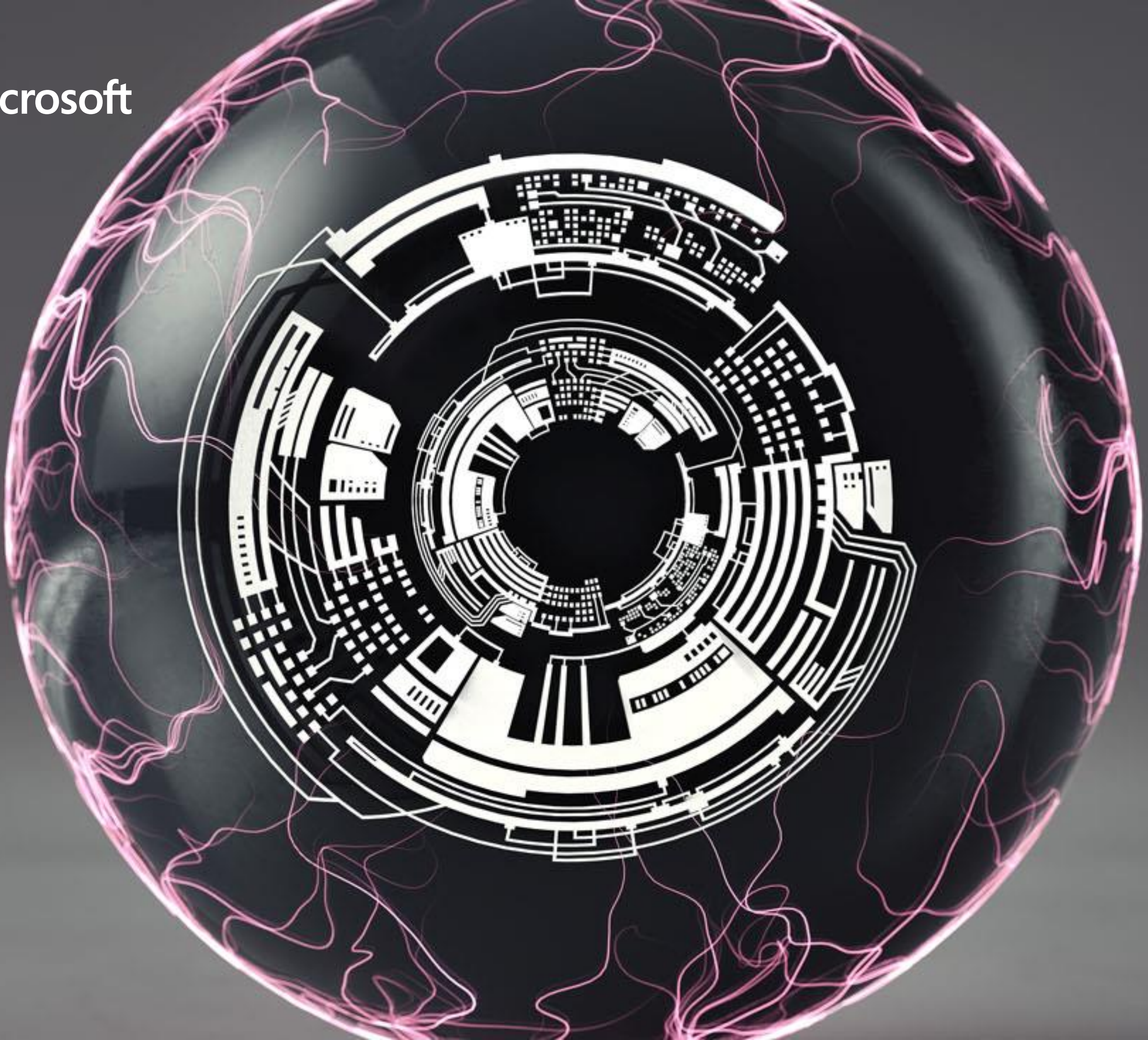
Microsoft

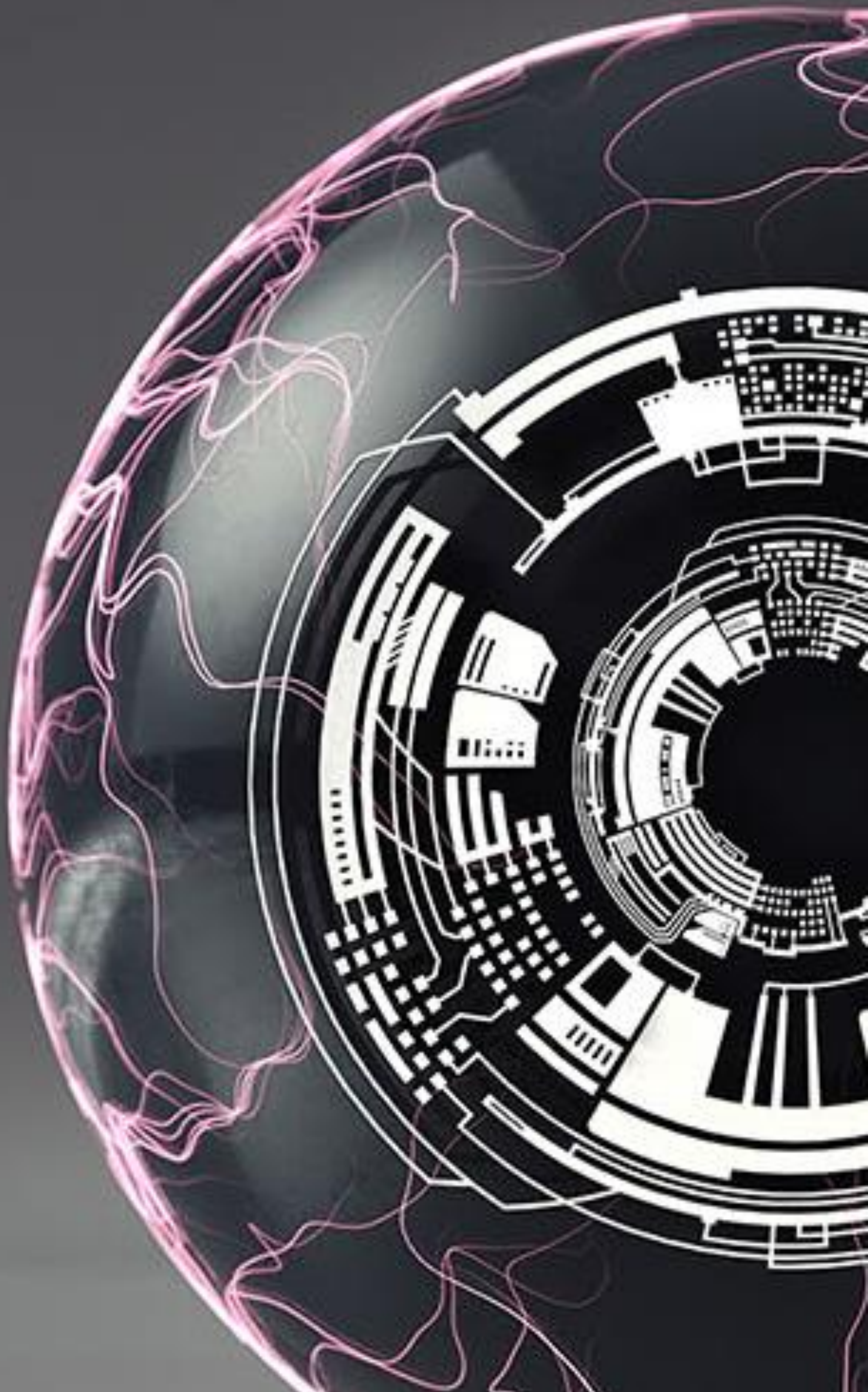


Microsoft Research Faculty Summit 2016

Microsoft

RDMA Congestion Control: ECN or Delay?

Vishal Misra
Columbia University, joint work with Yibo Zhu, Monia Ghobadi, Jitendra Padhye (all Microsoft)



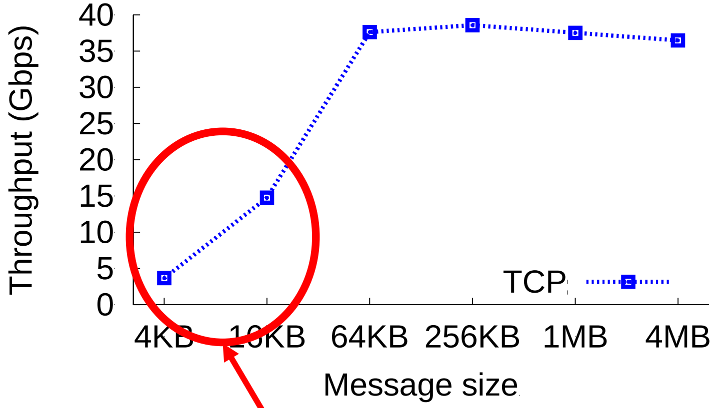
Outline

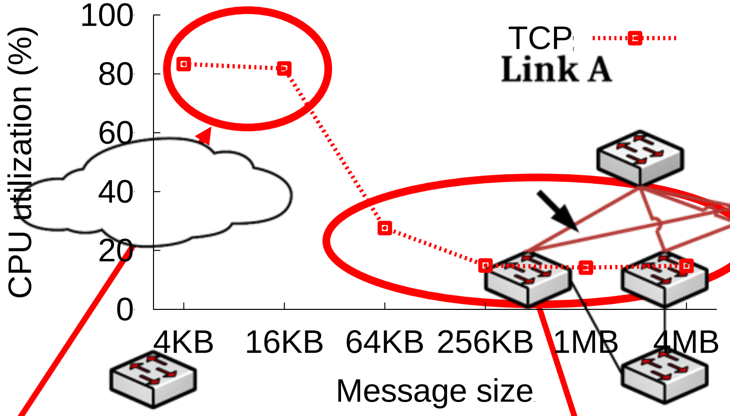
- Why RDMA Congestion Control?
- Congestion Signals
  - Google approach: delay
  - Microsoft approach: ECN
- ECN vs Delay comparison
  - Stability, Speed of Convergence
  - Fixed points
  - Flow completion time comparison for a standard datacenter benchmark
  - ECN: faster feedback. Delay: slower, distorted feedback
  - PI control: fundamental tradeoff

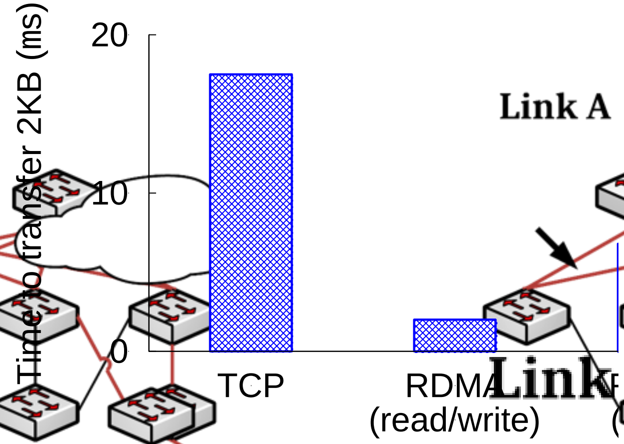
Host TCP Stack is Heavyweight

Sender → → Receiver

40Gbps NICs, state-of-the-art servers, 16 cores







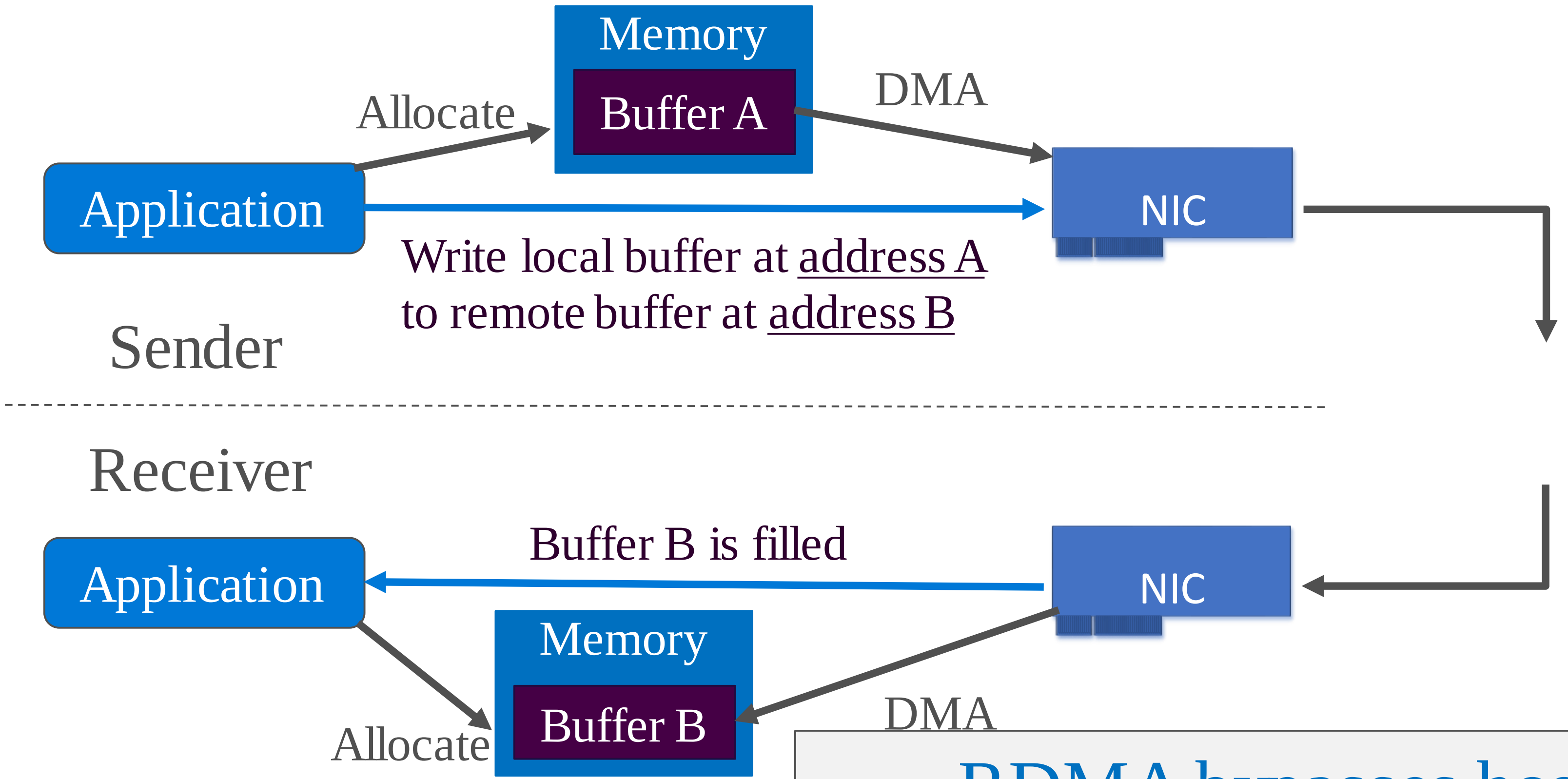
Small messages → CPU is the bottle k

Larger msgs PU

cores a

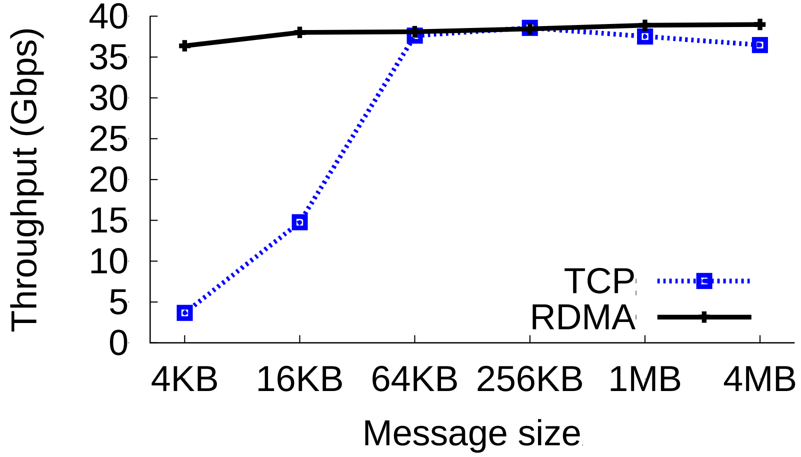
Reciever

Solution: RDMA

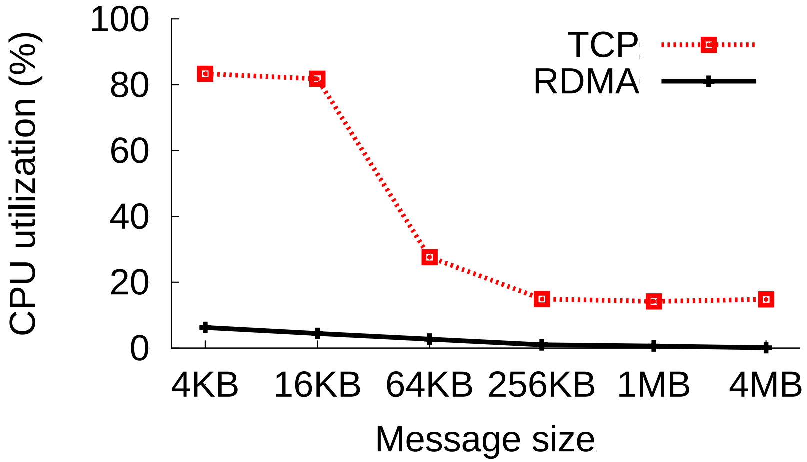


RDMA bypasses host OS stack
→ frees host CPU, lowers latency

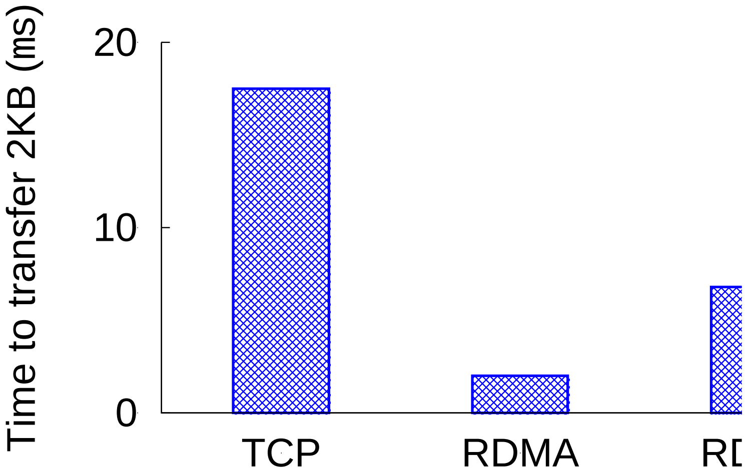
RDMA Outperforms TCP



RDMA single thread ~40Gbps



RDMA CPU ~0%



RDMA latency 1~2 μs

RDMA in Modern Datacenters

- In past, RDMA deployed on special fabrics, i.e., InfiniBand
- InfiniBand incompatible with Ethernet + IP
- Solution: RoCEv2 (RDMA over Converged Ethernet)
- Problem: RoCEv2 has very blunt congestion control called “PFC”
  - Stop flows when queues build up

Enter DCQCN and TIMELY: Congestion Control for ROCEv2

DCQCN (Microsoft)

- Based on DCTCP
- Switch marks packets on detecting congestion (ECN)
- Receiver reflects marked packets via ACKs
- Sender adjusts rate using DCQCN algorithm
- Ongoing deployment on Microsoft Azure

TIMELY (Google)

- Based on TCP Vegas
- Switch plays no role (FIFO queue assumed)
- Receiver sends ACKs(once per burst)
- Sender estimates Delay, and responds to derivative.
- Ongoing deployment at Google

Two solutions to the same problem

- Key difference: ECN vs. Delay
  - There are other differences as well – e.g. hardware packet pacing
- Comparing their design and performance can yield valuable insights
- Properties we care about:
  - Stability: flow rates and queue length stabilize
  - Fast convergence: system should stabilize quickly
  - Fairness: at stable point, flows should share bandwidth equally
  - High link utilization
  - Low flow completion time

Methodology

- Fluid model
  - For analytical results
- .. backed by NS simulations
  - For packet-level results
- .... backed by (in case of DCQCN) implementation comparison
  - to ensure some connection to reality
- Assumptions
  - Long lived flows
  - Identical RTT
  - Single shared bottleneck

Some equations to impress you …

$$p(t) = \begin{cases} 0, & q(t) \le K_{\min} \\ \frac{q(t)-K_{\min}}{K_{\max}-K_{\min}} p_{\max}, & K_{\min} < q(t) \le K_{\max} \\ 1, & q(t) > K_{\max} \end{cases} \tag{3}$$

$$\frac{dq}{dt} = \sum_{i=1}^{N} R_C^{(i)}(t) - C \tag{4}$$

$$\frac{d\alpha^{(i)}}{dt} = \frac{g}{\tau'}\left(\left(1-(1-p(t-\tau*))^{\tau' R_C(t-\tau*)}\right) - \alpha^{(i)}(t)\right) \tag{5}$$

$$\begin{aligned} \frac{dR_T^{(i)}}{dt} = &-\frac{R_T^{(i)}(t) - R_C^{(i)}(t)}{\tau}\left(1-(1-p(t-\tau*))^{\tau R_C^{(i)}(t-\tau*)}\right) \\ &+ R_{AI} R_C^{(i)}(t-\tau*)\frac{(1-p(t-\tau*))^{FB} p(t-\tau*)}{(1-p(t-\tau*))^{-B}-1} \\ &+ R_{AI} R_C^{(i)}(t-\tau*)\frac{(1-p(t-\tau*))^{FT R_C^{(i)}(t-\tau*)} p(t-\tau*)}{(1-p(t-\tau*))^{-T R_C^{(i)}(t-\tau*)}-1} \end{aligned} \tag{6}$$

$$\begin{aligned} \frac{dR_C^{(i)}}{dt} = &-\frac{R_C^{(i)}(t)\alpha^{(i)}(t)}{2\tau}\left(1-(1-p(t-\tau*))^{\tau R_C^{(i)}(t-\tau*)}\right) \\ &+ \frac{R_T^{(i)}(t) - R_C^{(i)}(t)}{2}\frac{R_C^{(i)}(t-\tau*)p(t-\tau*)}{(1-p(t-\tau*))^{-B}-1} \\ &+ \frac{R_T^{(i)}(t) - R_C^{(i)}(t)}{2}\frac{R_C^{(i)}(t-\tau*)p(t-\tau*)}{(1-p(t-\tau*))^{-T R_C^{(i)}(t-\tau*)}-1} \end{aligned} \tag{7}$$

Figure 1: DCQCN fluid model

$$\frac{dq}{dt} = \sum_i R_i(t) - C \tag{20}$$

$$\frac{dR_i}{dt} = \begin{cases} \frac{\delta}{\tau_i^*}, & q(t-\tau') < C * T_{low} \\ \frac{\delta}{\tau_i^*}, & g_i \le 0 \\ -\frac{g_i \beta}{\tau_i^*} R_i(t), & g_i > 0 \\ -\frac{\beta}{\tau_i^*}\left(1 - \frac{C * T_{high}}{q(t-\tau')}\right) R_i(t), & q(t-\tau') > C * T_{high} \end{cases} \tag{21}$$

$$\frac{dg_i}{dt} = \frac{\alpha}{\tau_i^*}\left(-g_i(t) + \frac{q(t-\tau') - q(t-\tau'-\tau_i^*)}{C * D_{\min RTT}}\right) \tag{22}$$

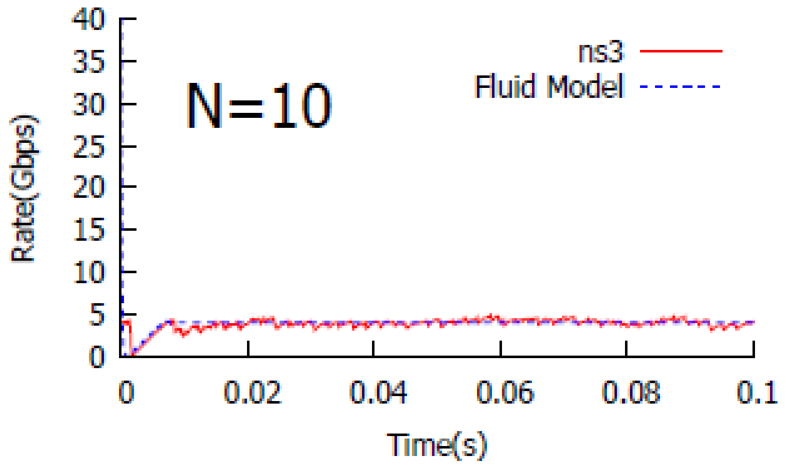
$$\tau_i^* = \max\left\{\frac{Seg}{R_i}, D_{\min RTT}\right\} \tag{23}$$

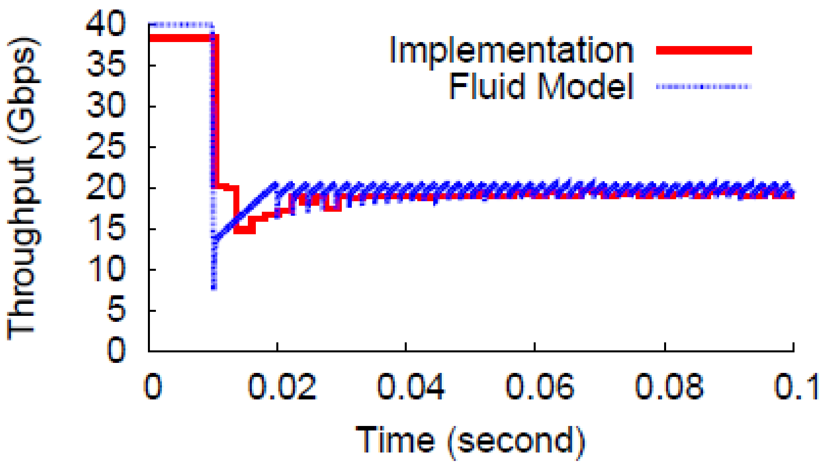
$$\tau' = \frac{q}{C} + \frac{MTU}{C} + D_{prop} \tag{24}$$

Figure 7: TIMELY fluid model

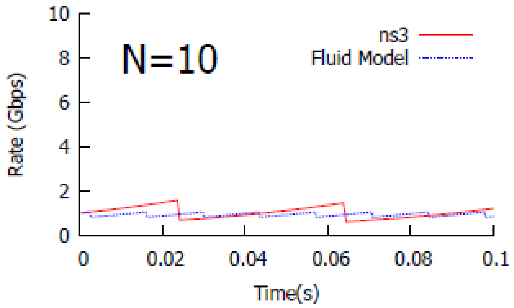
Takeaway:
DCQCN is a little too complicated

… those equations do model "reality"





DCQCN model matches simulations and implementation



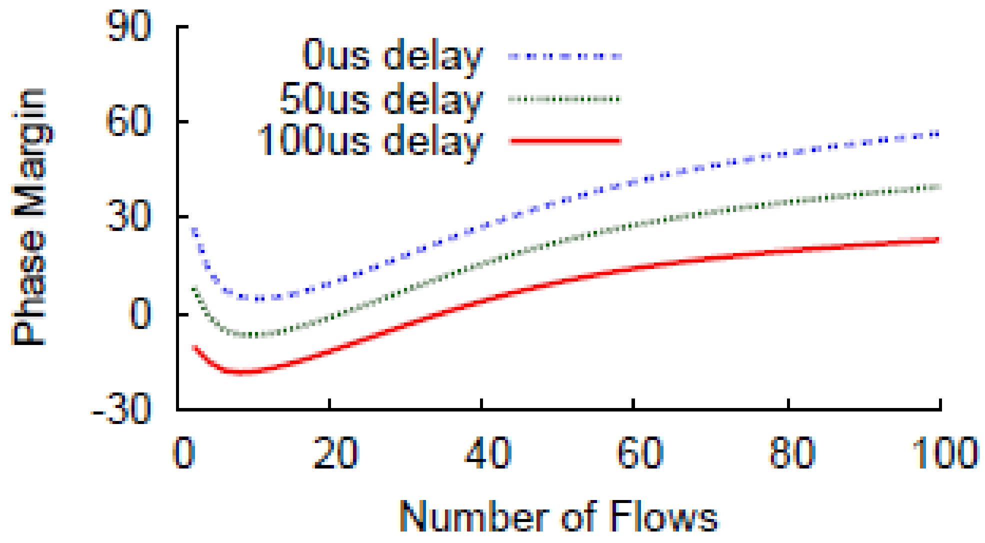
TIMELY model matches simulations

Congestion Control: Desirable properties

- Stability
  - Queue does not oscillate (or worse, exhibits runaway behavior)
- Rate of convergence
  - Quickly converge to stable operating point
- Fairness
  - At convergence, all flows equally share bottleneck bandwidth
- High utilization
  - Otherwise, you can achieve all of the above by dropping all packets
- Low flow completion time
  - But without doing fancy stuff at the switch

DCQCN

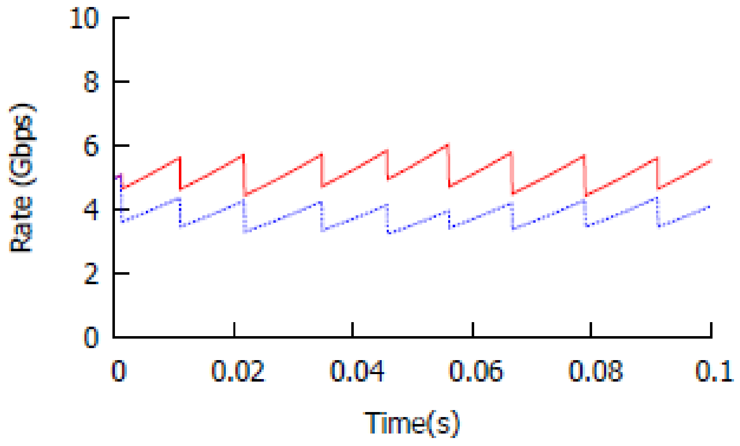
- DCQCN has a unique fixed point
- At the fixed point, all flows share the bottleneck equally
- Convergence is fairly rapid
- Relationship between stability and number of flows is non-monotonic



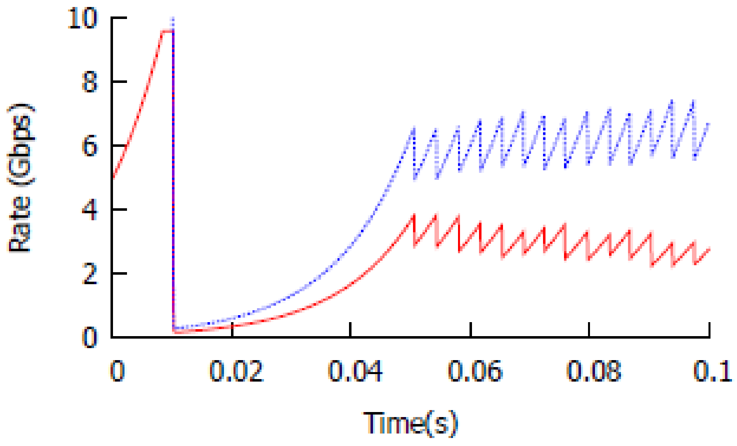
We don't have an intuitive explanation

TIMELY

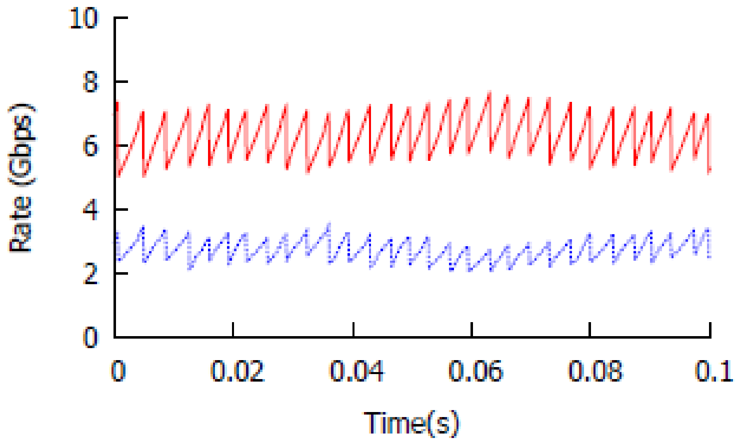
- Timely has no fixed point
  - changes rate in response to changes in latency (derivative)
  - Can stabilize at any point where sum of rates = bottleneck bandwidth



(a) Both flows start at time 0 at 5Gbps

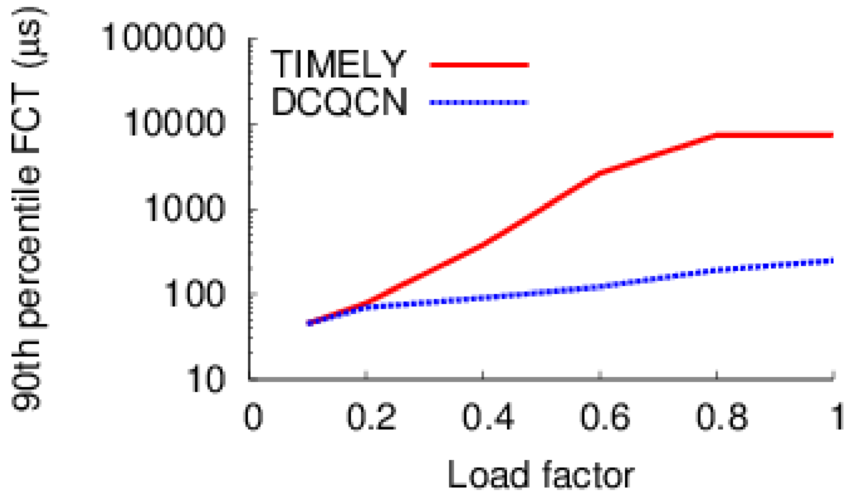


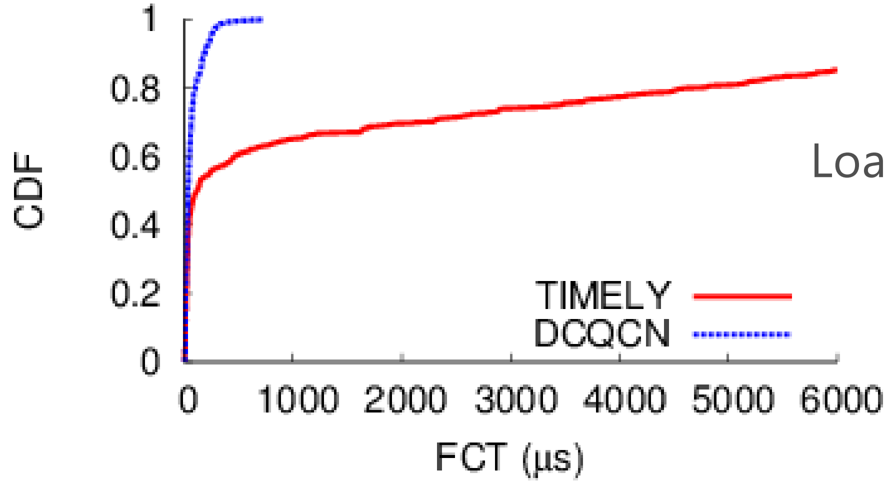
(b) Both start at 5Gbps, one starts 10ms late



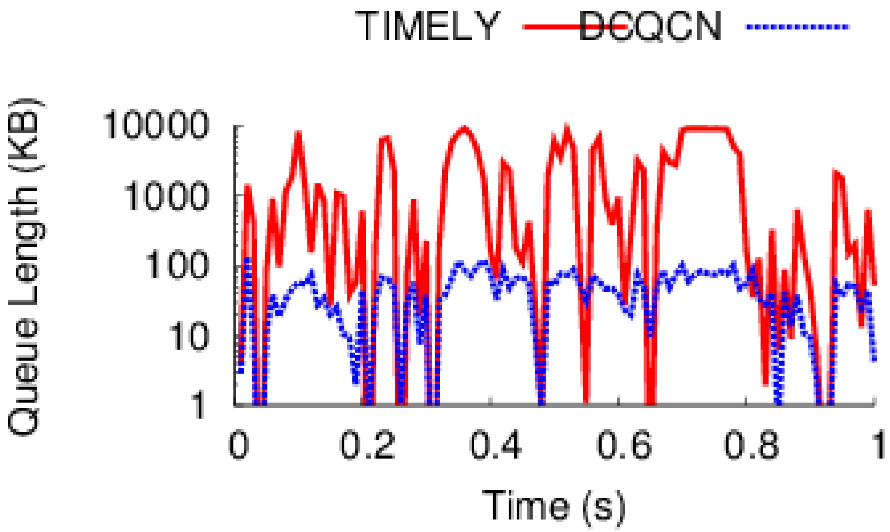
(c) One starts at 7Gbps, the other at 3Gbps

"Web Search" workload experiments





Load factor = 0.8



Why is TIMELY performing poorly?

- Reliance on delay differential
  - Can be fixed by making rate changes in response to absolute delay
- Feedback is delayed as queue builds up
- Can have fixed queue or fairness – but not both!
- ECN marking is resistant to feedback jitter

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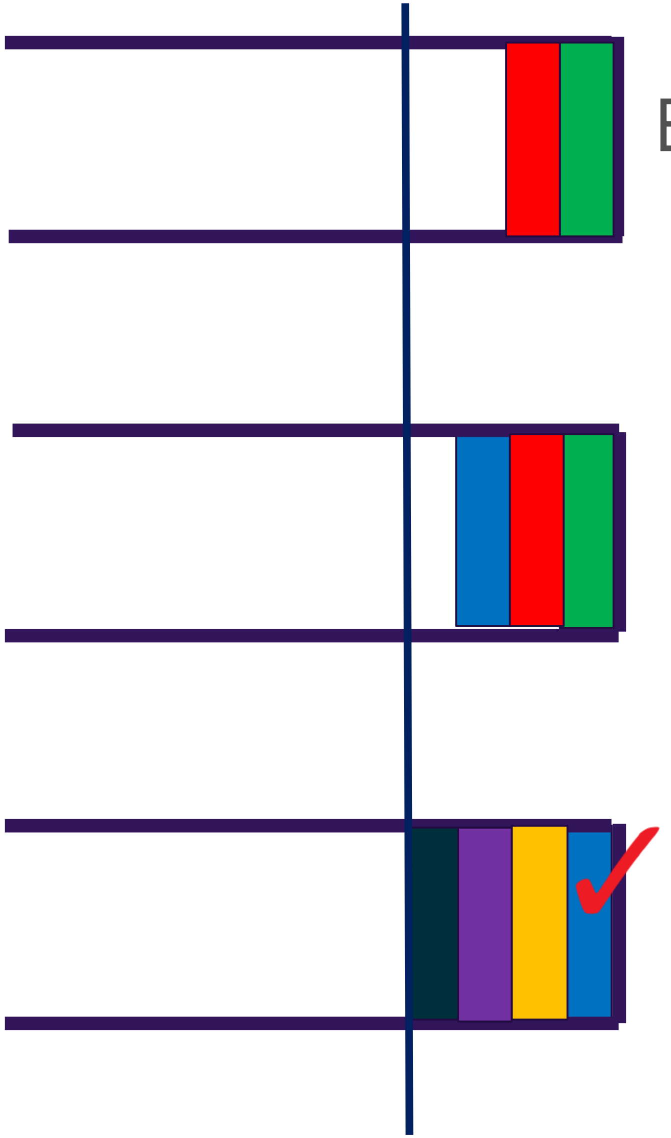
What happens with ECN

Marking threshold = 4 packets



T0, Q = 2 — Blue packet is about to arrive

T1, Q = 3 — Blue packet arrival complete

T2, Q = 4 — Blue packet ready to depart ... and is marked, reflecting state of queue at T2

What happens with delay

T0, Q = 2

Blue packet is about to arrive

T1, Q = 3

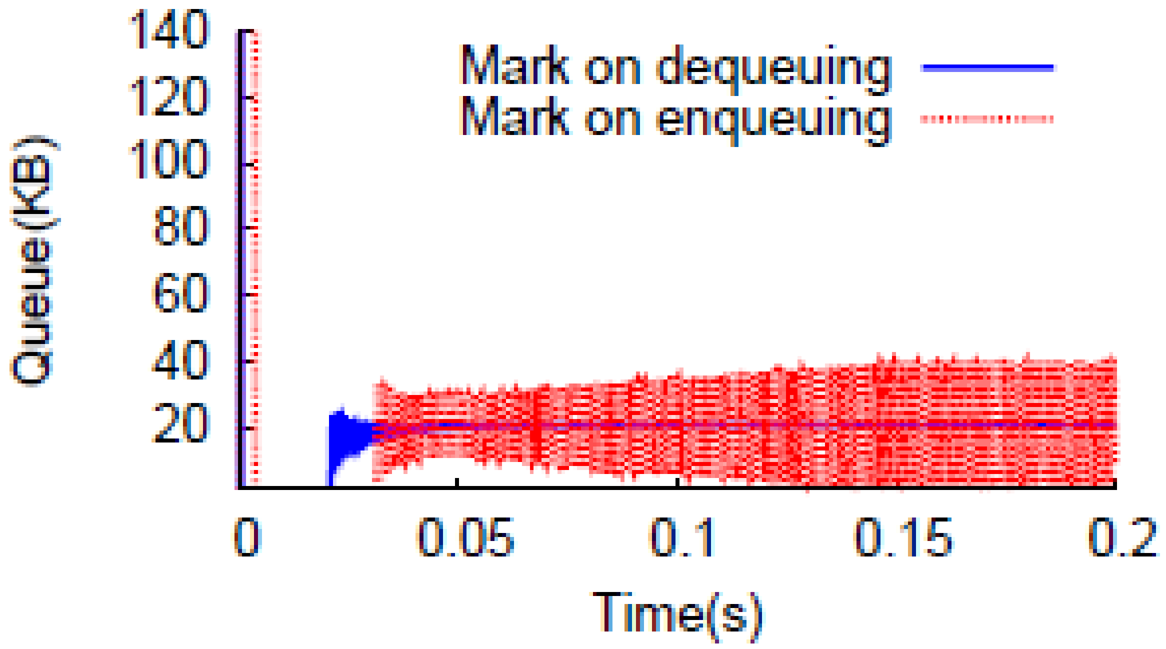
Blue packet arrival complete.
... timer starts

T2, Q = 4

Blue packet ready to depart
... and reflects state of queue at T0

In other words

- Delay inherently reports "stale" information
- The staleness is affected by queue length!
  - Longer queue ➔ more stale feedback
- This can lead to instability



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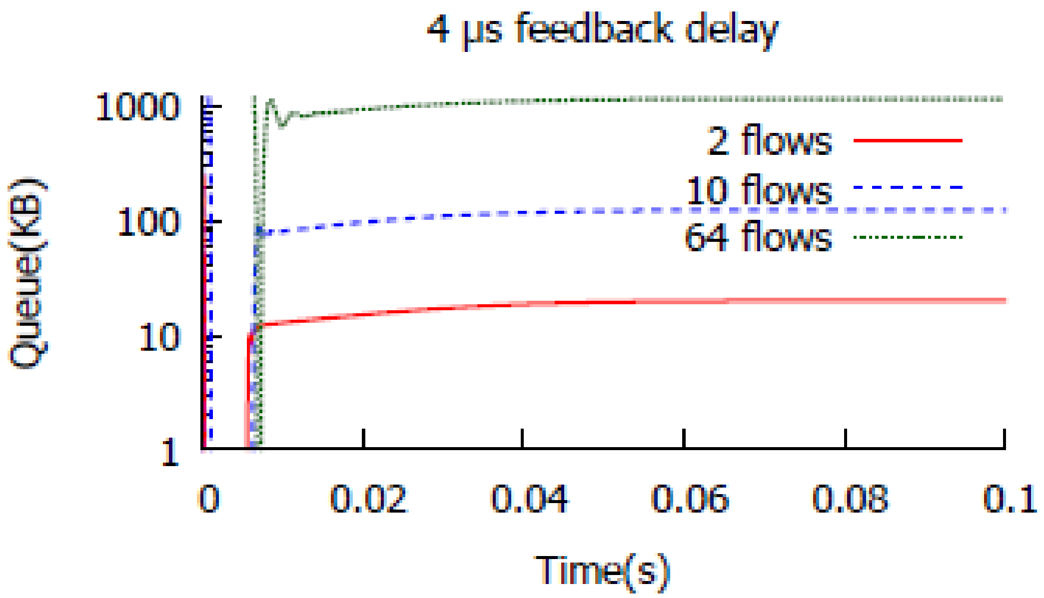
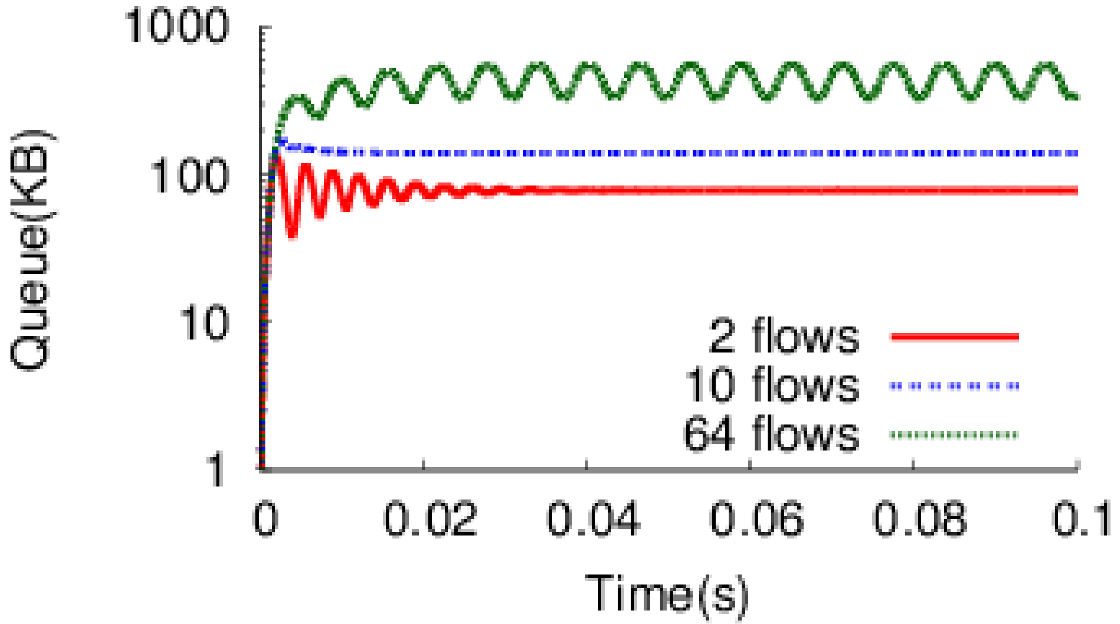
A problem with both DCQCN and TIMELY



DCQCN (40Gbps link)



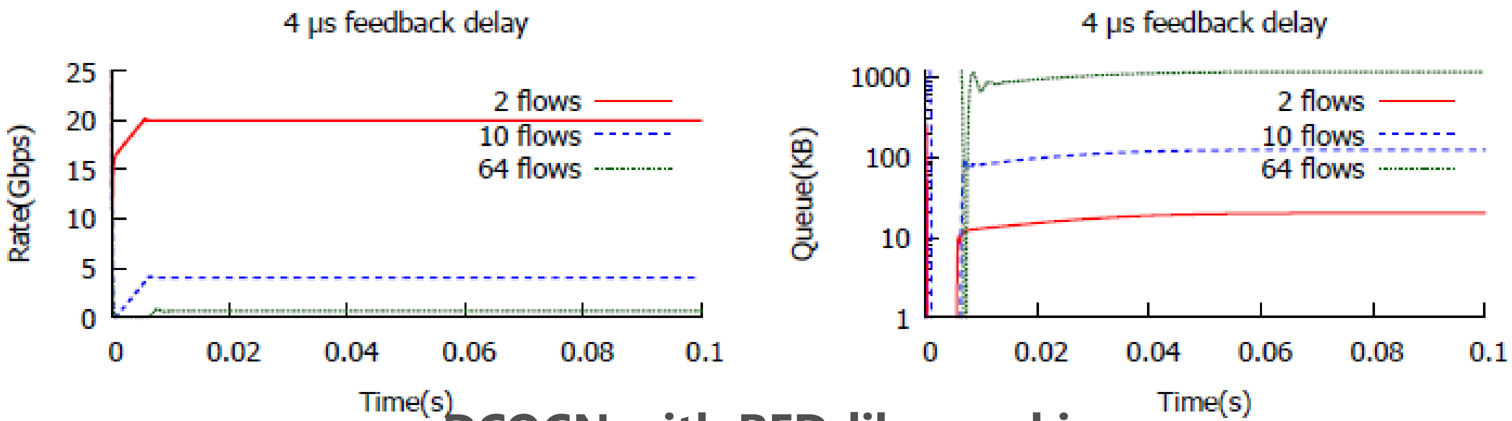
TIMELY (10Gbps link)

Bottleneck queue is a function of number of flows.

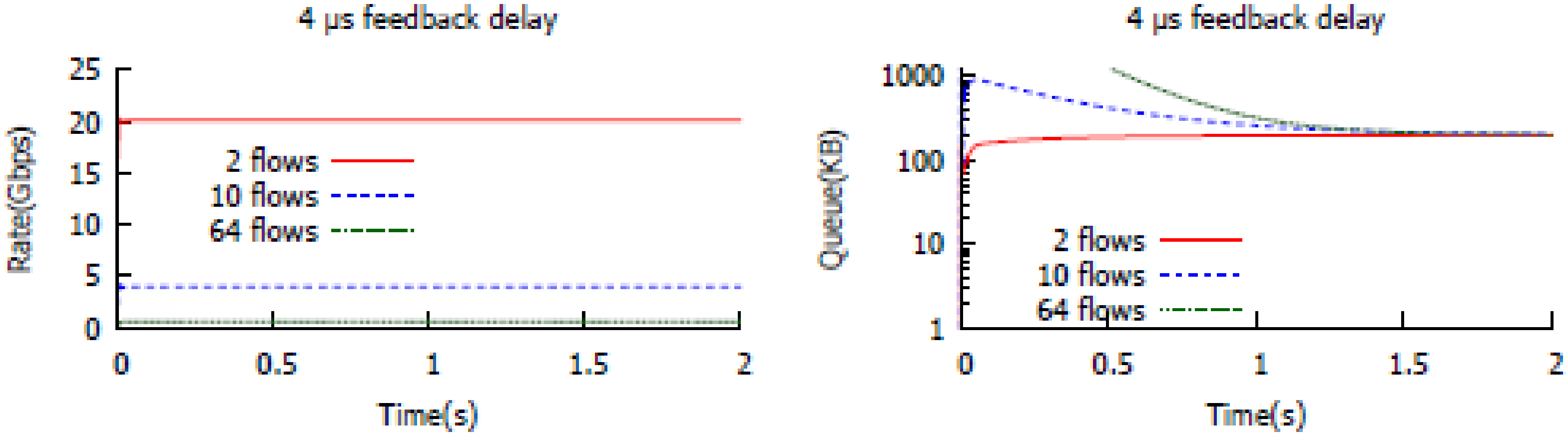
Converge to a fixed queue length regardless of number of flows

- FCT is more predictable!
- Can be done with a Proportional-Integral (PI) controller
  - See C. V. Hollot, Vishal Misra, Don Towsley and Wei-Bo Gong, **On Designing Improved Controllers for AQM Routers Supporting TCP Flows**, *Proceedings of IEEE Infocom*, April, 2001.
  - Cisco's variant of PI (PIE) part of DOCSIS 3.1 standard to control bufferbloat in consumer cable modems
- DCQCN ➔ use PI controller to mark packets
  - instead of RED-like marking
- TIMELY ➔ implement PI controller at the host with delay as the signal

PI controller works with DCQCN

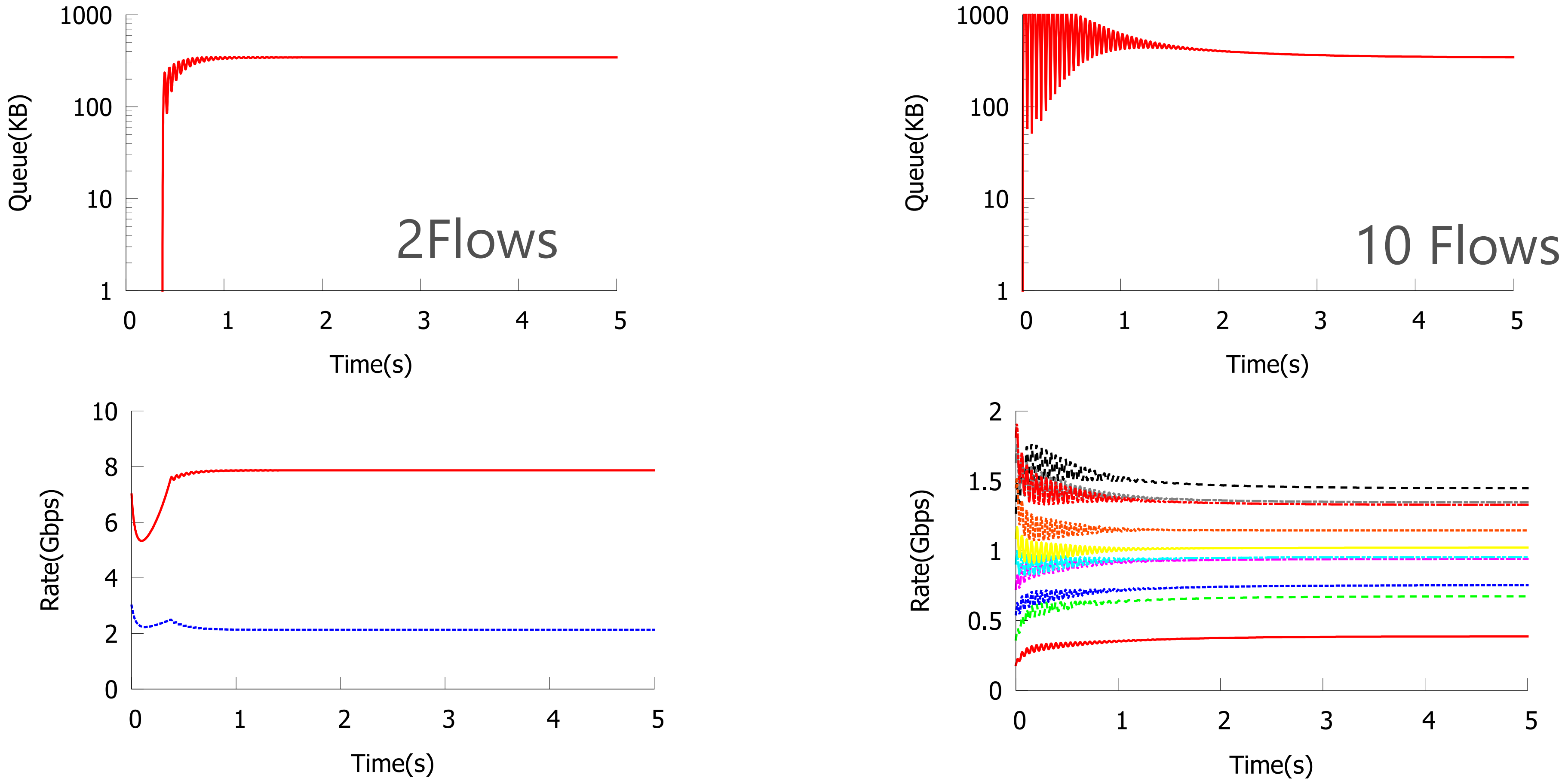


DCQCN with RED-like marking



DCQCN with PI-like marking

PI Controller with TIMELY: lose fairness



Fundamental limitation

- Delay-based protocols can have fixed queue or fairness – but not both!

- Proof sketch:
  - N flows need to make decisions separately (i.e. distributed), and calculate C/N to be their fair share
  - At steady state, since delay is fixed, this feedback is independent of the number of flows.
  - Need an additional variable to signal ”N" back to the flows, and that is the ECN marking probability

Why is TIMELY performing poorly?

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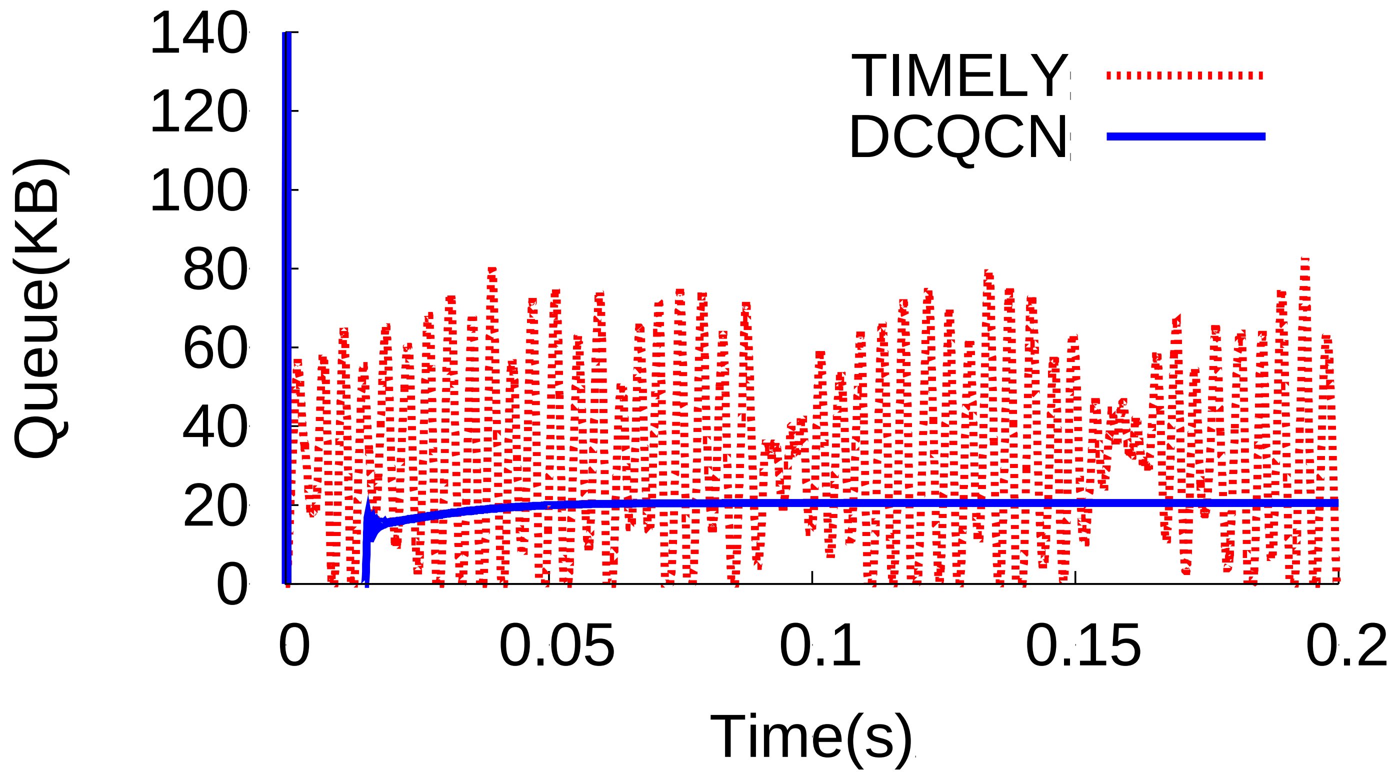
- ECN marking is resistant to feedback jitter

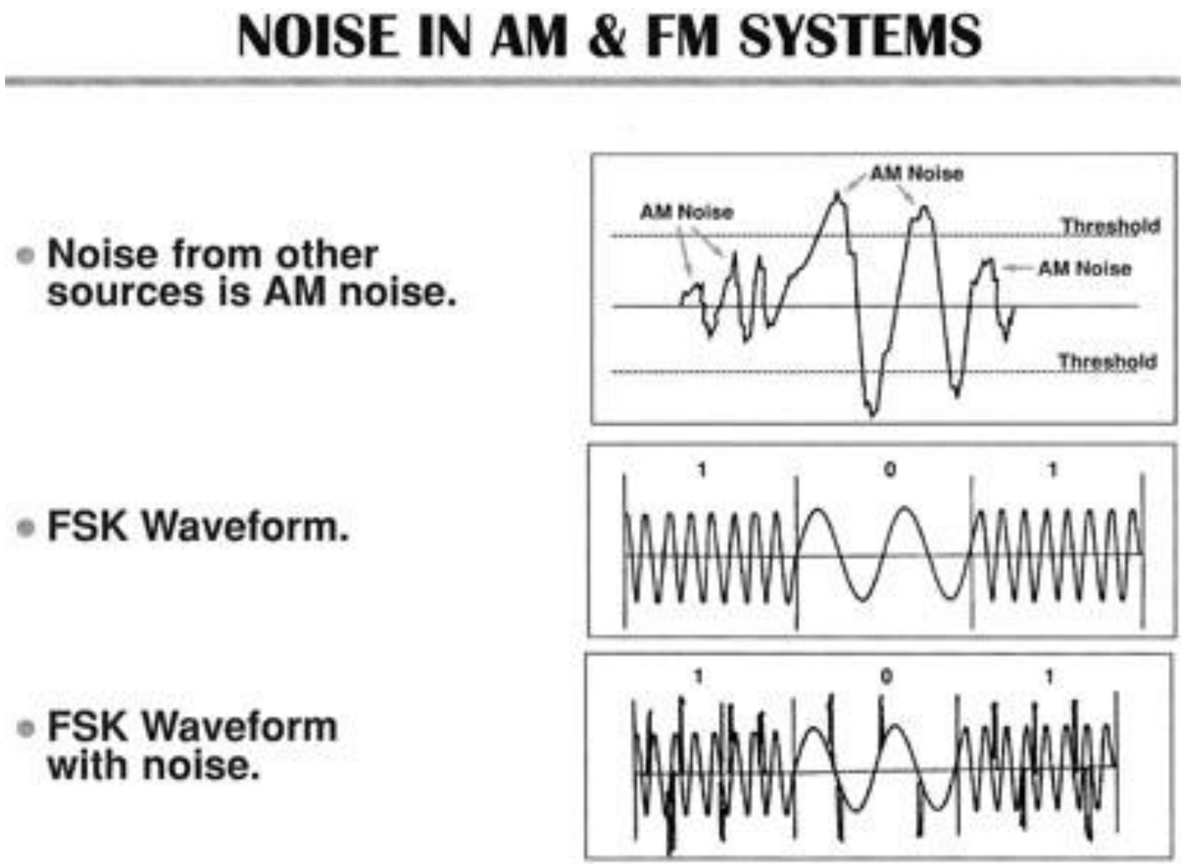
Impact of reverse path delay



ECN is more resistant as feedback signal is only *delayed*

With Delay, the feedback signal is both delayed and *distorted*

Analogy: Decoupling Signal from Noise



Delay

ECN

Conclusion: ECN appears better

RoCEv2

Delay → ***(Patched) TIMELY***

- \+ Generally stable
- \+ Fair & converging
- **- Affected by bufferbloat**
- **- Delay increases with the number of flows**
- **- Sensitive to variable feedback delay**

PI →

- \+ Generally stable
- **- Unfair**
- \+ Addressed bufferbloat
- \+ Fixed delay regardless of the number of flows
- **- Sensitive to variable feedback delay**

ECN → ***DCQCN***

- \+ Generally stable
- \+ Fair & converging
- \+ Addressed bufferbloat
- **- Delay increases with the number of flows**
- \+ Resilient to variable feedback delay

PI →

- \+ Generally stable
- \+ Fair & converging
- \+ Addressed bufferbloat
- \+ Fixed delay regardless of the number of flows
- \+ Resilient to variable feedback delay

Microsoft