ProLet: Proactive Load Balancing for Lossless RDMA

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Lossless RDMA

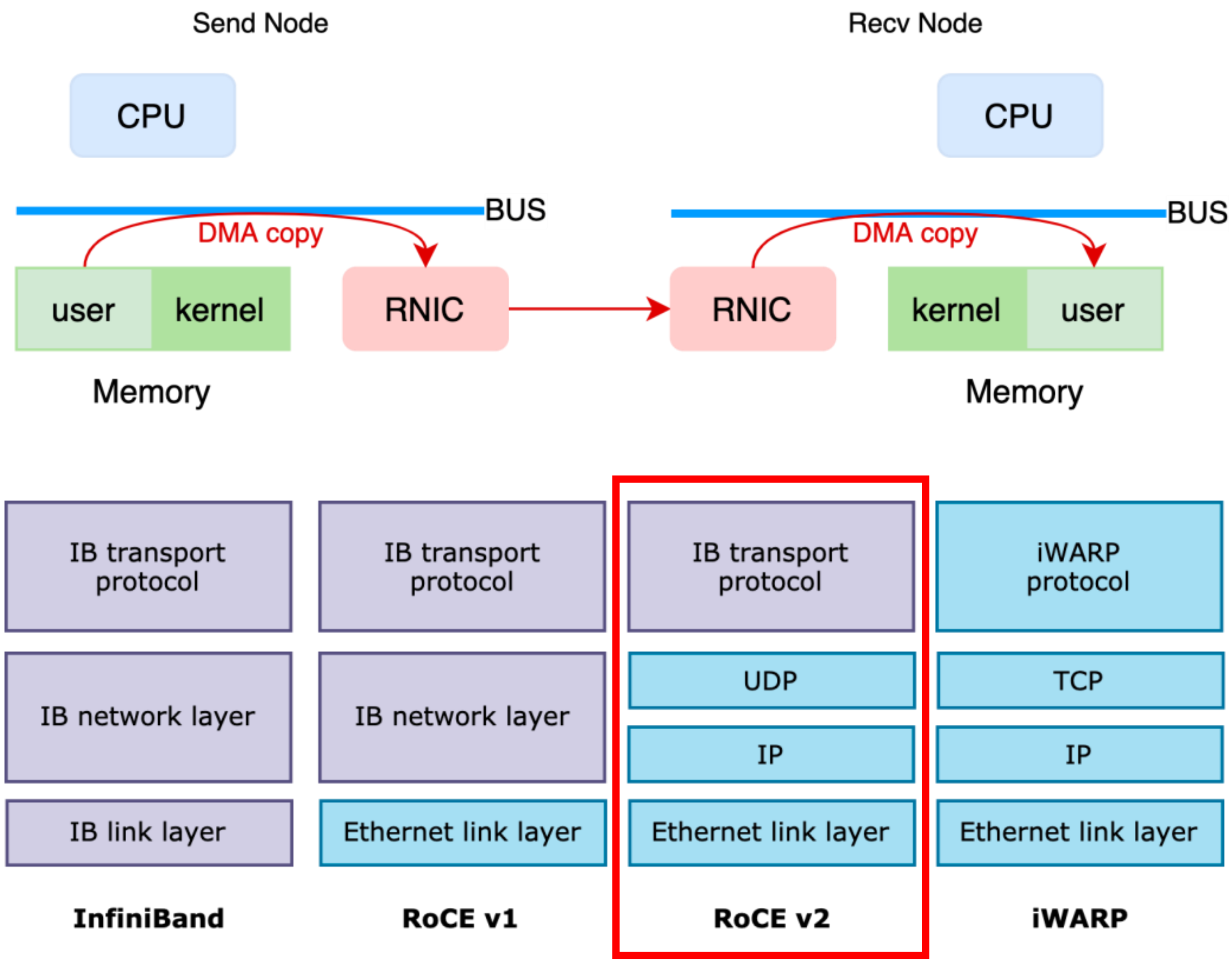


Image source: Alibaba Cloud

Lossless RoCEv2

Priority Flow Control (PFC)

- Suspends upstream egress queues via PAUSE frames during congestion
- No packet drops due to congestion

Go-Back-N ARQ

- Enforces strict in-order delivery
- Subsequent packets are dropped until the expected packet is received

Load Balancing Schemes in Lossless RDMA

Rerouting Granularity	Schemes	Rerouting Condition	Drawbacks
Flow	ECMP	No rerouting	Hash collisions
Packet spraying	MPRDMA [NSDI ’18], Eunomia [APNET ’25]	Per-packet independent routing decisions	Massive out-of-order delivery
Subflow	ConWeave [SIGCOMM ’23], RoCELet [ToN ’25]	Occurrence of congestion on the current path	Delayed rerouting and frequent queue buildup
Flowlet	CONGA [SIGCOMM ’14], LetFlow [NSDI ’17]	Inter-packet time gap exceeding a predefined timeout	Static timeout tuning challenge

Observation in Lossless RDMA

PAUSE frames lead to packet accumulation, while subsequent RESUME frames release them

DCQCN reacts to ECN markings by dynamically pacing the transmission rate of subsequent packets

Such patterns result in larger inter-packet gaps and TCP-like bursts

Gap (μs)	**50% Load**	**80% Load**
0–2	34,110,501 (97.84%)	49,852,314 (88.21%)
2–5	483,929 (1.39%)	2,242,268 (3.97%)
5–10	129,755 (0.37%)	2,122,590 (3.76%)
>10	139,630 (0.40%)	2,298,309 (4.07%)
≥ One-way Lat.	0.98%	8.64%
≥ RTT	0.48%	4.96%
PAUSE Frames	35,830	9,778,958

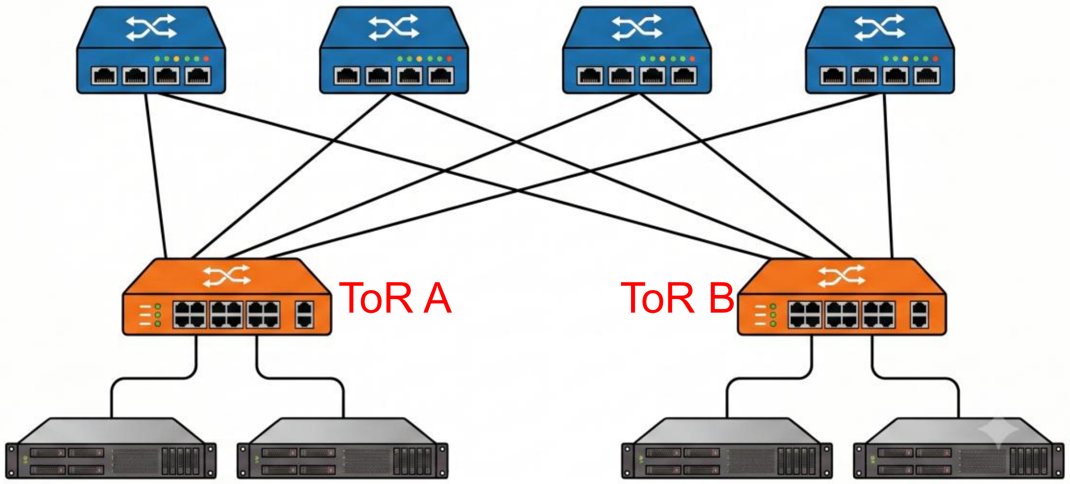
Inter-packet time gap analysis for a CONGA simulation in a 128-host Spine-Leaf topology

Research Question

Small fixed timeouts lead to massive out-of-order delivery

Large fixed timeouts miss rerouting opportunities

Research question: How can we effectively identify flowlets while minimizing out-of-order delivery?



Dynamically fine-tunes per-destination ToR timeouts to replace static thresholds

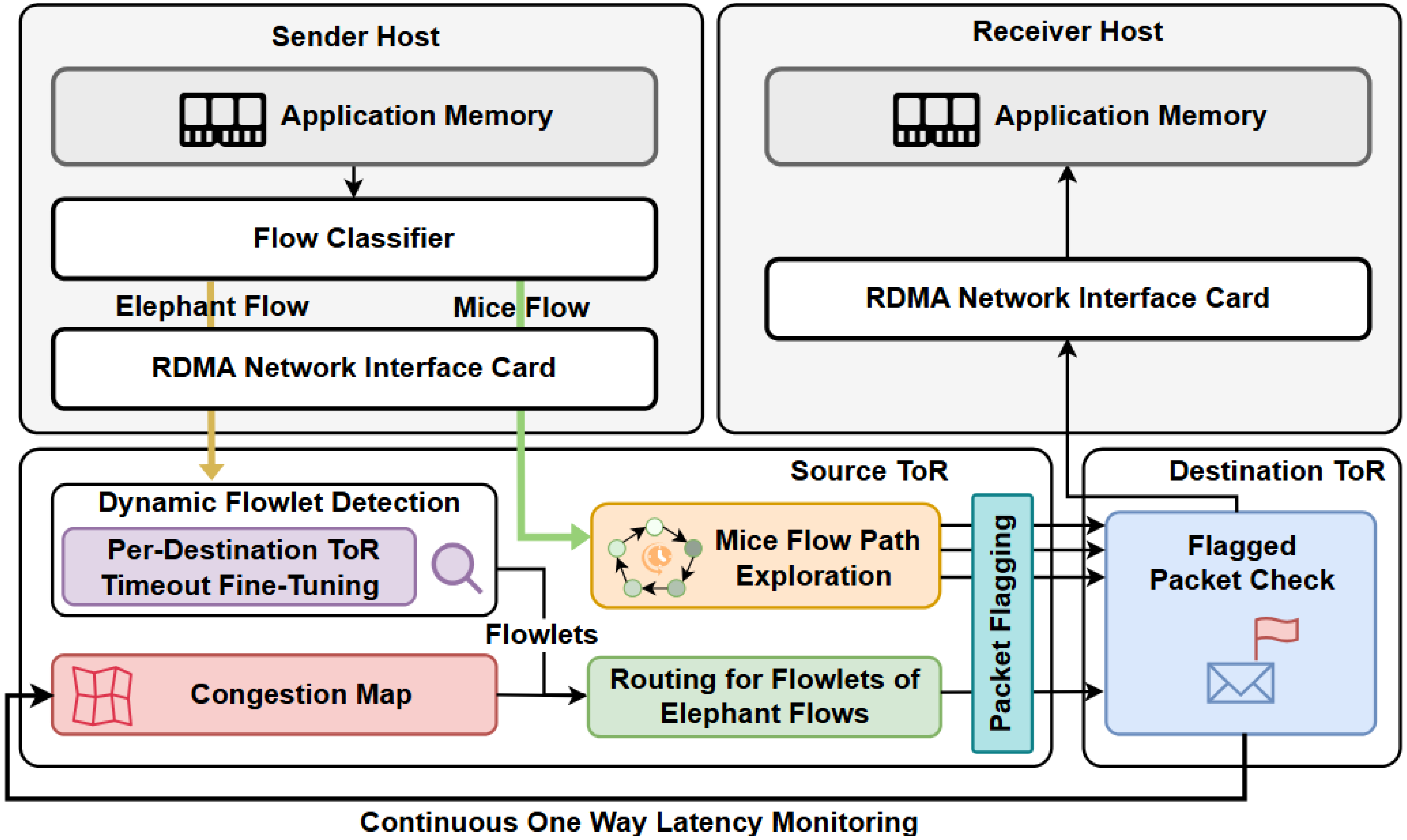
Overview of ProLet

Host Memory

- Queue pairs (QPs) are created with distinct DSCP settings in QP contexts
- Work requests (WRs) are posted to the corresponding QPs based on data length relative to a threshold
- QPs for mice flows are restricted by either a WQE limit or a byte threshold
- The RNIC marks outbound packets with the DSCP value bound to that QP

Source ToR

- Applies divergent strategies for packets from mice or elephant flows
- Dynamically fine-tunes the per-destination ToR timeouts to promote in-network flowlet identification



QoS-based Routing Strategies

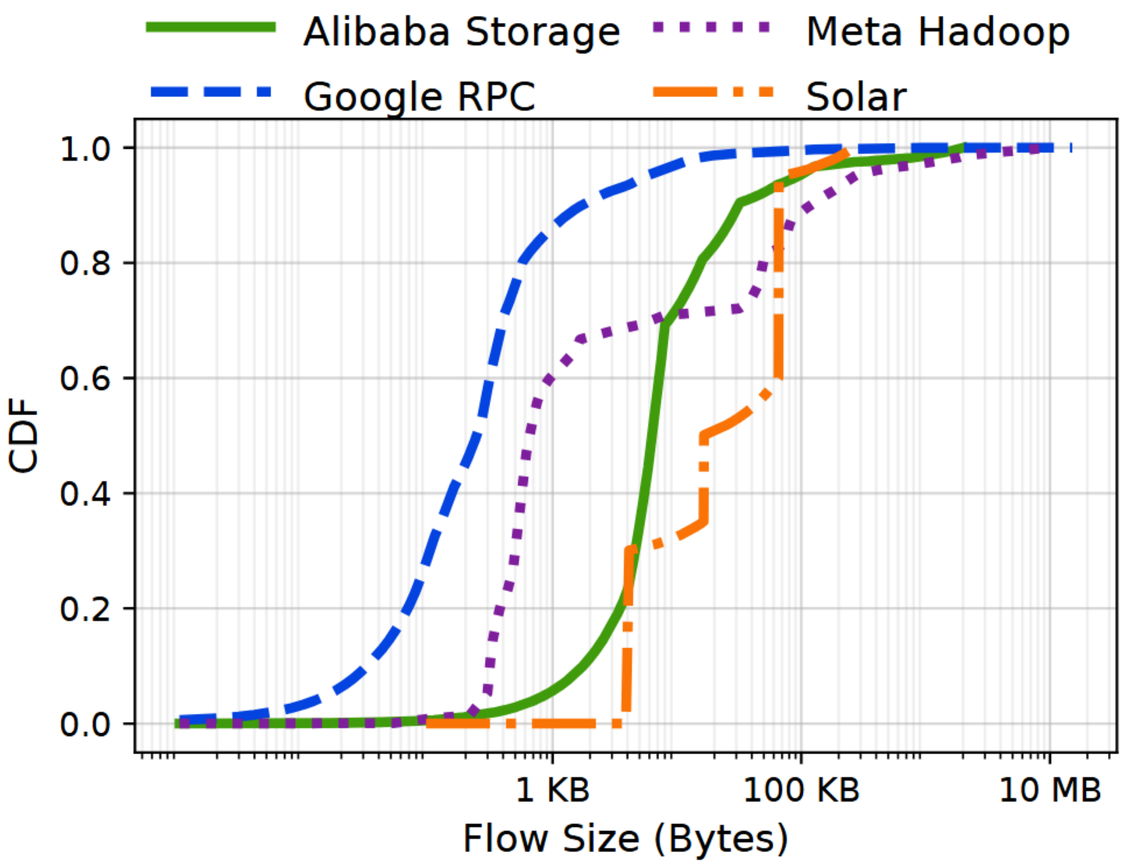
Mice flows

- Dominate the flow count
- Preserve in-order delivery over a single path
- Proactively explore all available paths in a randomized round-robin manner

Per-destination ToR timeouts

Elephant flows

- Partition into flowlets using per-destination ToR timeouts
- Route flowlets across distinct paths
- Exploit the least congested path



Continuous One-way Latency Monitoring

- Hardware-paced RDMA traffic lacks inter-packet time gaps greater than one RTT
- Asymmetric congestion levels on forward and backward paths necessitate one-way latency measurement

- Monitors **one-way latency** of each path, calculated as the difference between the flagged packet's transmission time and its arrival time with at most one probe per path
- Enables more efficient flowlet detections

Source ToR

pathID	d_{205}^{trans}	d_{205} (ns)
205	45000	MAX

pathID	d_{205}^{trans}	d_{205} (ns)
205	0	5000

0 indicates there is no pending request on this path

$5000 = d_{205}^{rec} - d_{205}^{trans}$ is the new one-way latency

Flagged data packet

pathID	flagging
205	1

Destination ToR

Receives a flagged packet and notes down the receiving time d_{205}^{rec}

Triggers a control packet back to the source ToR

OWL_REPLY

pathID	d_{205}^{rec}
205	50000

An example of one-way latency calculation

Per-destination ToR Timeout Update

We update the timeout $T_{s,d}$, stored in ToR $\boldsymbol{s}$, using an Exponentially Weighted Moving Average upon the arrival of an OWL_REPLY or an aging event.

1. One-way latency gap calculation

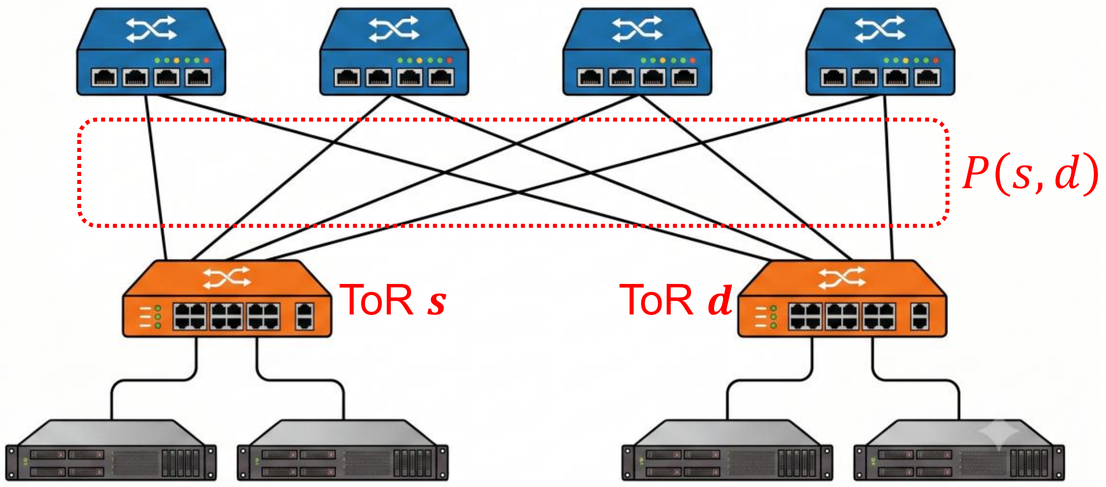
$$G_{s,d} = \max_{i \in P(s,d)} (d_i) - \min_{i \in P(s,d)} (d_i)$$

2. Target timeout calculation

$$T_{s,d}^{\text{target}} = G_{s,d} + t^{lb}$$

3. Asymmetric timeout update

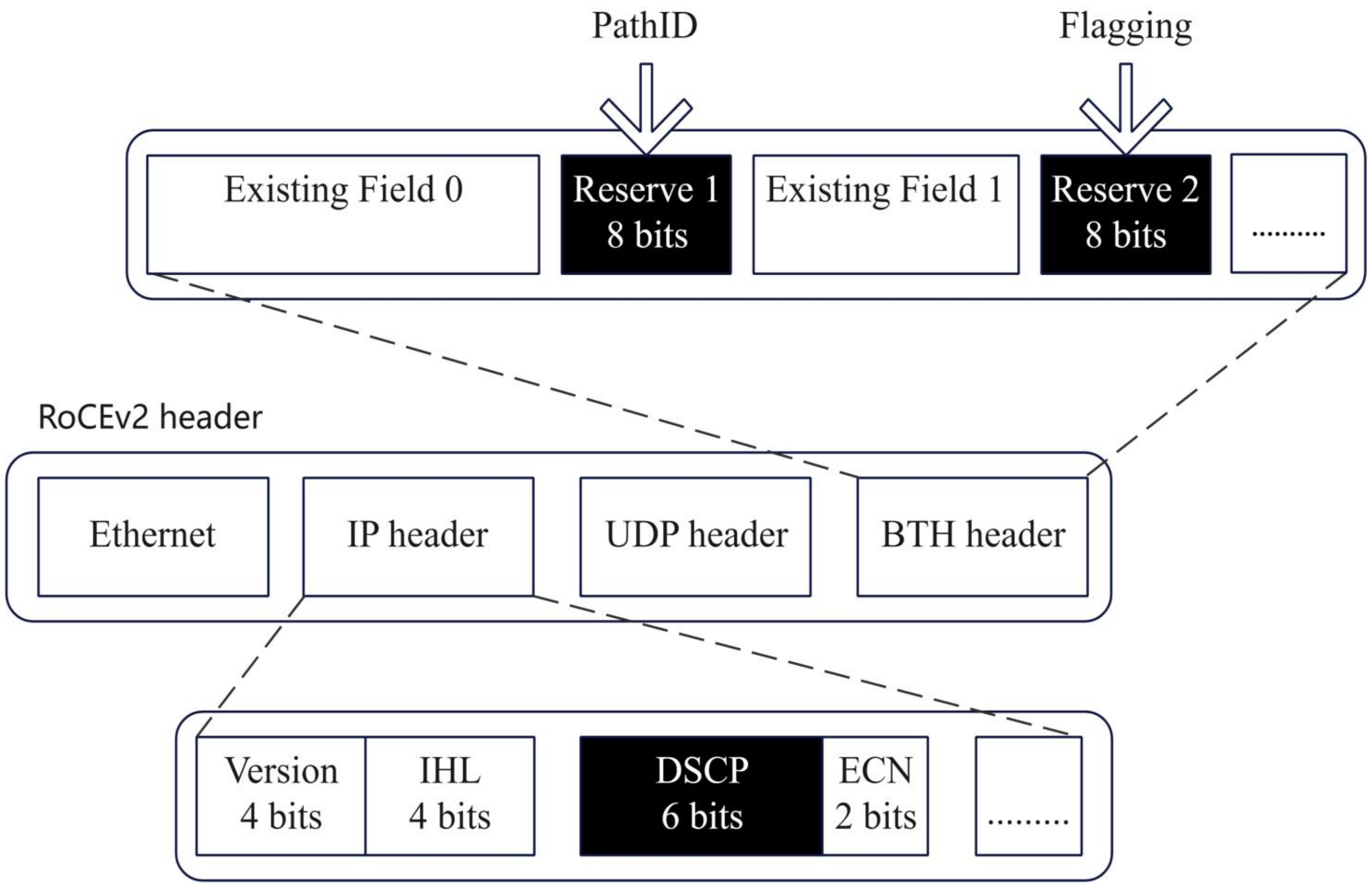
$$T_{s,d} = (1-\alpha) \cdot T_{s,d} + \alpha \cdot T_{s,d}^{\text{target}}$$



Header Format

Source ToR encodes the PathID and flagging into the IB **Base Transport Header**

- Preserves the original RoCEv2 data packet header format
- Implements source routing using PathID or SRV6



The ProLet data packet format

Evaluation Overview

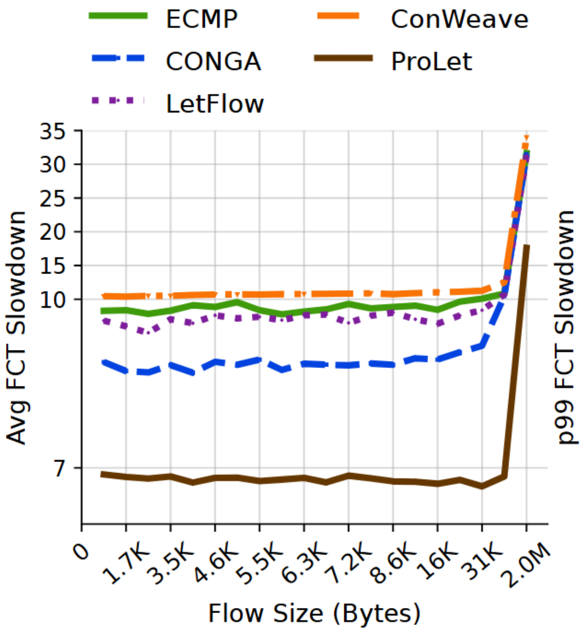
Workloads:
- Alibaba storage
- All-to-all traffic

Metrics:
- Average FCT slowdown; P99 FCT slowdown
- Average flowlet packet count; PFC pause frame count

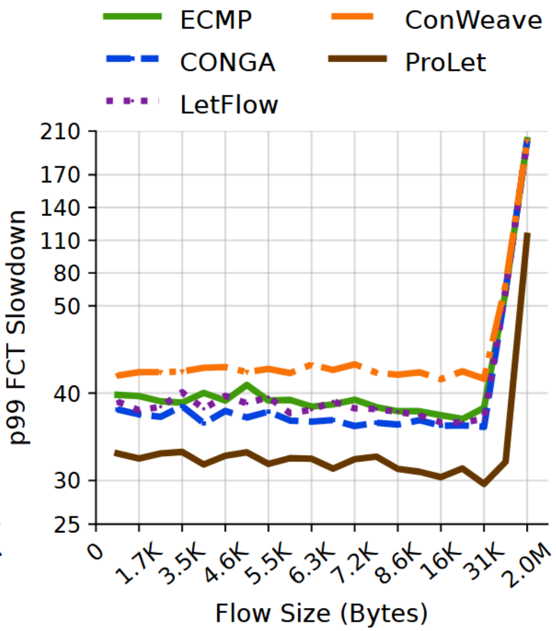
Topology:
- 32-host Fat Tree topology
- 128-host Spine Leaf topology

Baseline
- ECMP
- Conga
- LetFlow
- ConWeave

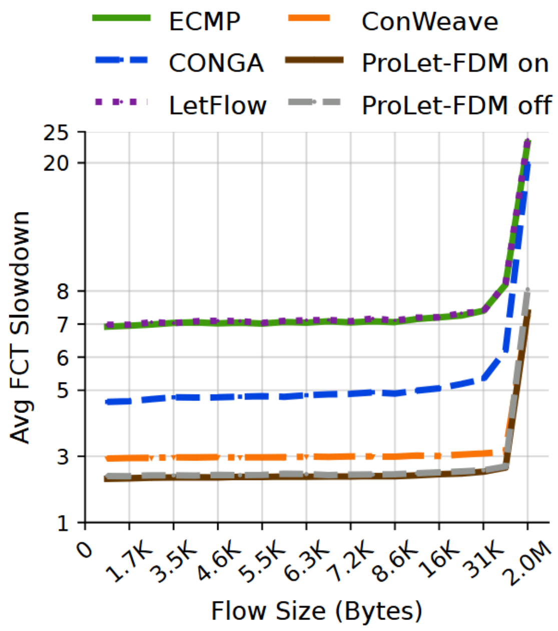
FCT Performance Gain



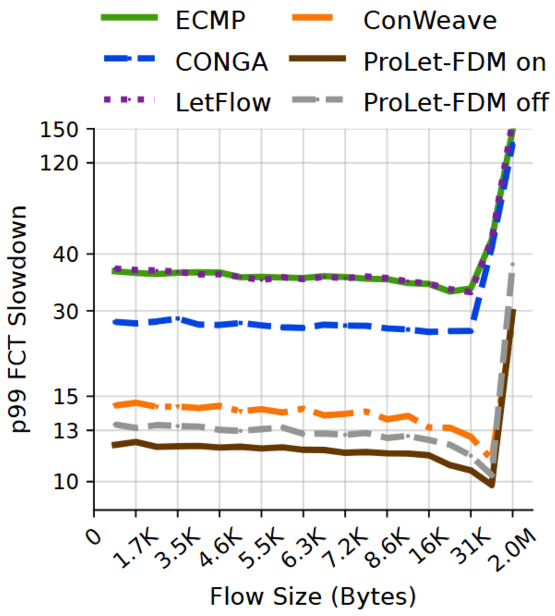
(a) Average FCT, Fat-Tree-32.



(b) P99 FCT, Fat-Tree-32.



(c) Average FCT, Spine-Leaf-128.



(d) P99 FCT, Spine-Leaf-128.

ProLet reduces the average and P99 FCT slowdowns by up to 69% and 79%, respectively

Dynamic per-destination ToR timeout fine-tuning reduces the average and tail FCT slowdowns by 9% and 21%, respectively

Flowlet Identification and PFC Count Comparison

- **ProLet** with timeout fine-tuning reduces PFC pause frames by up to 96%
- **ProLet** reduces the average flowlet packet count (flowlets with > 100 packets) from 669 to 407, a 39% decrease

Scheme	**Avg. Packet Count**	**PFC Frames (M)**
ECMP [6]	—	12.7
CONGA [1]	638	9.8
LetFlow [26]	612	12.9
ConWeave [24]	—	0.8
ProLet-FDM off	669	0.7
ProLet-FDM on	407	0.5

Conclusion and Future Work

Conclusion

- **ProLet** leverages lightweight mice flows as proactive probes to maintain network-wide congestion awareness. This enables rerouting of elephant flows before congestion accumulates
- **ProLet** dynamically fine-tunes per-destination ToR timeouts to enable efficient in-network flowlet identification
- **ProLet** reduces the average and P99 FCT slowdowns by up to 69% and 79%, respectively

Future Work

- Automate parameter tuning for diverse workloads
- Dynamically adjust routing granularity between packet spraying and flowlets to adapt to path congestion asymmetry in lossless RDMA

Thank You!

The code for simulation is available at https://github.com/MUN-DML/prolet