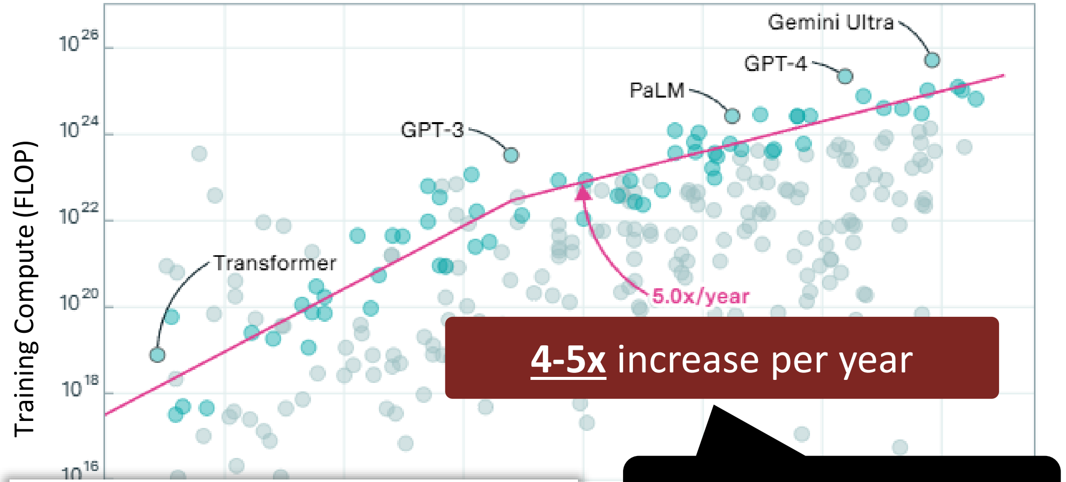
Uno: A One-Stop Solution for Inter- and Intra-Data Center Congestion Control and Reliable Connectivity

Tommaso Bonato* [1,3], Sepehr Abdous* [2,3], Abdul Kabbani [3], Ahmad Ghalayini [3], Nadeen Gebara [3], Terry Lam [3], Anup Agarwal [3,5], Tiancheng Chen [1], Zhuolong Yu [3], Konstantin Taranov [3], Mahmoud Elhaddad [3], Daniele De Sensi [4], Soudeh Ghorbani [2], Torsten Hoefler [1]

[1]ETH Zürich, [2]Johns Hopkins University, [3]Microsoft, [4]Sapienza University Of Rome, [5]CMU, * Equal contribution

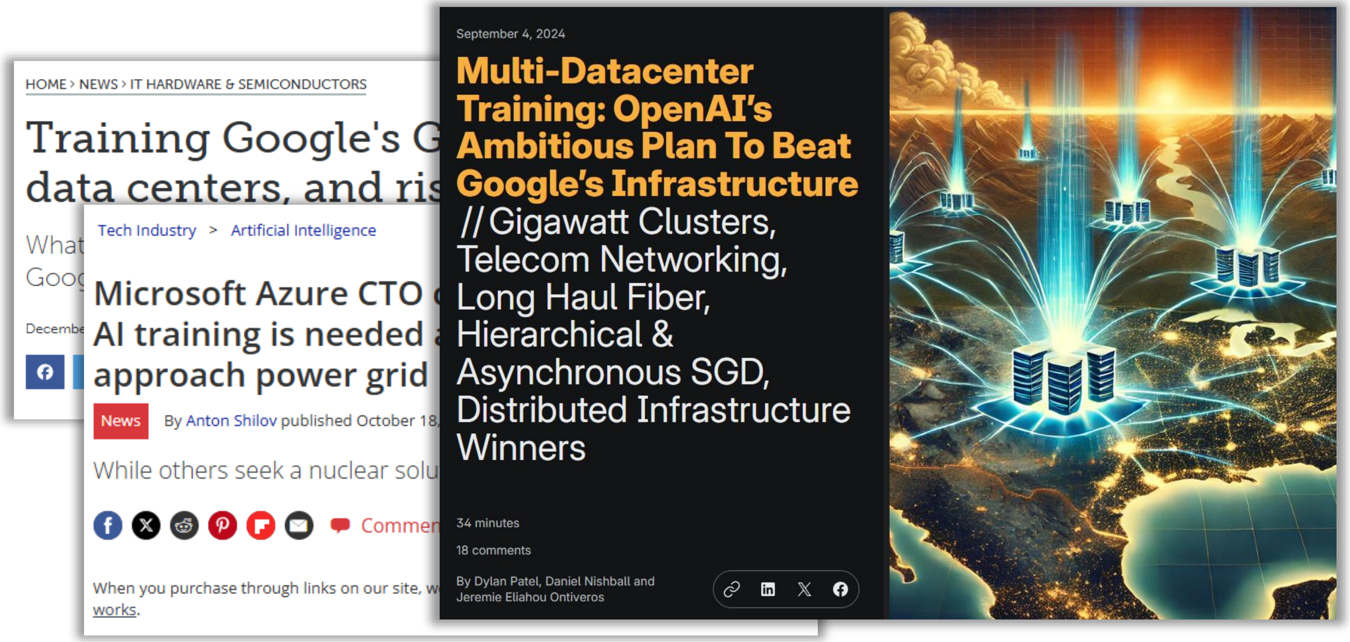
Motivation

Frontier LLM Models [1]



4-5x increase per year

Increasing power demand



"We had to scale to more compute, and that compute was not available as part of one cluster. We had to go to **multi-cluster training**"

GPT4.5 Team
April 2025

*"**We don't disclose exactly the details** of how many locations but Gemini Ultra was trained **across multiple sites**, and multiple clusters within those sites."*

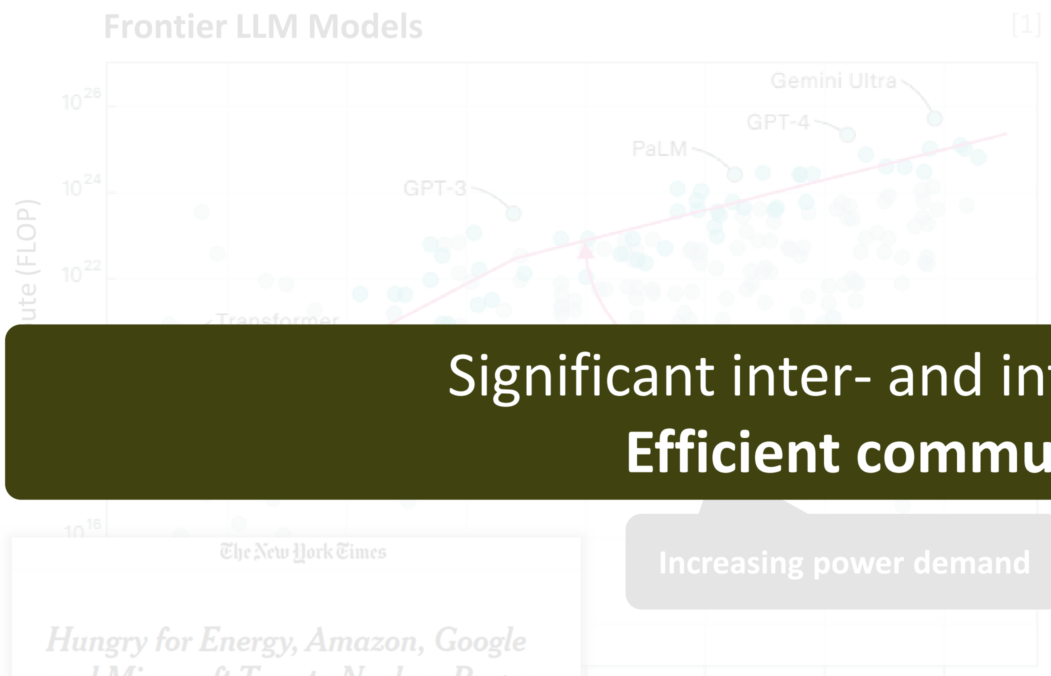
Thomas Kurian, CEO Google Cloud
December 2023

Problem: local power limitation, increased complexity

Solution: training across **multiple** datacenters

[1] Training Compute of Frontier AI Models Grows by 4-5x per Year, Report, Epoch AI, 2024

Motivation



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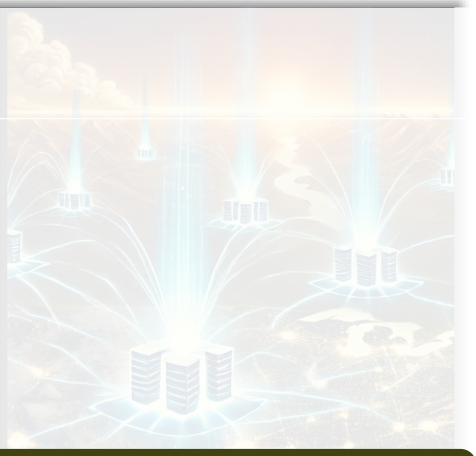
By Anton Shilov published October 18

September 4, 2024

Multi-Datacenter Training: OpenAI's Ambitious Plan To Beat Google's Infrastructure

// Gigawatt Clusters, Telecom Networking, Long Haul Fiber, Hierarchical & Asynchronous SGD, Distributed Infrastructure Winners



Significant inter- and intra-DC traffic co-existence inside DCs

Efficient communication becomes challenging

The New York Times

Hungry for Energy, Amazon, Google and Microsoft Turn to Nuclear Power

Large technology companies are inve… nuclear energy as an emissions-free … artificial intelligence and other busin…

IN-BRIEF ANALYSIS

OCTOBER 1, 2024

Data center owners turn to nuclear as potential electricity source

Nuclear power plants that have signed agreements to power data centers (as of Sep 2024)

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> GPT4.5 Team, April 2025

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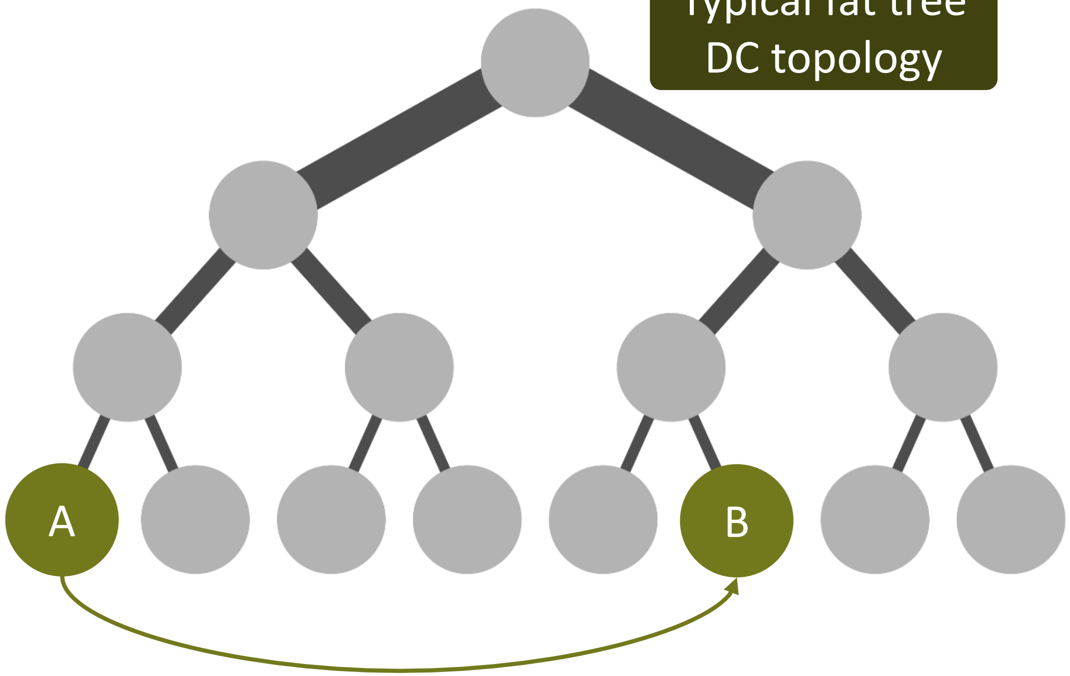
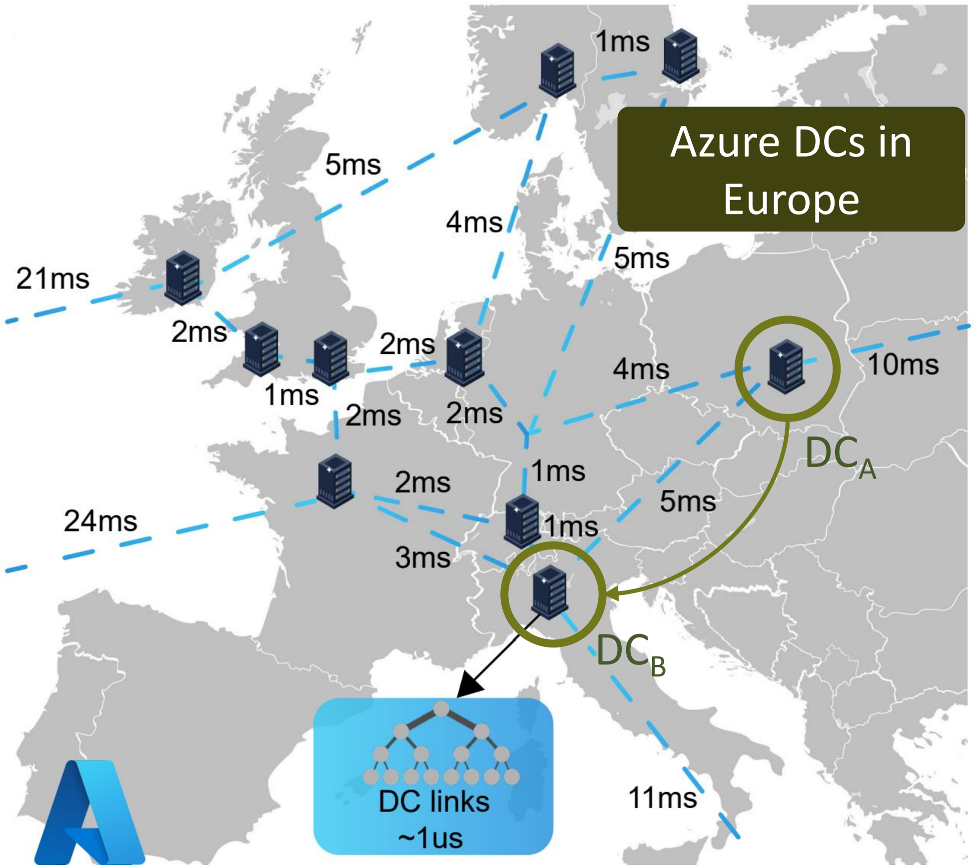
Motivation

Typical fat tree DC topology



Azure DCs in Europe



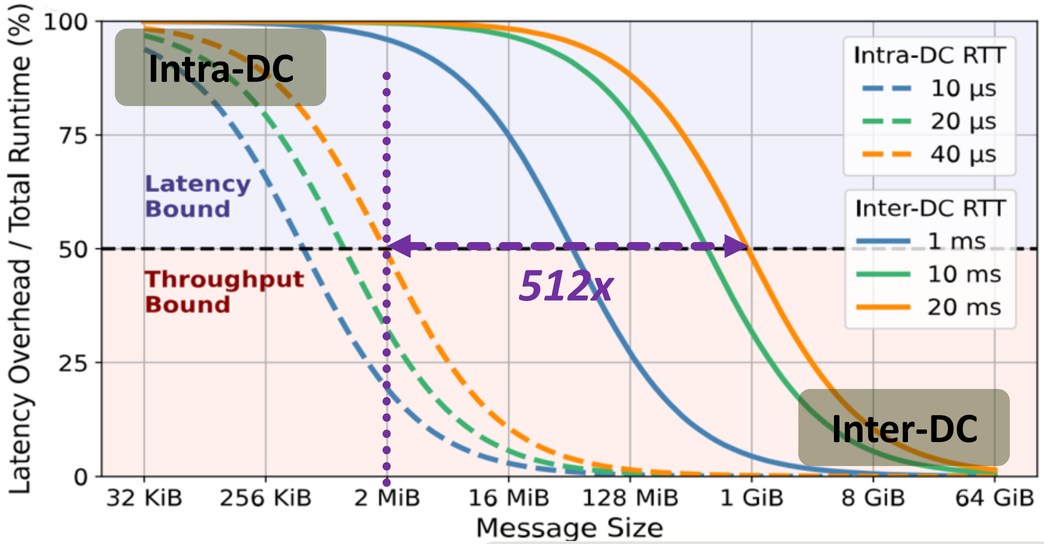
Short Cables (<100m) → ~1us latency
RTT from A to B → ~12us

Long cables (>100km) → >1ms latency
RTT from DC_A to DC_B → 10ms

1000x latency difference

RTT = Round-Trip Time

Inter- and intra-DC RTTs have huge gaps



Slow loss detection and recovery

>1 ms RTT across datacenters

BDP <-> Buffer sizes mismatch

~ 100 MB buffering **per port** with 10 ms inter-DC RTT

Unfairness / slow convergence to fairness

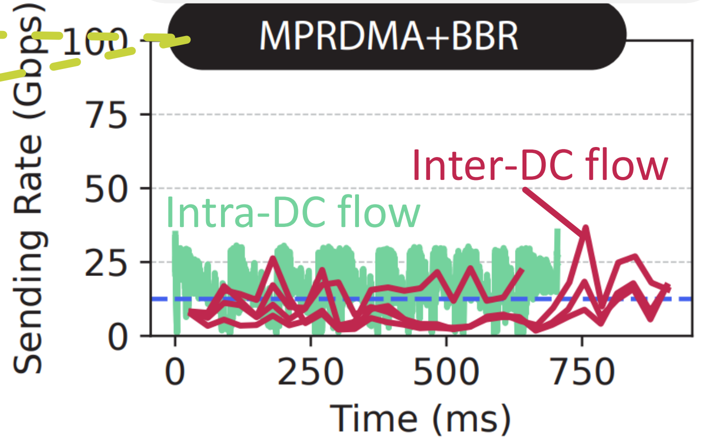
Huge gap in congestion notification and reaction granularity

Existing solutions fall short in **efficiently** converging to fairness

8:1 incast from senders both inside and across datacenters

Reaching guaranteed fairness is **challenging**

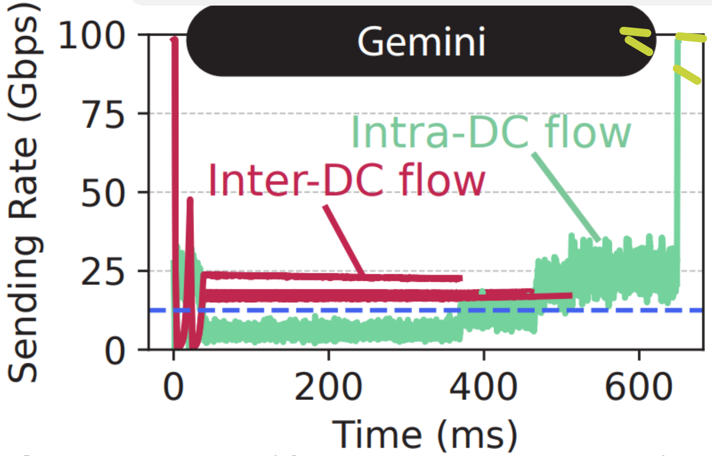
Separate control loops



[BBR: Congestion-based congestion control., Commun. ACM 2017]

[Multi-Path transport for RDMA in datacenters, NSDI 2018]

Unified control loops



[Congestion Control for Cross-Datacenter Networks, ToN 2022]

Reaches **fairness** but convergences is **very slow**

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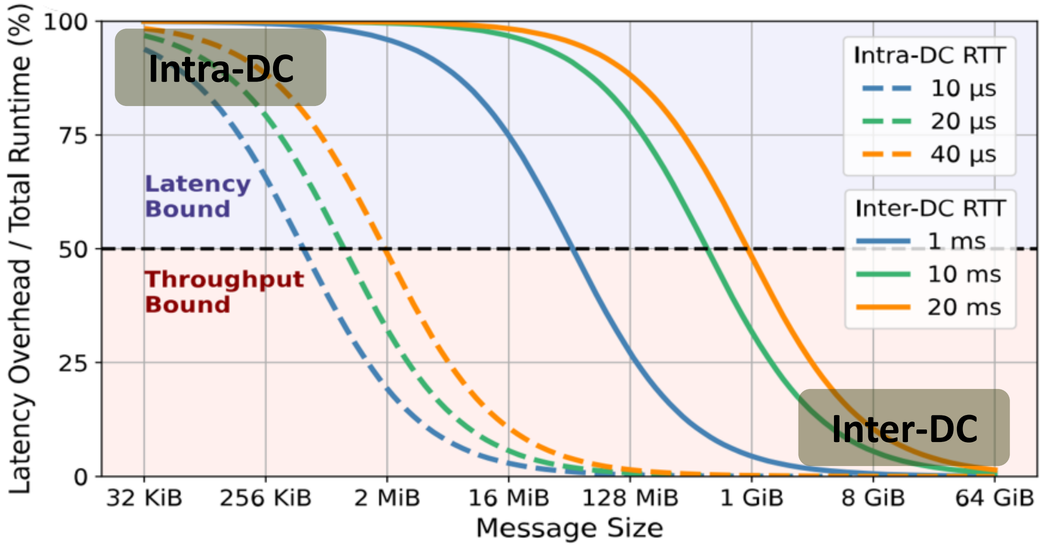

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Congestion Control is crucial

Uno

Throughput Bound

Vastly diverse RTTs and delayed feedback

Mismatch between BDP and buffer capacity.

UnoCC
Fair between different RTTs.
Uses phantom queues to mitigate BDP mismatch.

Latency Bound

Most messages are latency bound.

Single loss can have a dramatic impact.

UnoRC
Incorporates erasure coding with load balancing (UnoLB) to limit drops.

Reliability is the most important aspect

UnoCC: fast and fair congestion control for intra- and inter-DC traffic

BDP <-> buffer size mismatch

Phantom Queues (PQs)

Phantom Queues
- Virtual queues implemented as a counter
- Increase when a packet arrives
- Decrease at a constant rate

Input Ports

PQ

Physical Queue

PQ

Physical Queue

Output Ports

Switch

Can grow potentially **unbounded** to better assess congestion levels

Leaving **headroom** to absorb **bursts**

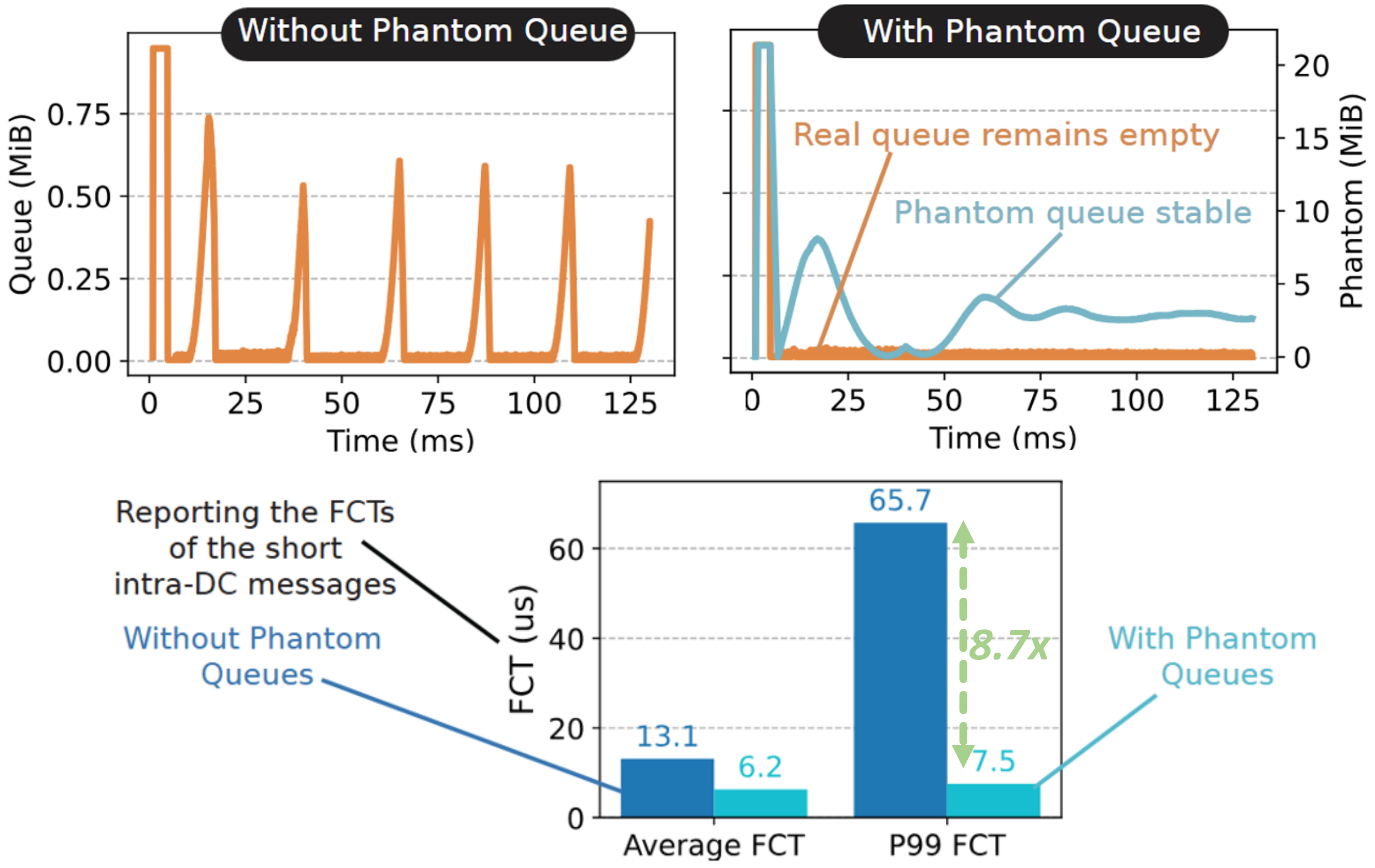
Enabling **early congestion detection**

UnoCC: fast and fair congestion control for intra- and inter-DC traffic

BDP <-> buffer size mismatch

Phantom Queues (PQs)

Google RPCs beside eight long-lived cross-DC flows



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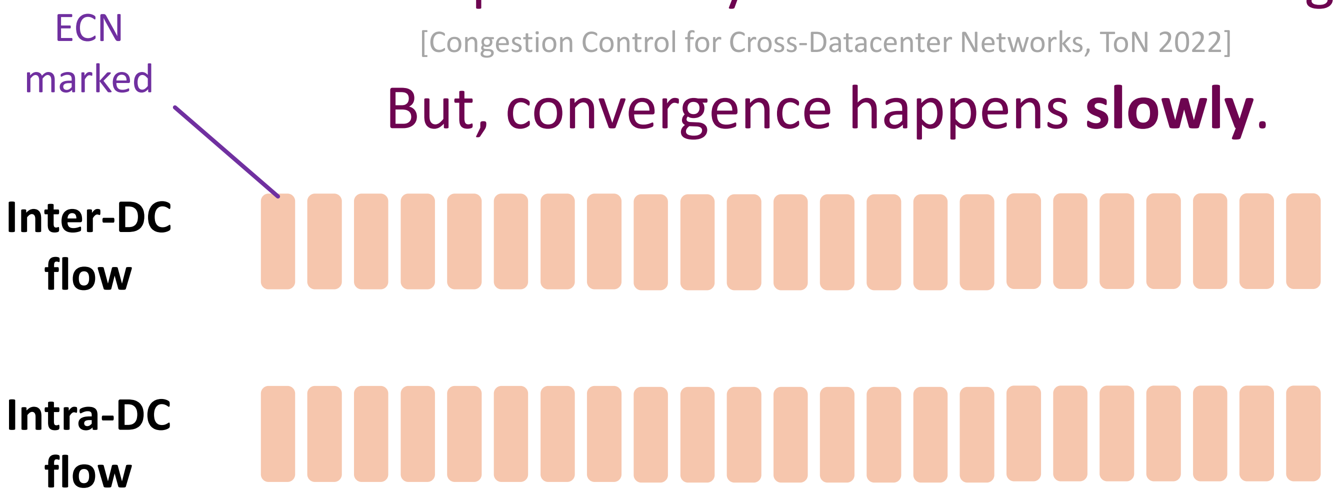
Unfairness/slow convergence

We can potentially achieve **fairness** using **AIMD**.

[Congestion Control for Cross-Datacenter Networks, ToN 2022]

But, convergence happens **slowly**.



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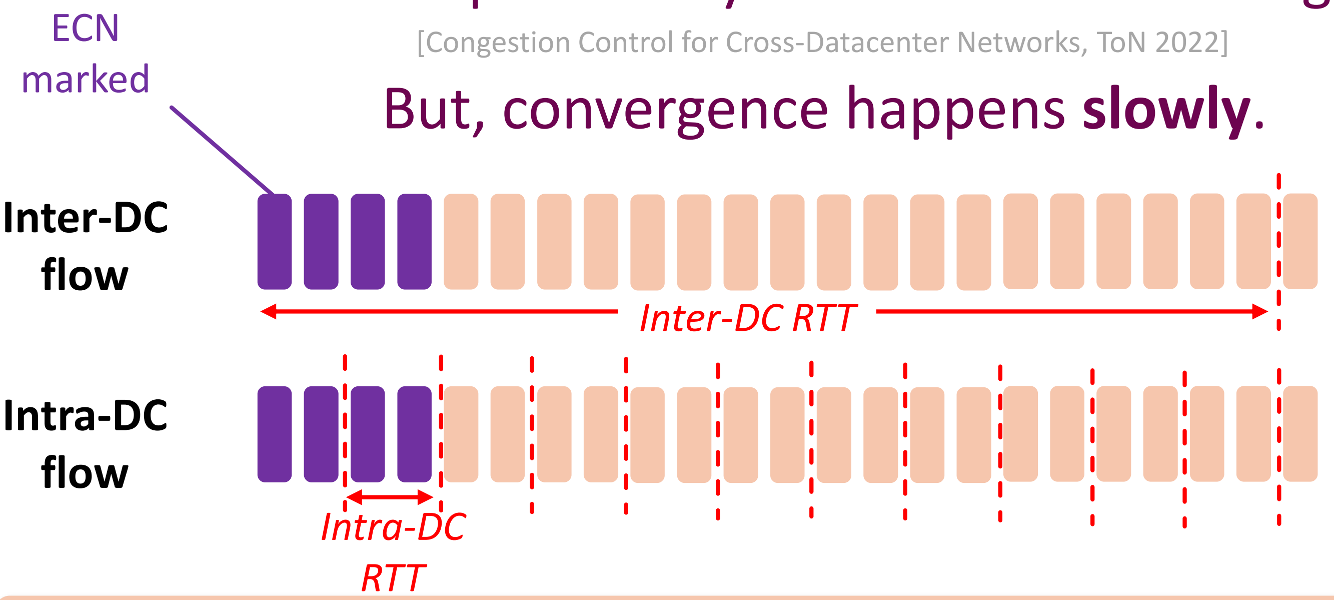

Rate reduced at different granularities, **prolonging convergence to fairness**

Same degree of congestion captured differently, **causing configuration sensitivity**

UnoCC: fast and fair congestion control for intra- and inter-DC traffic

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Unified reaction granularity to congestion

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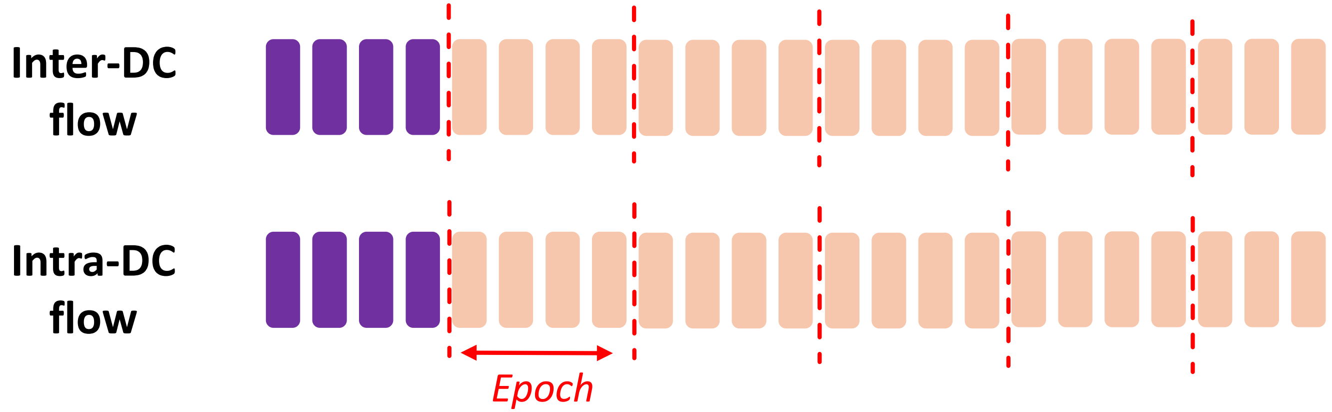

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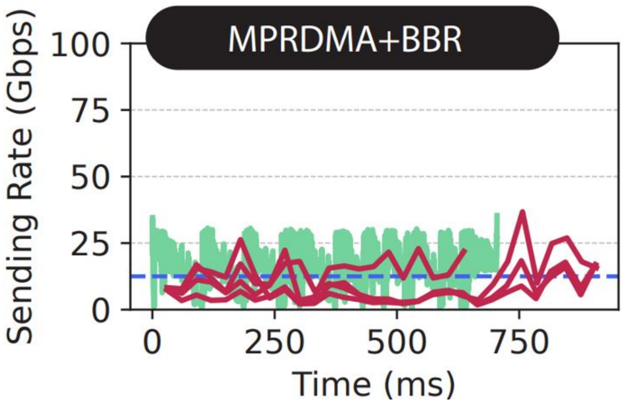
Unfairness/slow convergence

Unified reaction granularity to congestion

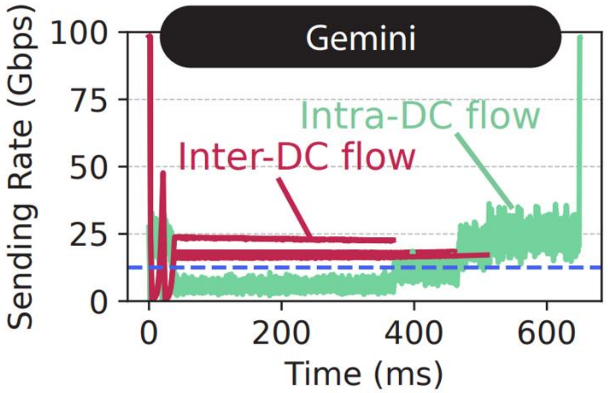
Drastic rate reduction under extreme congestion

Smoother rate reduction upon phantom queue congestion

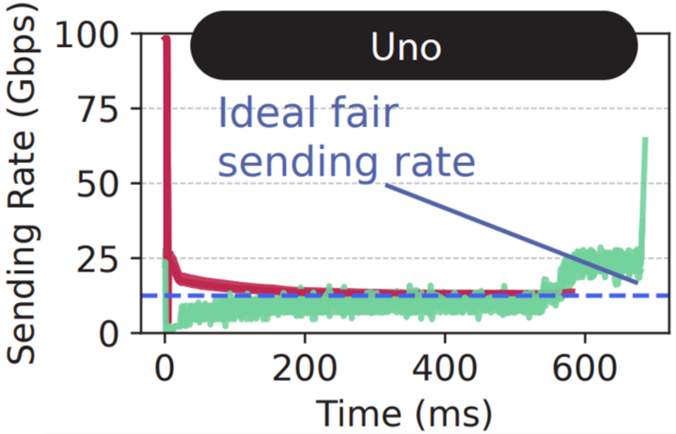
8:1 incast from senders both inside and across datacenters



Unfairness



Slow convergence to fairness

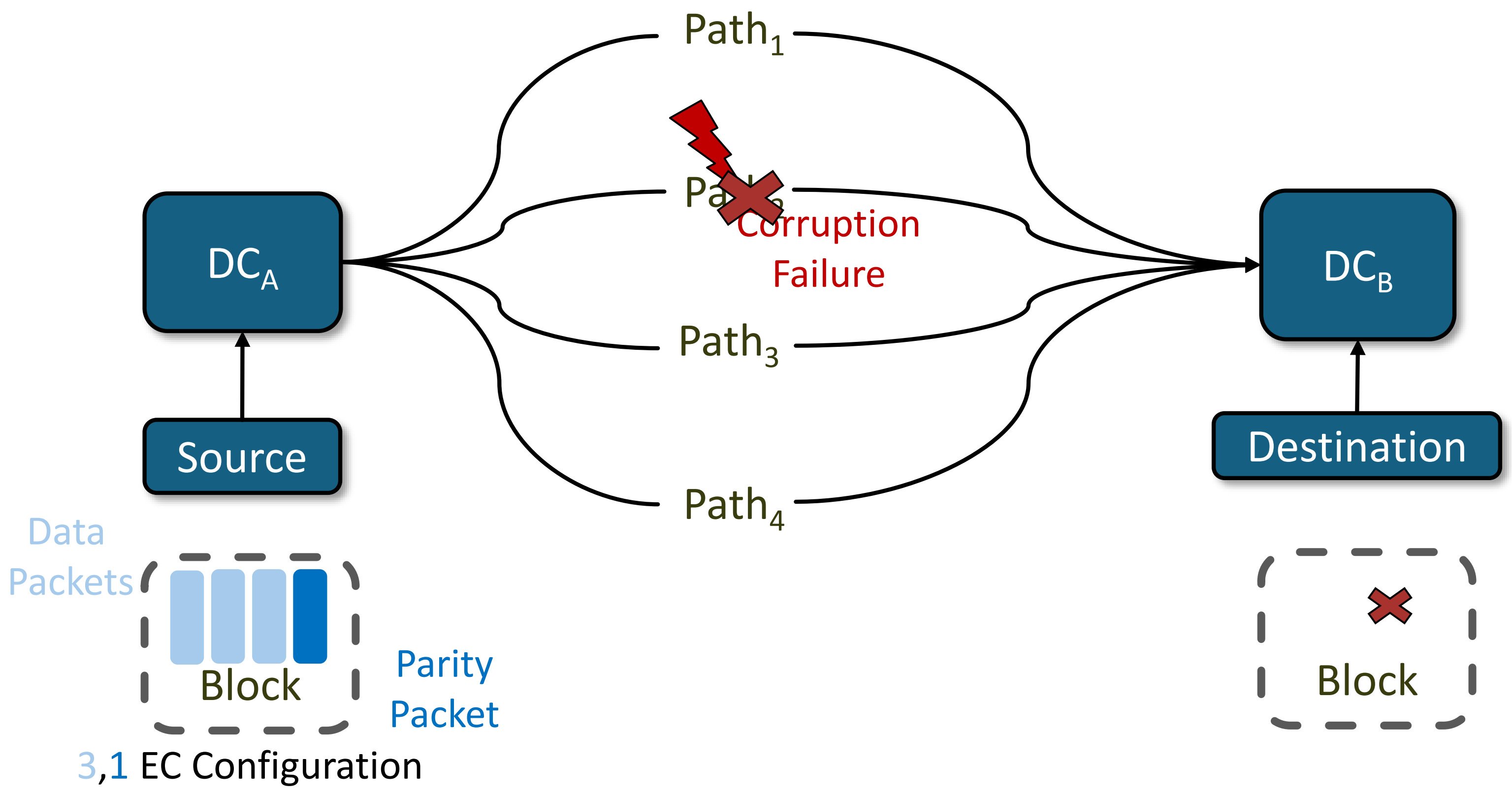


Fast convergence to fairness

UnoRC: Reliable connectivity through load balancing and erasure coding

Packet losses are destructive when latency-bound

Losses are recovered through erasure coding



Data Packet is lost but receiver can still reconstruct the block

However, a link failure would still prevent the block from being delivered

UnoRC: Reliable connectivity through load balancing and erasure coding

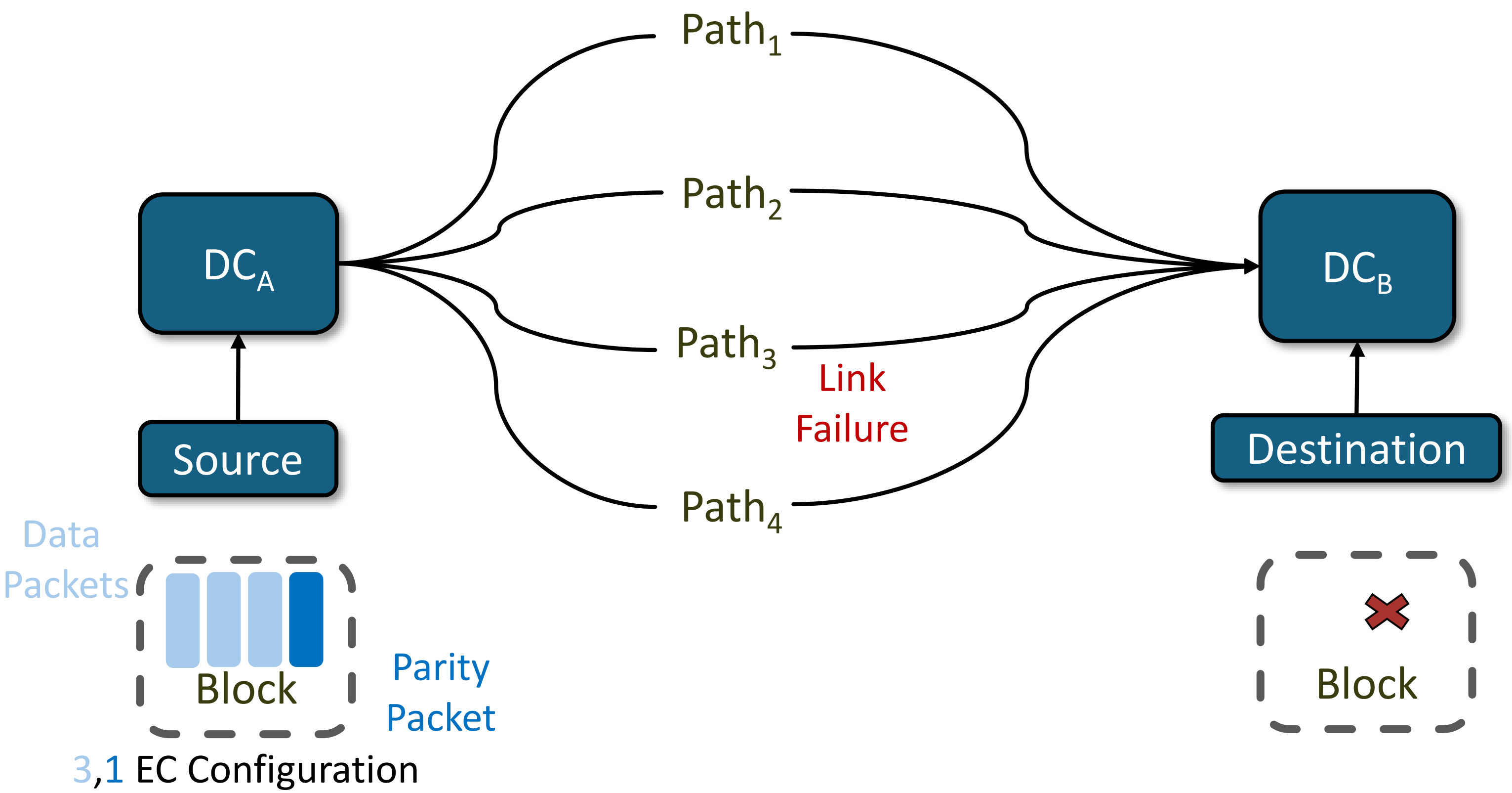
Packet losses are destructive when latency-bound

Losses are recovered through erasure coding

Erasure coding helps recovery from drops but not from failures

Adaptive load balancing to utilize multipathing

Tightly integrate LB with EC to ensure resiliency even with failures



The block is reconstructed even with a link failure thanks to multipathing

UnoRC quickly learn to avoid the failing path by looking at when it last was active

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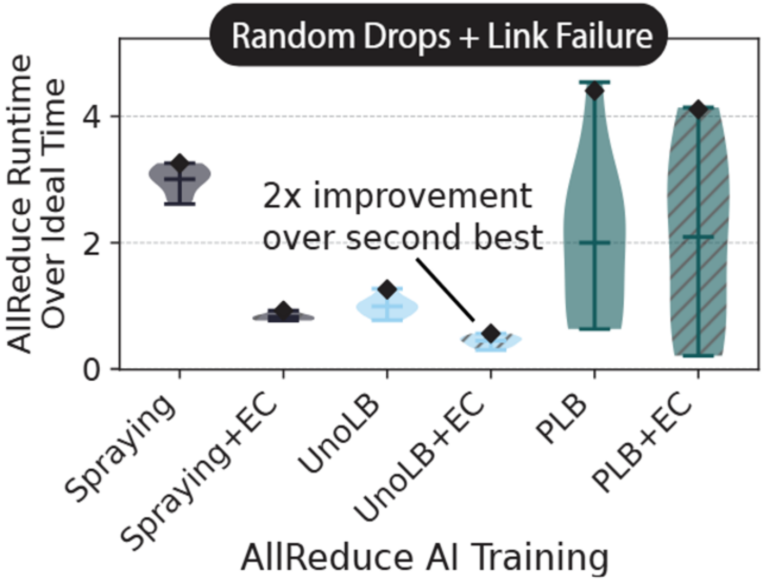
Measured Drop Rates

Losses Within a Block	Setup 1 (65ms RTT)		Setup 2 (33ms RTT)	
	Drops	Loss Rate	Drops	Loss Rate
1	97 403	3.0×10^{-4}	12 785	4.0×10^{-5}
2	23 984	7.5×10^{-5}	7 262	2.3×10^{-5}
3	5 007	1.6×10^{-5}	1 560	4.9×10^{-6}

Table 1: Packet loss information for two datacenter configurations.

CrossPipe Schedule

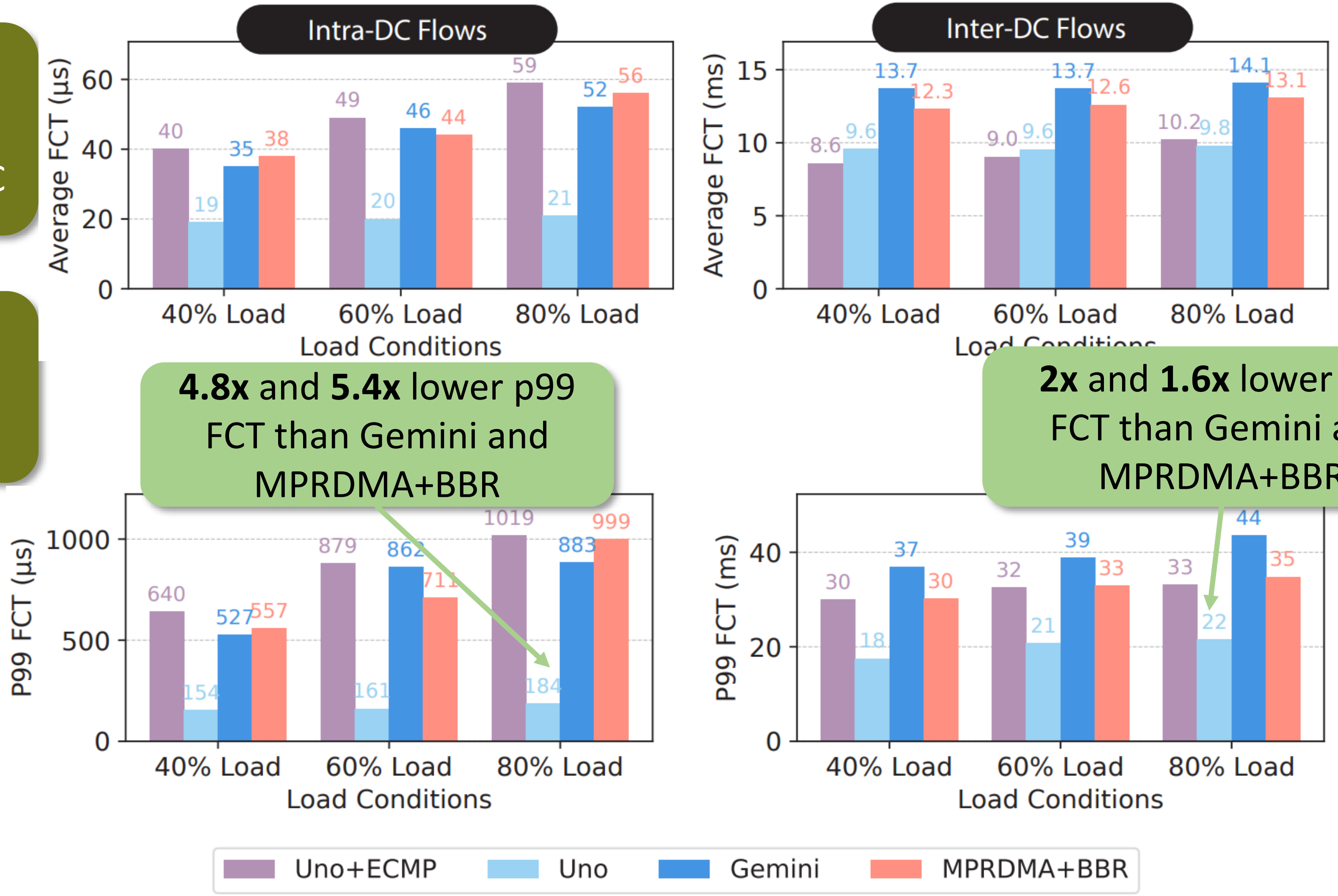


[CrossPipe: Towards Optimal Pipeline Schedules for Cross-Datacenter Training, ATC 2025]

Uno is performant under realistic workload

Large-scale simulations with ***100 Gbps*** links and an RTT difference of ***128x*** between intra-DC and inter-DC

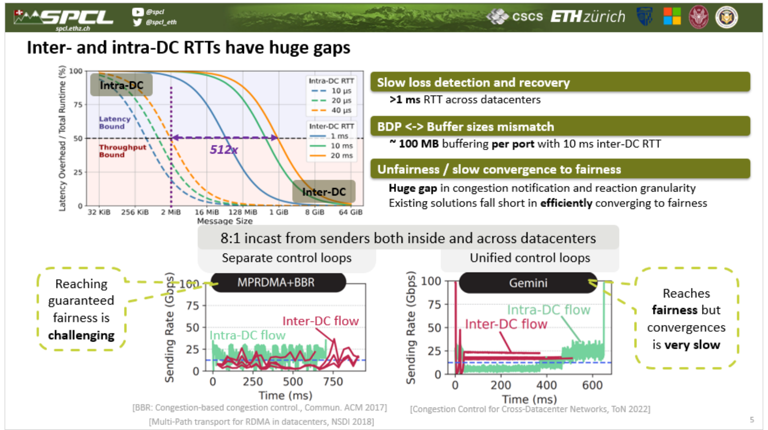
Running Datacenter Traces
Google web search + Alibaba WAN

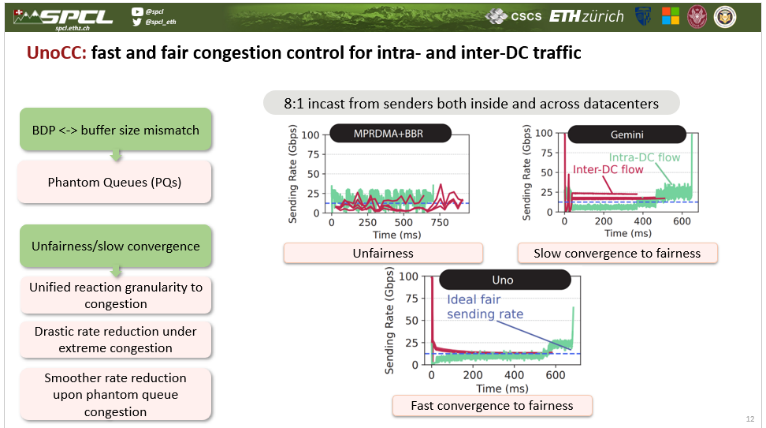


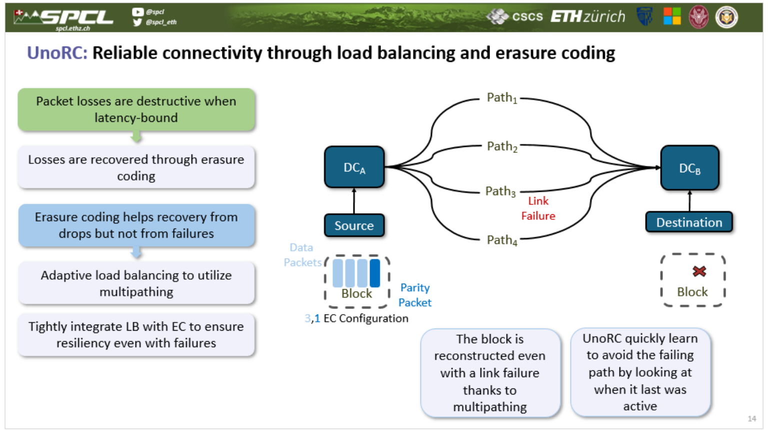
4.8x and **5.4x** lower p99 FCT than Gemini and MPRDMA+BBR

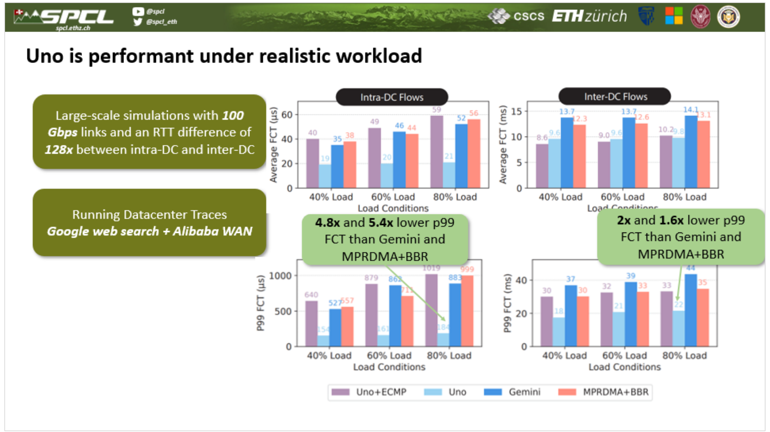
2x and **1.6x** lower p99 FCT than Gemini and MPRDMA+BBR

Conclusions









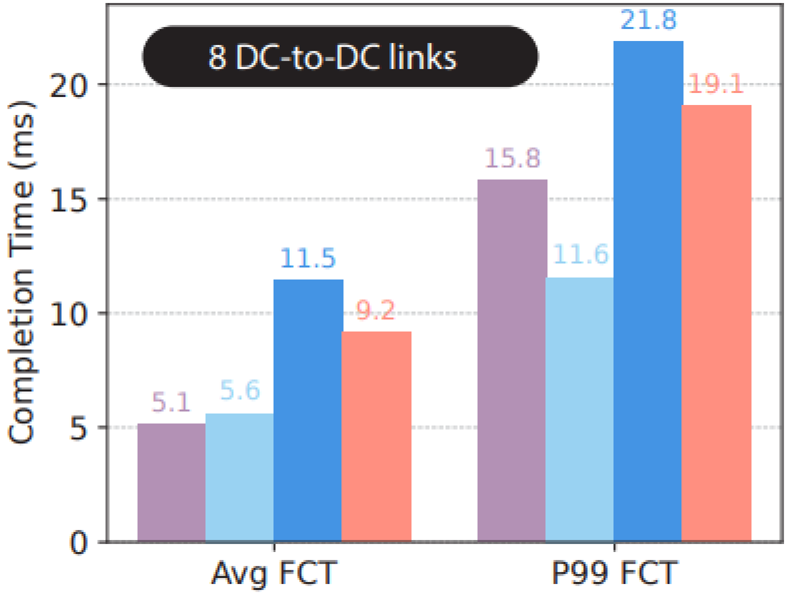
Paper:

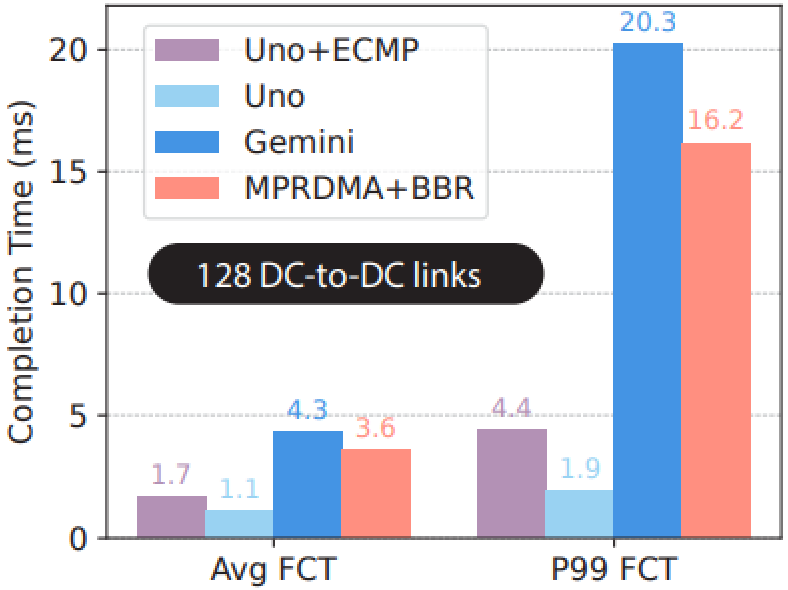
Open-source code and artifact:

BackUp Slides

Uno Benchmarks

Permutation Workload





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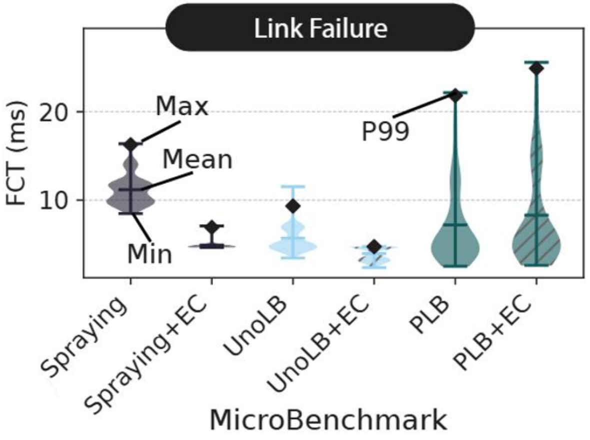

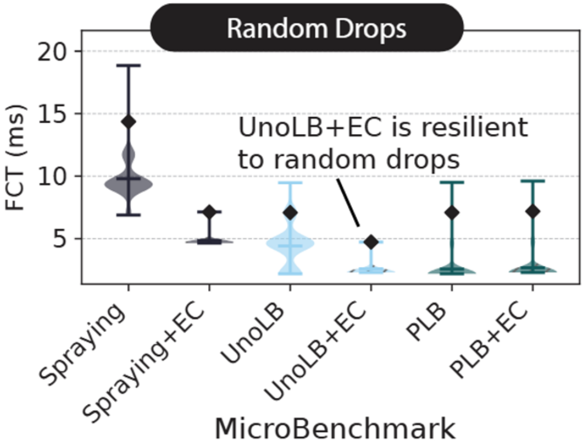

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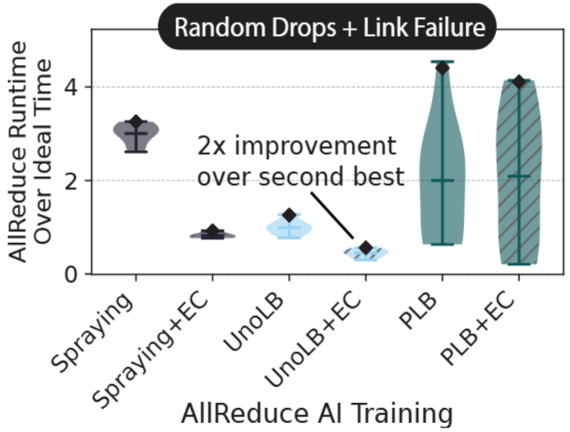

[CrossPipe: Towards Optimal Pipeline Schedules for Cross-Datacenter Training, ATC 2025]