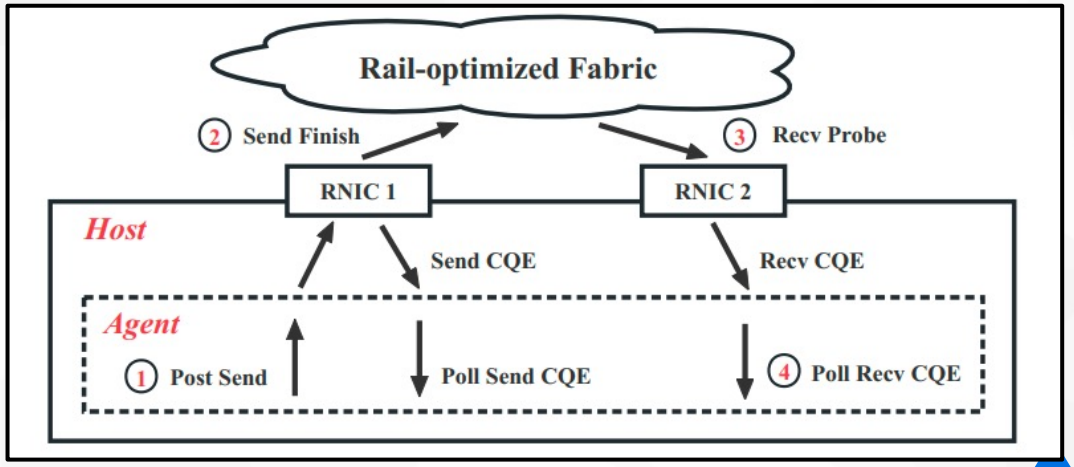


# Hostmesh Design

## ■ Hostemesh Agent - (1) Measure Processing Delay and One-way Latency

- **Choice of QP type: RC, UC, or UD?**
- **For accurate measurement:**
  - **Network latency: (③-②)**
  - **Processing delay: (④-①)-(③-②)**
  - **Commodity RNICs provide an RNIC timestamp when generating CQE.**
  - **All three QP types can obtain timestamps ③ from receive CQE.**
  - **② can only be obtained in UC or UD.**

| Features | RC | UC | UD |
|---|---|---|---|
| Accurate LAT Measurement | ✗ | ✓ | ✓ |
| Connection Overhead | High | High | **Low** |



# Hostmesh Design

## ■ Hostemesh Agent - (1) Measure Processing Delay and One-way Latency

- **Choice of QP type: RC, UC, or UD?**
- **For connection overhead:**
  - **With RC or UC, the local RNIC must create a QP for each target RNIC.**
  - **With UD, Agent only needs to create one QP on each RNIC, which has little connection overhead.**

**UD!**

| Features | RC | UC | UD |
|---|---|---|---|
| Accurate LAT Measurement | ✗ | ✓ | ✓ |
| Connection Overhead | High | High | **Low** |

# Hostmesh Design

## ■ Hostemesh Agent - (2) Path Tracing

- Periodically Traceroute the latest paths of probe packets.
- Easy to deploy and does not rely on advanced switch features such as INT.
- Continuous path tracing instead of path tracing when detecting anomalies.
  - Continuous path tracing allows Analyzer to locate network problems immediately as they occur.
  - In the case of a persistent failure, such as a link failure, the replayed dropped packets will be rehashed to other normal links, leading to inaccurate fault inference.

# Hostmesh Design

## ■ Hostemesh Analyzer - (1) Detect Anomalous RNICs in Real Time

- Detected packet drops can be attributed to RNICs or switches.
- If we can detect anomalous RNICs, we can filter out anomalous probes caused by RNICs and use switch drops to accurately locate switch network problems.
- A simple but effective method:
  - If many probes to an RNIC show anomalies at the same time, that RNIC is probably abnormal.
  - Premise: For each RNIC, there should be enough probes from other RNICs over a fine-grained time period.

# Hostmesh Design

## ■ Hostemesh Analyzer - (2) Locate Switch Network Problems

- **After detecting anomalous RNICs and filtering out anomalous probes caused by them, we can get anomalous probes caused only by switches.**
- **Analyzer uses a simple voting algorithm to infer abnormal devices. It traverses the paths of these probes and counts the number of times each link/switch is traversed.**
- **The link/switch with the highest number of votes is the most suspicious.**

**Algorithm 1** Identify the Most Suspicious Switch Links

**Input:** *abnormal paths*
**Output:** *the most suspicious links*

```
1:  function DetectAbnormalLinks()
2:      InitLinkStatus()
3:      for path_j in abnormal paths do
4:          for link_i in path_j do
5:              link_i.status ← abnormal
6:              link_i.abnormal_cnt ++
7:      return abnormal links with the largest abnormal_cnt
8:  function InitLinkStatus()
9:      for link_i in all network links do
10:         link_i.status ← normal
11:         link_i.abnormal_cnt ← 0
```

# Evaluation & Problems Found

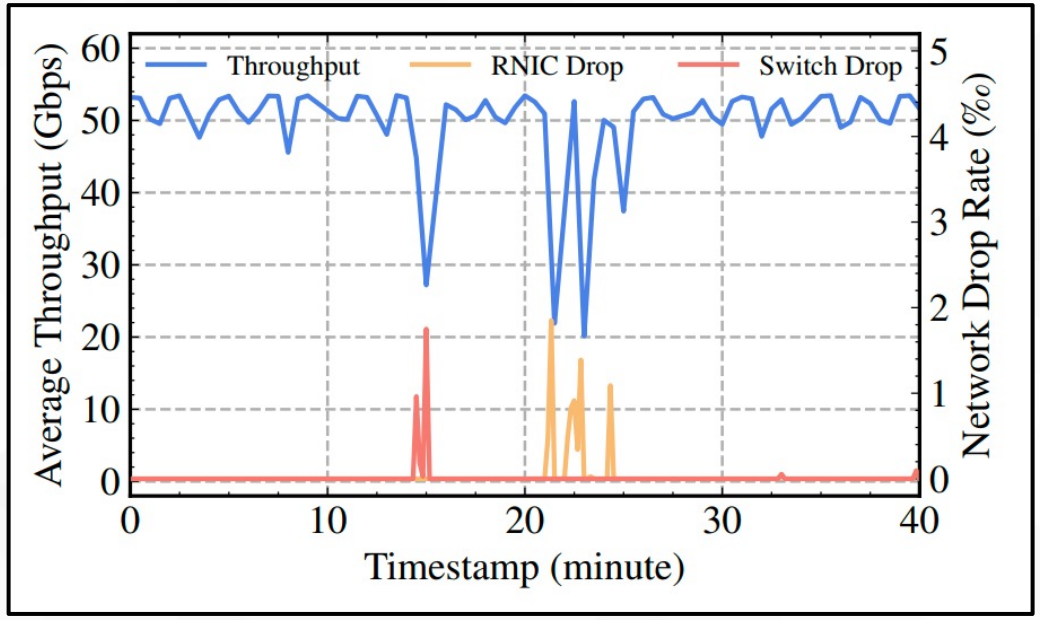
■ We Deployed Hostmesh for over 3 Months on a Multi-tenant DML RoCE Cluster

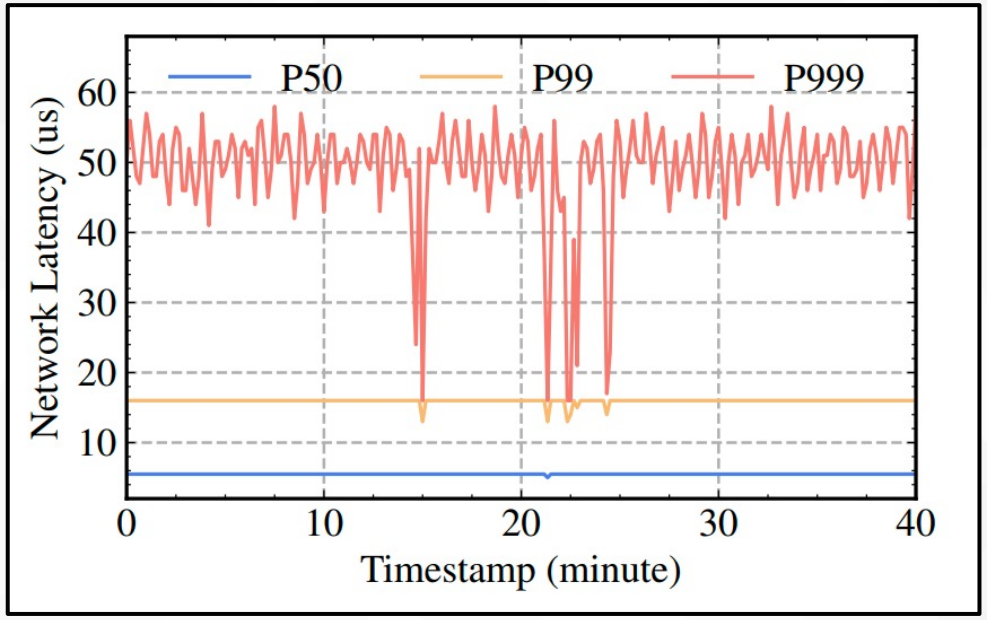
- Rail-optimized network topology.
- Hundreds of servers in total.
- Effectively detected and located 8 types of problems, including:
  - Hardware failures: (#1) RNIC/link flapping, (#2) packet corruption.
  - Misconfigurations: (#3) RNIC routing, (#4) switch ACL, and (5) PFC.
  - Network congestion: (#6) Uneven load balancing.
  - Intra-host bottlenecks: (#7) CPU overload, (#8) PCIe link downgrads.

# Evaluation & Problems Found

## ■ Detect and Categorize Packet Drops in Real Time

- Effectively determine the cause of degradations in training throughput.
- Accurately measure network latency and use it to reflect service states.



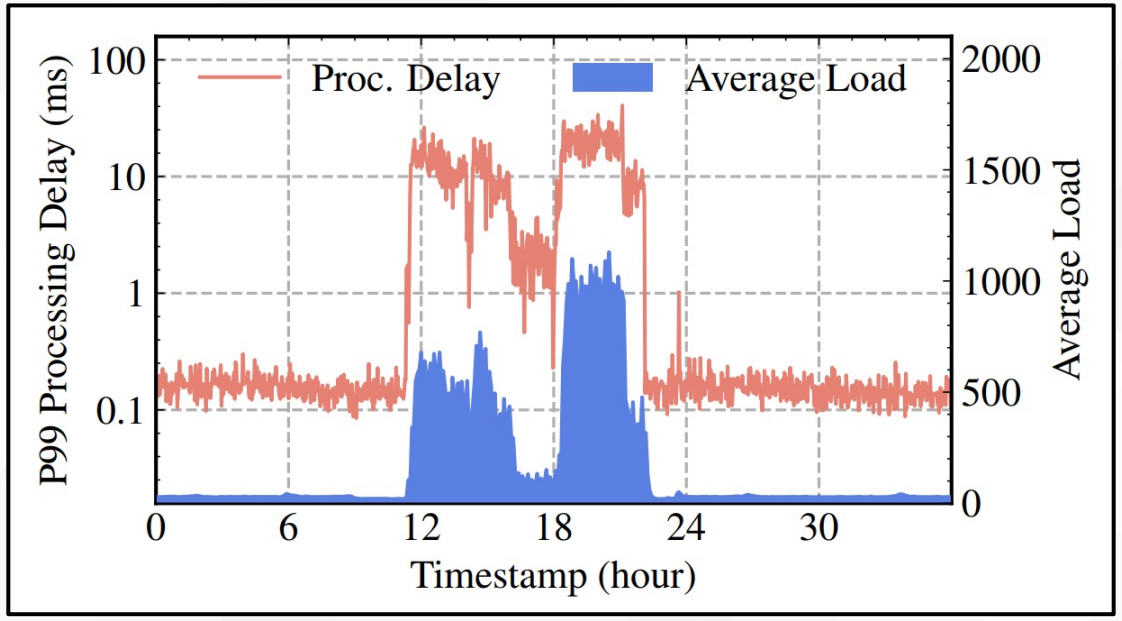

Packet drops lead to training throughput degradation

Measured network latency decreases at the same time

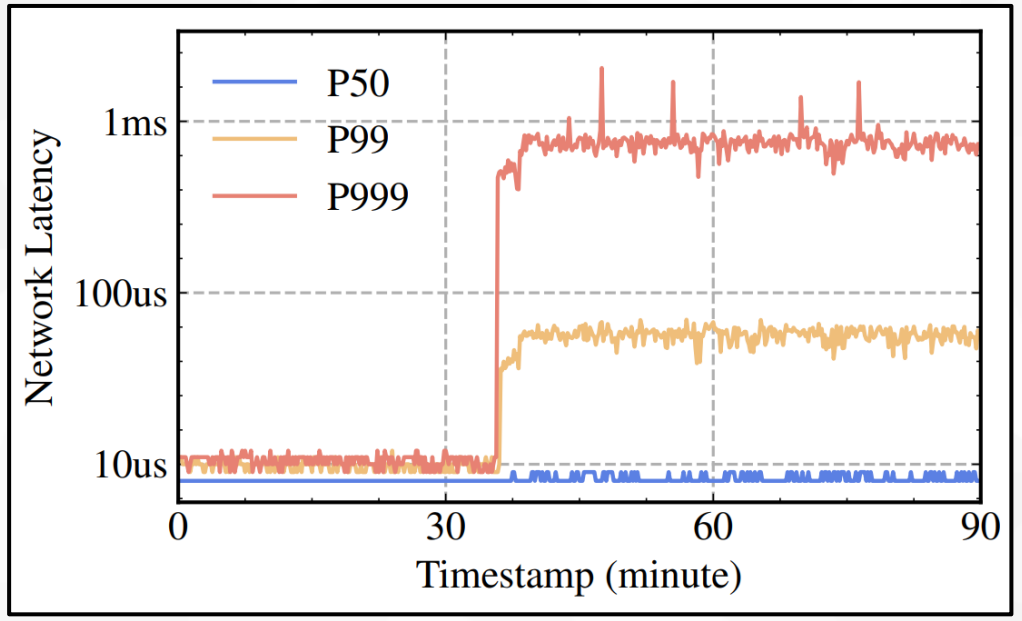
# Evaluation & Problems Found

## ■ Effectively Detect and Locate Performance Bottlenecks

- The measured end-host processing delay can **accurately reflect CPU utilization**.
- Use accurate network latency to **perceive network congestion**.




CPU overload results in high processing delay on a host




A PFC storm results in high tail network latency

# Conclusion

- We rethink the design of the network monitoring and diagnostic system.
- For rail-optimized RoCE clusters, Controller is not necessary.
  - Probing between RNICs on the same host can cover all links in the cluster.
- Easier to deploy in rail-optimized clusters, especially multi-tenant clusters.
- Finer-grained network measurements and less probing noise.

# THANK YOU