The UNIVERSITY of NORTH CAROLINA at CHAPEL HILL

The Effects of Active Queue Management on Web Performance

The Good, the Bad, and the Ugly

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http://www.cs.unc.edu/Research/dirt

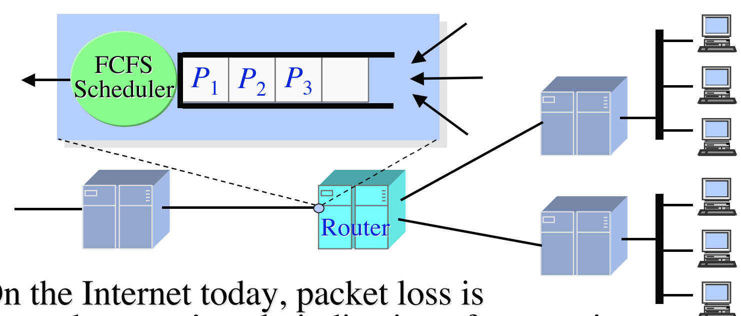
Making AQM Work

Outline

- Background: Router-based congestion control
  - Active Queue Management
  - Explicit Congestion Notification
- State of the art in active queue management (AQM)
  - Control theoretic *v.* traditional randomized dropping AQM
- Do AQM schemes work?
  - An empirical study of the effect of AQM on web performance
- Analysis of AQM performance
  - The case for *differential congestion notification* (DCN)
- A DCN prototype and its empirical evaluation

Router-Based Congestion Control

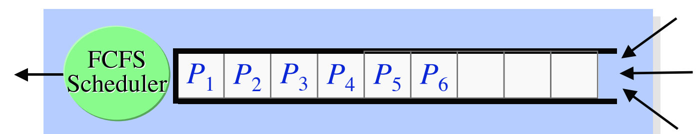
Status quo



- On the Internet today, packet loss is the end-system's only indication of congestion
- As switch's queues overflow, arriving packets are dropped
  - "Drop-tail" FIFO queuing is the default
- TCP end-systems detect loss and respond by reducing their transmission rate

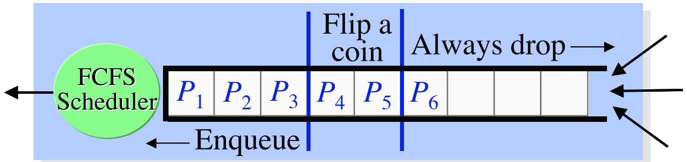
Router-Based Congestion Control

The case against drop-tail queuing



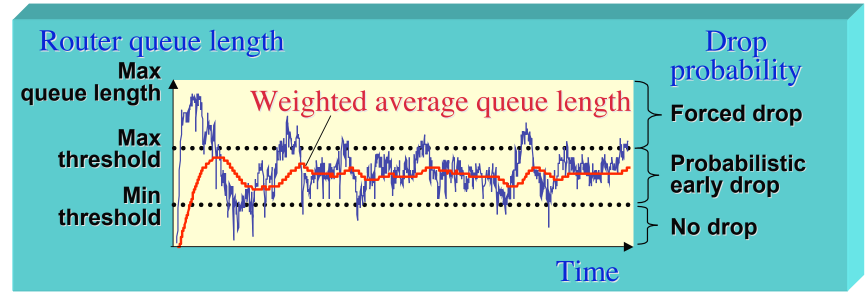
- Large (full) queues in routers are a bad thing
  - End-to-end latency is dominated by the length of queues at switches in the network
- Allowing queues to overflow is a bad thing
  - Connections that transmit at high rates can starve connections that transmit at low rates
  - Causes connections to synchronize their response to congestion and become unnecessarily bursty

Router-Based Congestion Control
Active queue management (AQM)



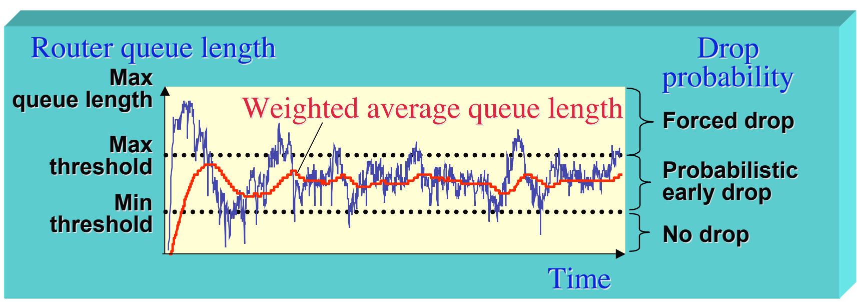
- Key concept: Drop packets *before* a queue overflows to signal *incipient* congestion to end-systems
- Basic mechanism: When the queue length exceeds a threshold, packets are probabilistically dropped
- *Random Early Detection* (RED) AQM:
  - Always enqueue if queue length less than a low-water mark
  - Always drop if queue length is greater than a high-water mark
  - Probalistically drop/enqueue if queue length is in between

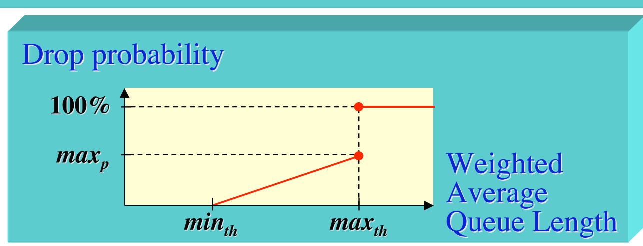
Active Queue Management
The RED Algorithm [Floyd & Jacobson 93]



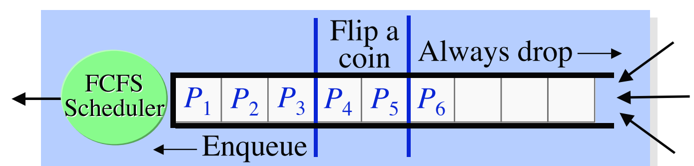
- RED computes a weighted moving average of queue length to accommodate bursty arrivals
- Drop probability is a function of the current average queue length
  - The larger the queue, the higher the drop probability

Active Queue Management
The RED Algorithm [Floyd & Jacobson 93]



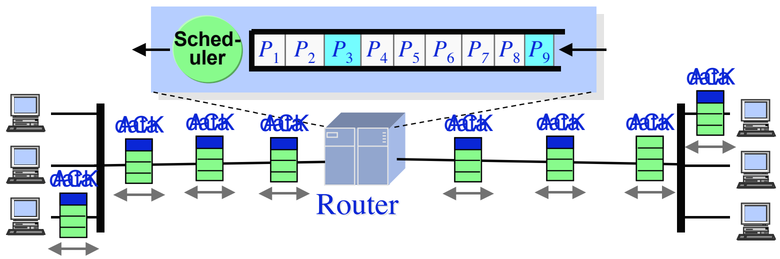


Active Queue Management
Explicit Congestion Notification (ECN)



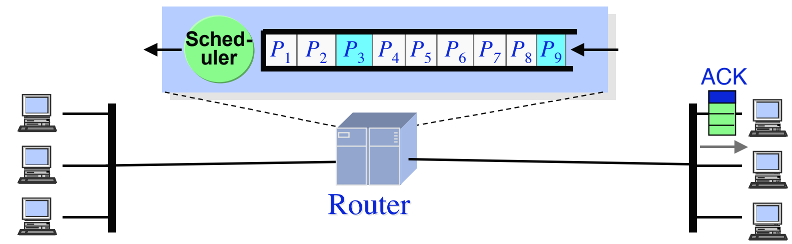
- Dropping packets is a simple means of signaling congestion but it's less than ideal
  - It may take a long time for a sender to detect and react to congestion signaled by packet drops
  - There are subtle fairness issues in the way flows are treated
- ECN: Instead of dropping packets, send an explicit signal back to the sender to indicate congestion
  - (An old concept: ICMP Source Quench, DECbit, ATM, …)

Explicit Congestion Notification
Overview



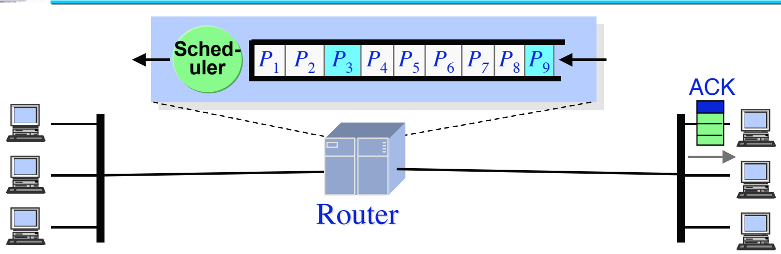
- Modify a RED router to "mark" packets rather than dropping them
- Set a bit in a packet's header and forward towards the ultimate destination
- A receiver recognizes the marked packet and sets a corresponding bit in the next outgoing ACK

Explicit Congestion Notification
Overview



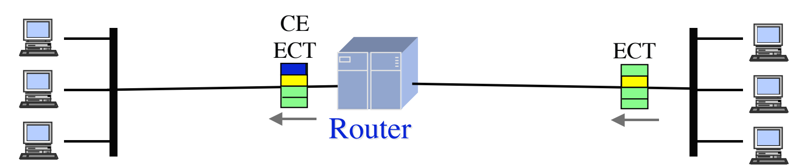
- When a sender receives an ACK with ECN it invokes a response similar to that for packet loss:
  - Halve the congestion window *cwnd* and halve the slow-start threshold *ssthresh*
  - Continue to use ACK-clocking to pace transmission of data packets

Explicit Congestion Notification
Overview



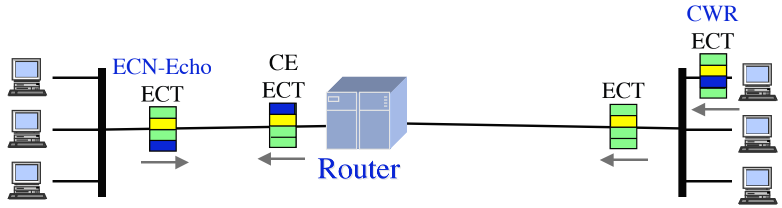
- When a sender receives an ACK with ECN it invokes a response similar to that for packet loss
- In any given RTT, a sender should react to either ECN or packet loss *but not both*!
  - Once a response has begun, wait until all outstanding data has been ACKed before beginning a new response

Explicit Congestion Notification
TCP details



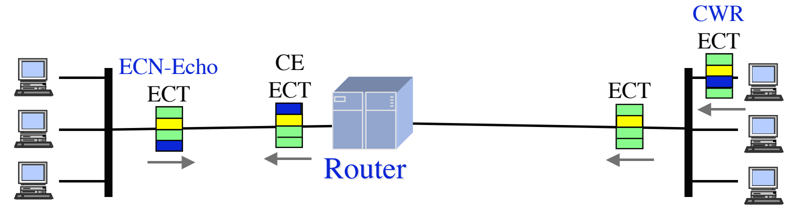
- Two bits in the IP header are used to convey the ability/willingness to respond to ECN
  - Bits 6 and 7 in the IP *type-of-service* field
    - » "ECN-Capable Transport" (ECT) bit
    - » "Congestion Experienced" (CE) bit
  - ECT bit is set by the sender on any/all packets for which ECN is requested
  - CE bit is set by a router and never reset

Explicit Congestion Notification
TCP details



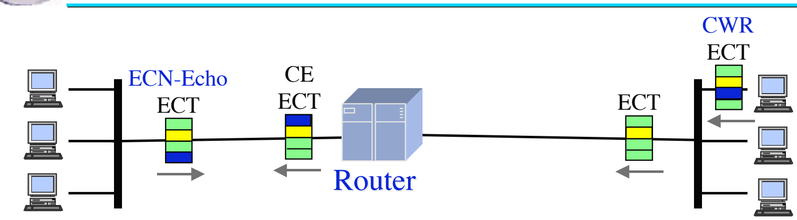
- Two bits in the *TCP header* are used to negotiate ECN function between end-systems
  - ECN-Echo flag indicates that a packet was received with the CE bit set
  - Congestion Window Reduced (CWR) flag that is used by the sender to signal its response to receipt of an ECN

Explicit Congestion Notification
TCP details



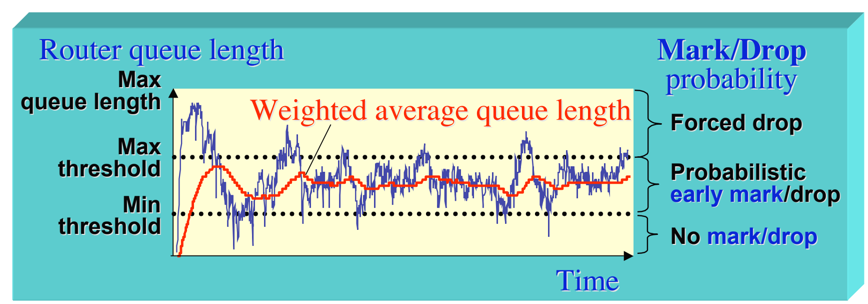
- Protocol operation:
  - Sender sets ECT bit in the IP header
  - If a packet should be marked the router sets the CE bit in the IP header
  - Upon receipt the receiver sets the ECN-Echo bit in the TCP header
    - » And continues to do so until a packet is received with the CWR bit set (in the TCP header)
  - The same process occurs on the reverse path

Explicit Congestion Notification
TCP details



- A sender sets ECN-Echo and CWR in the SYN packet to signal ECN capabilities to receiver
  - Receiver responds with (just) the ECN-Echo set in the SYN-ACK

Explicit Congestion Notification
Putting the pieces together: AQM + ECN



- If a RED router detects congestion it will mark arriving packets
- The router will then forward marked packets from ECN-capable senders…
- …and drop marked packets from all other senders

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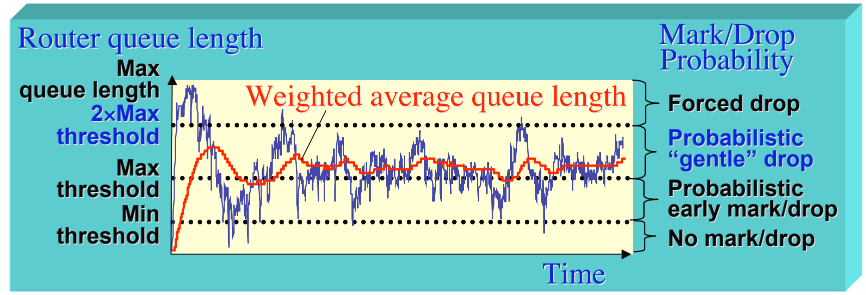
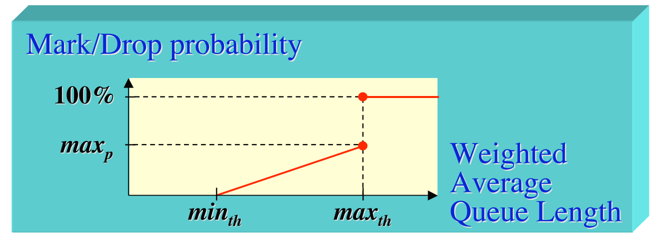
The State of the ART in AQM
Adaptive/Gentle RED (ARED)





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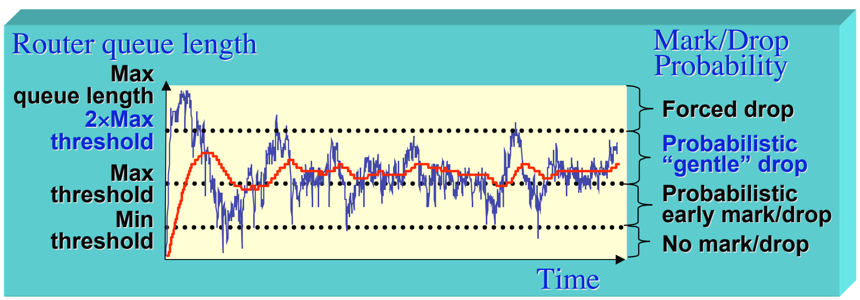
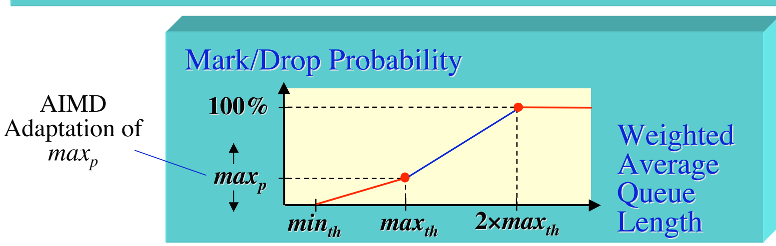
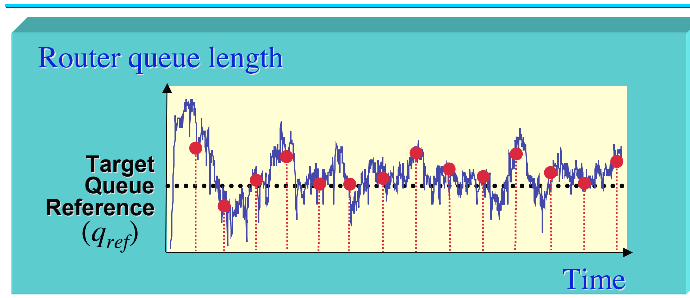
Adaptive/Gentle RED (ARED)



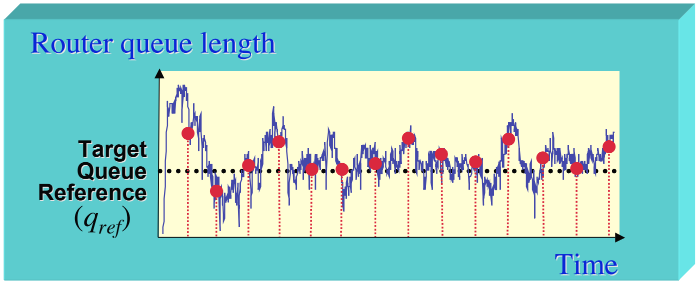


The State of the ART in AQM
The Proportional Integral (PI) controller



- PI attempts to maintain an explicit target queue length
- PI samples instantaneous queue length at fixed intervals and computes a mark/drop probability at k^{th} sample:
  - $p(kT) = a \times (q(kT) - q_{ref}) - b \times (q((k-1)T) - q_{ref}) + p((k-1)T)$
  - a, b, and T depend on link capacity, maximum RTT and the number of flows at a router

The State of the ART in AQM
Random Exponential Marking (REM)



- REM is similar to PI (though differs in details)
- REM mark/drop probability depends on:
  - Difference between input and output rate
  - Difference between instantaneous queue length and target
  - $p(t) = p(t-1) + \gamma\, [\alpha\, (q(t) - q_{ref})) + x(t) - c]$
  - $prob(t) = 1 - \phi^{-p(t)}$, $\phi > 1$ a constant

Do AQM Schemes Work?
(Why do we care?)

- RFC 2309 strongly advocates deployment of RED active queue management in routers:

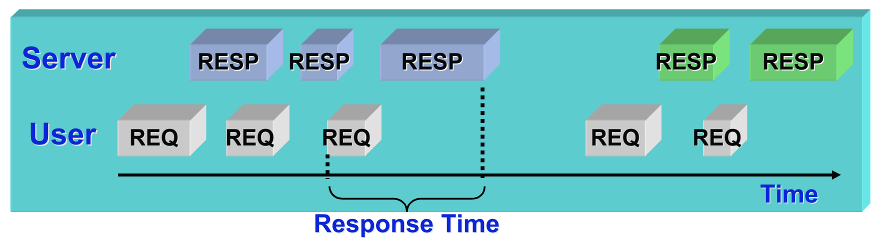
  "All available empirical evidence shows that the deployment of active queue management mechanisms in the Internet would have substantial performance benefits. There are seemingly no disadvantages to using the RED algorithm, and numerous advantages. Consequently, we believe that RED active queue management algorithm should be widely deployed."

- Why do we care about the effect of AQM on Web traffic?
  - Web traffic makes up a significant fraction of traffic on most links
  - In theory, a key goal of AQM is to "provide lower delays for interactive applications such as web browsing"

Do AQM Schemes Work?
Evaluation methodology

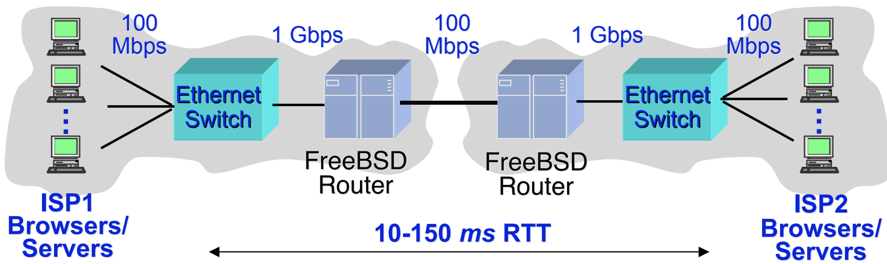
- Evaluate AQM schemes through "live simulation"
- Emulate the browsing behavior of a large population of users surfing the web in a laboratory testbed
  - Construct a physical network emulating a congested peering link between two ISPs
  - Generate synthetic HTTP requests and responses but transmit over real TCP/IP stacks, network links, and switches

Experimental Methodology
HTTP traffic generation



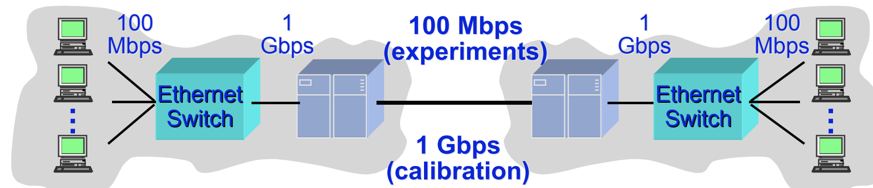
- Synthetic web traffic generated using the UNC HTTP model [SIGMETRICS 2001, MASCOTS 2003]
- Primary random variables:
  - Request sizes/Reply sizes
  - User think time
  - Persistent connection usage
  - Nbr of objects per persistent connection
  - Number of embedded images/page
  - Number of parallel connections
  - Consecutive documents per server
  - Number of servers per page

Experimental Methodology
Testbed emulating an ISP peering link



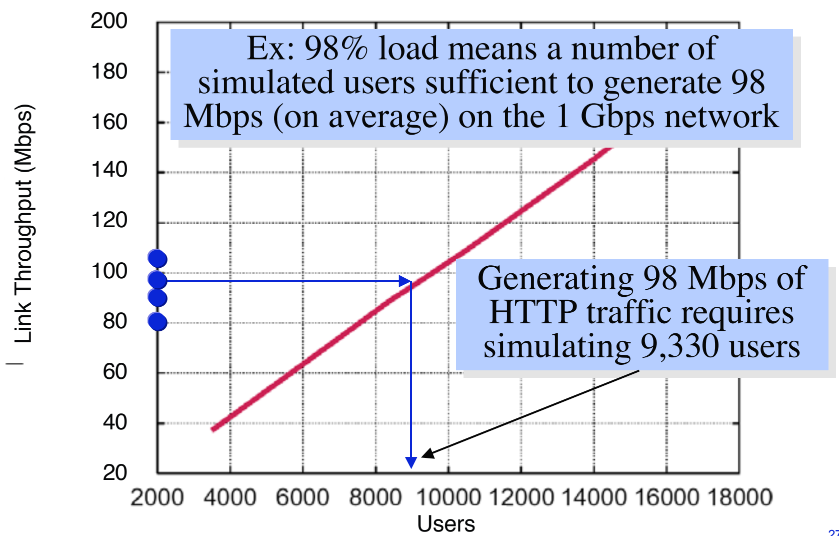
- AQM schemes implemented in FreeBSD routers using ALTQ kernel extensions
- End-systems either a traffic generation client or server
  - Use *dummynet* to provide *per-flow* propagation delays
  - Two-way traffic generated, equal load generated in each direction

Experimental Methodology
1 Gbps network calibration experiments



- Experiments run on a congested 100 Mbps link
- Primary simulation parameter: Number of simulated browsing users
- Run calibration experiments on an uncongested 1 Gbps link to relate simulated user populations to average link utilization
  - (And to ensure offered load is linear in the number of simulated users — *i.e.*, that end-systems are not a bottleneck)

Experimental Methodology
1 Gbps network calibration experiments



Experimental Methodology
Experimental plan

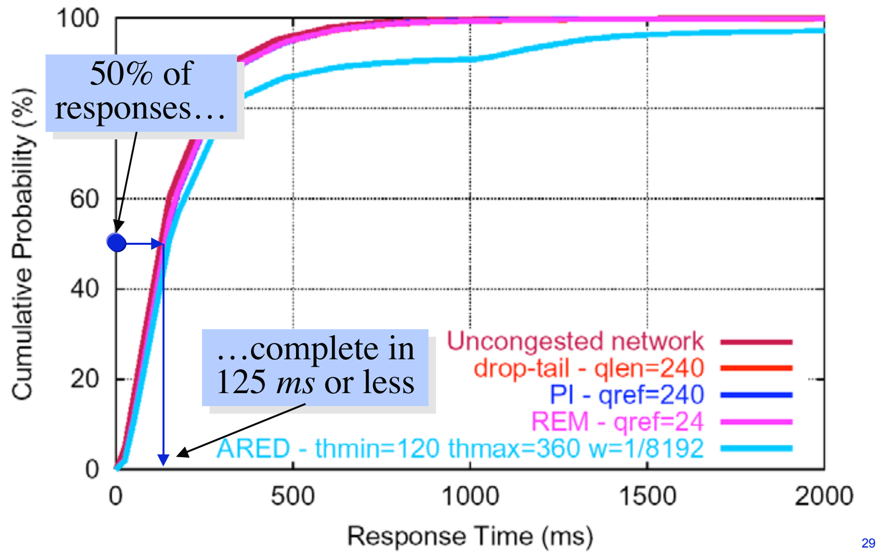
	80%	90%	98%	105%
uncongested drop-tail ARED PI REM	*loss rate* *utilization* *response times* *completed requests*			

- Run experiments with ARED, PI, and REM using their recommended parameter settings at different offered loads
- Compare results with drop-tail FIFO at the same offered loads…
  - (the "negative" baselines — the performance to beat)

  …and compare with performance on the 1 Gbps network
  - (the "positive" baseline — the performance to achieve)
- Redo the experiments with ECN

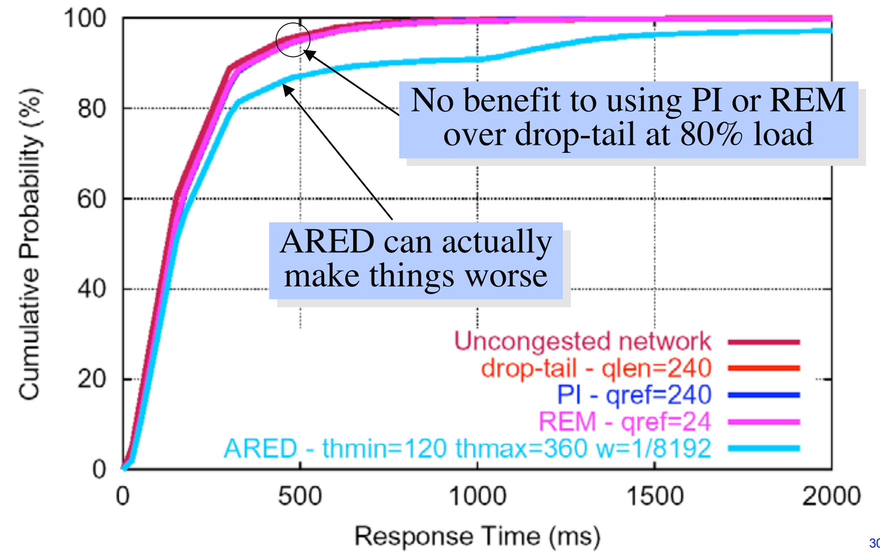
Experimental Results — 80% Load

Performance with packet drops



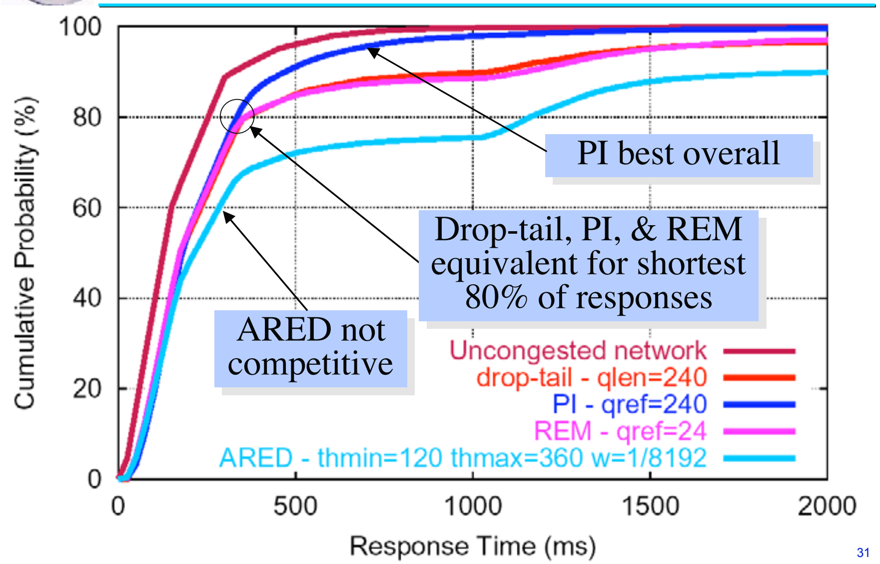
Experimental Results — 80% Load

Performance with packet drops



Experimental Results — 90% Load

Performance with packet drops



Experimental Results — 98% Load

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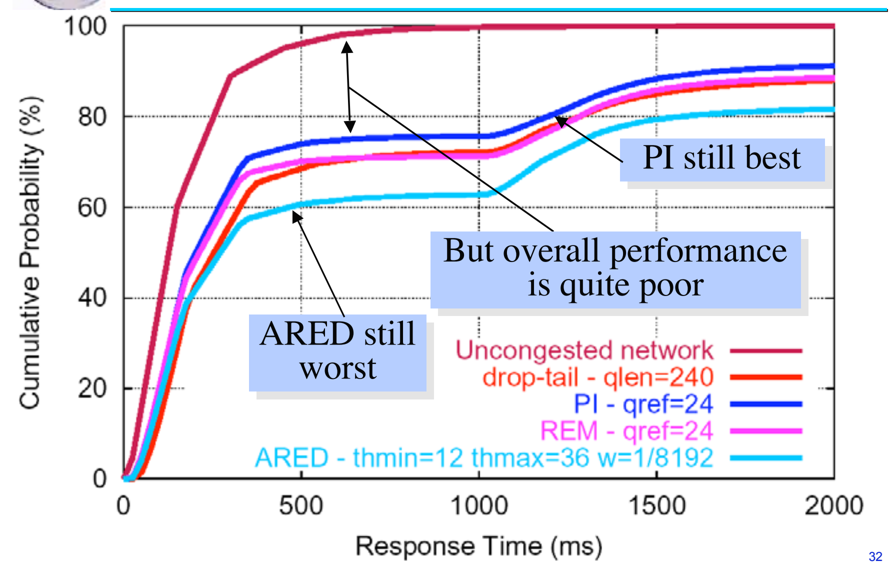
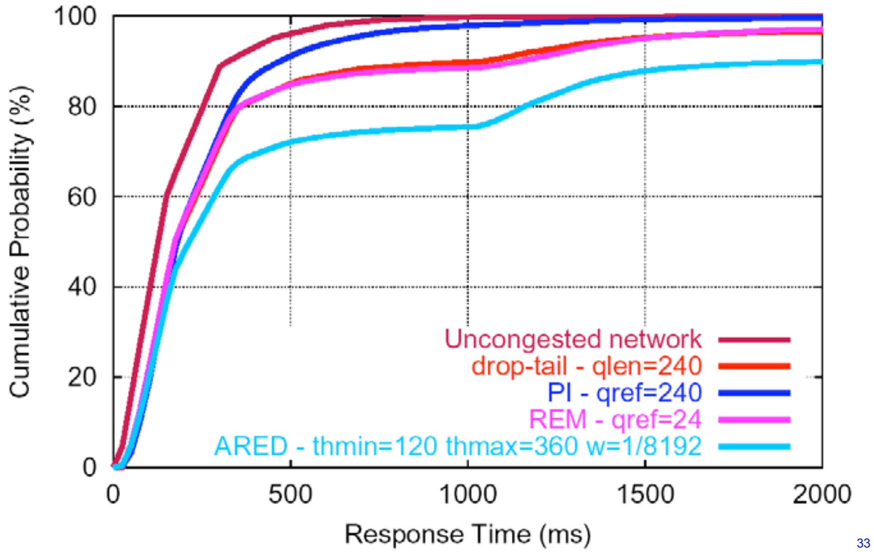


Experimental Results — 90% Load
Performance with packet drops



Experimental Results — 98% Load
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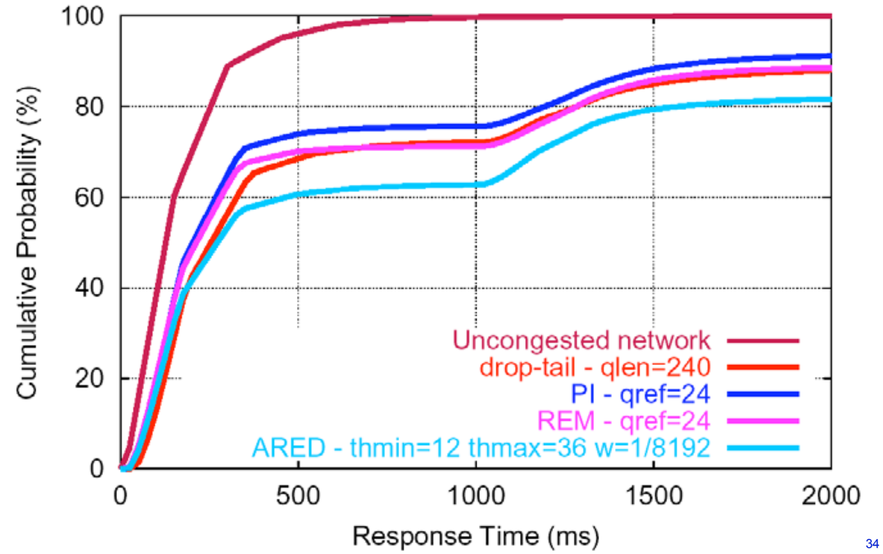
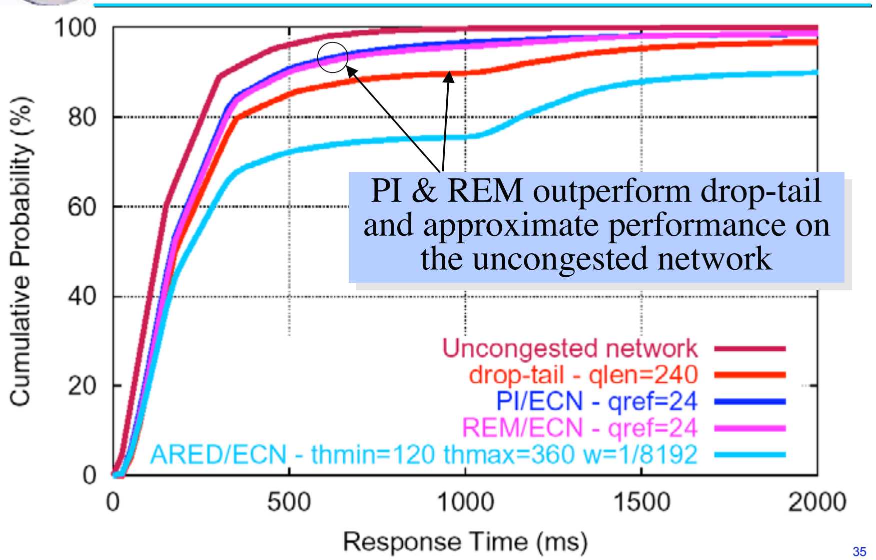


ECN Results — 90% Load
Comparison of all schemes



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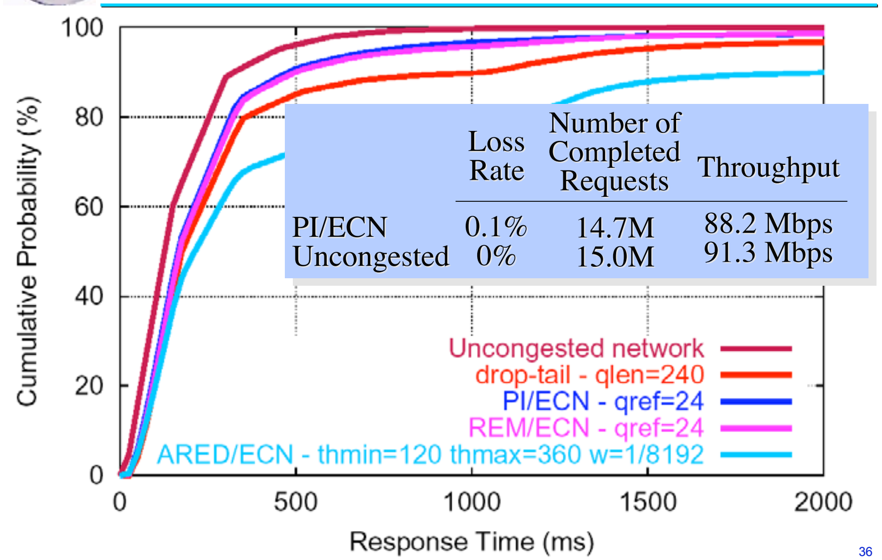
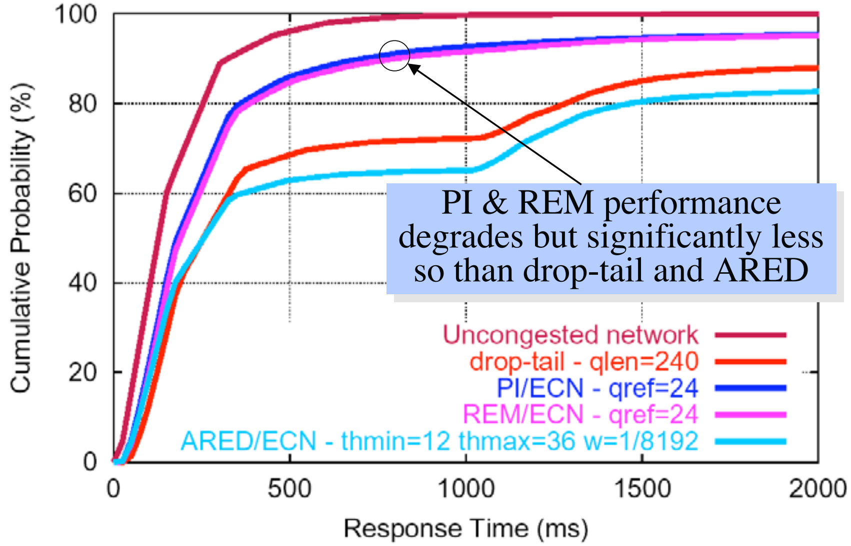


	Loss Rate	Number of Completed Requests	Throughput
PI/ECN	0.1%	14.7M	88.2 Mbps
Uncongested	0%	15.0M	91.3 Mbps

ECN Results — 98% Load

Comparison of all schemes



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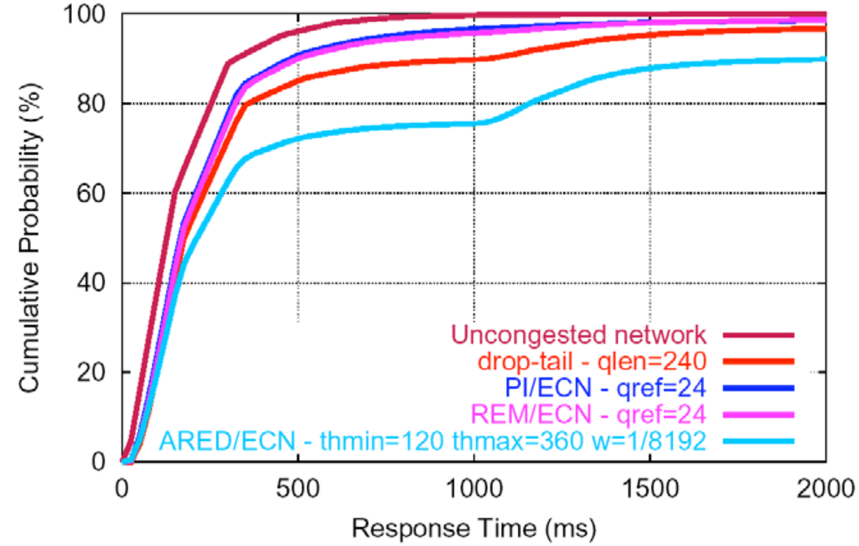

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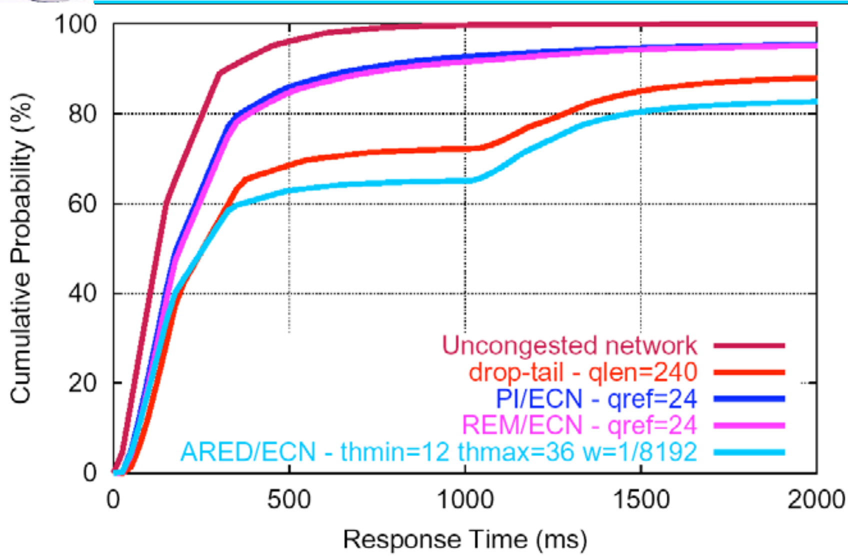

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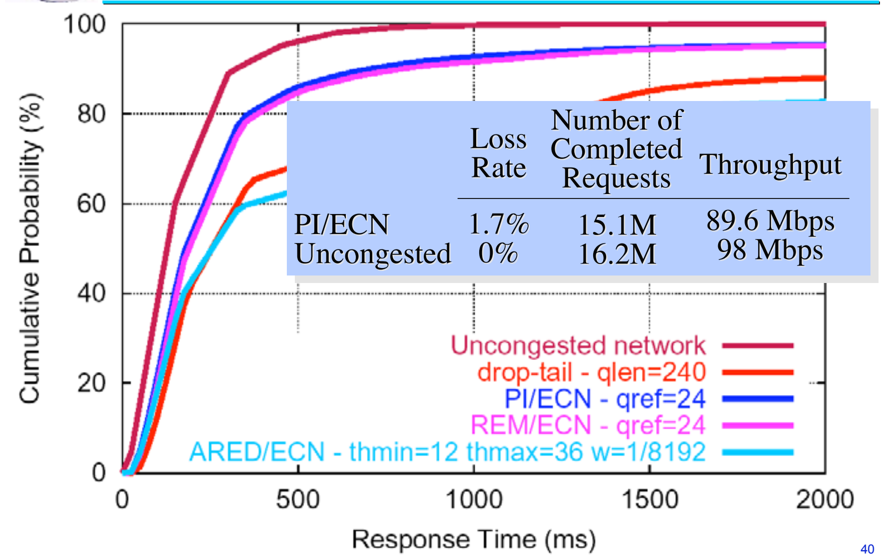
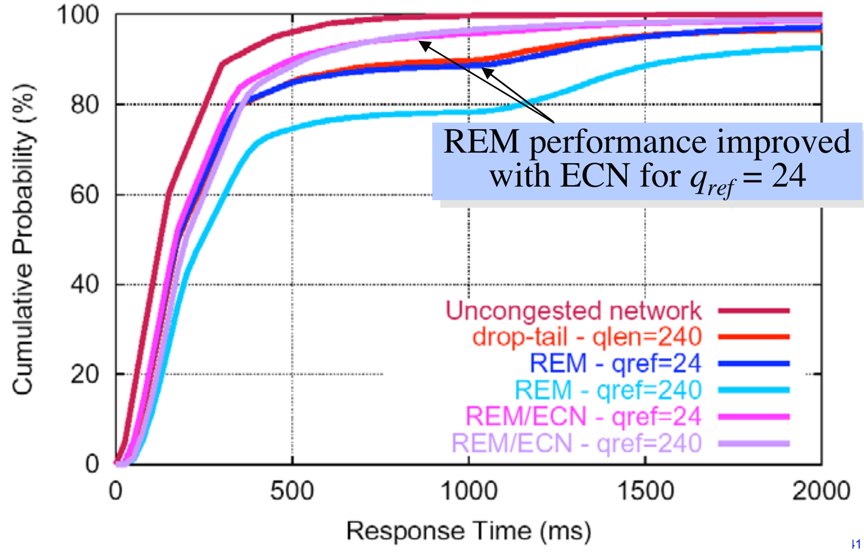
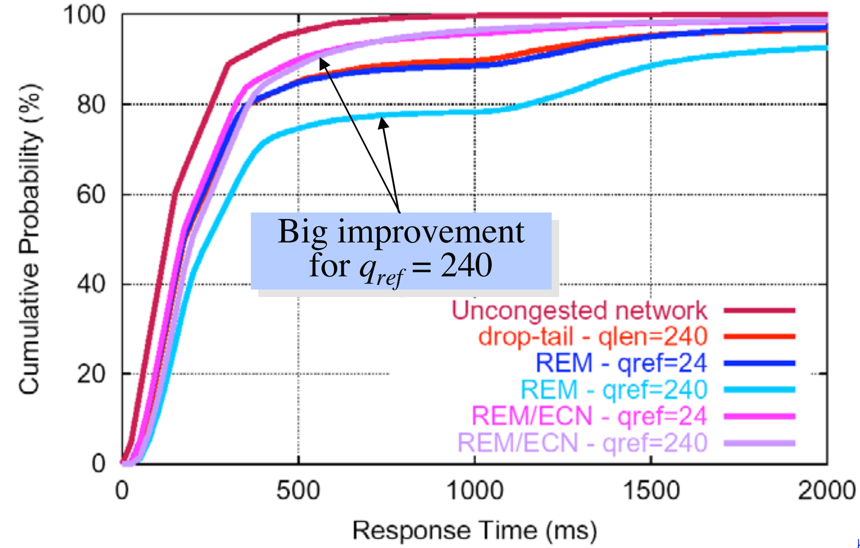


	Loss Rate	Number of Completed Requests	Throughput
PI/ECN	1.7%	15.1M	89.6 Mbps
Uncongested	0%	16.2M	98 Mbps

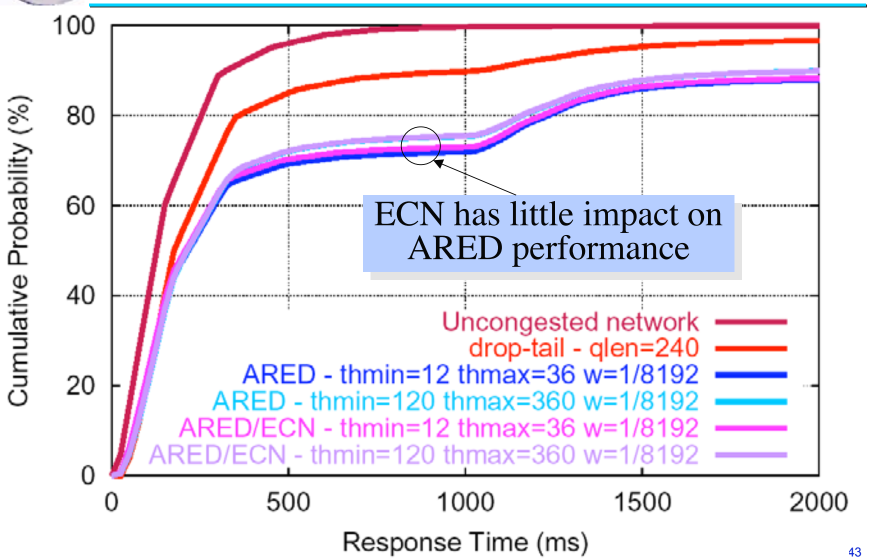
Impact of ECN on REM
Performance with/without ECN at 90% load



Impact of ECN on REM
Performance with/without ECN at 90% load



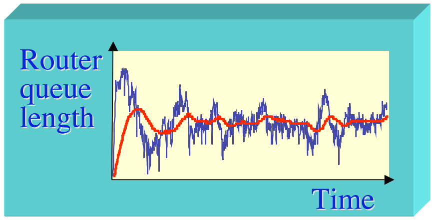
Impact of ECN on ARED
Performance with/without ECN at 90% load



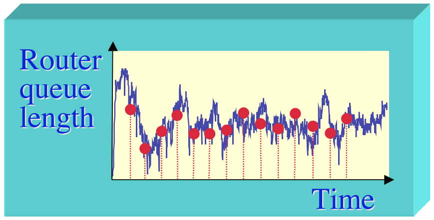
Do AQM Schemes Work?
Summary

- For offered loads up to 80% of link capacity, no AQM scheme gives better performance than drop-tail FIFO
  - All give comparable response time performance, loss rates, and link utilization
- For offered loads of 90% or greater…
  - Without ECN, PI results in a modest performance improvement over drop-tail and other AQM schemes
  - With ECN, both PI and REM provide significant performance improvement over drop-tail
- ARED consistently results in the poorest performance
  - Often worse than drop-tail FIFO

Discussion
Why does ARED perform so poorly?



Weighted Queue Length (RED)

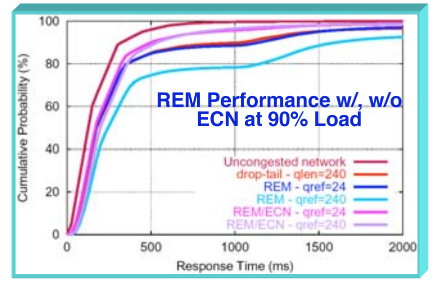


Instantaneous Queue Length (PI/REM)

- ARED bases mark/drop probability on the (weighted) average queue length
- PI, REM use instantaneous measures of queue length
- ARED's reliance on the average queue length limits its ability to react effectively in the face of bursty traffic

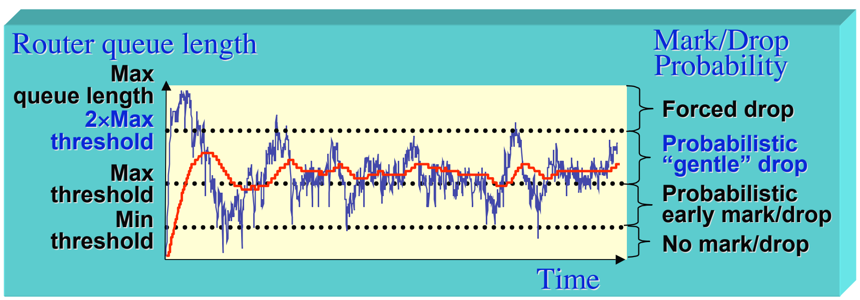
Discussion
Why does ECN improve REM more than PI?

- Without ECN, REM drops more packets than PI
- REM causes more flows to experience multiple losses within a congestion window
  - Loss recovered through timeout rather than fast recovery



- In general ECN allows more flows to avoid timeouts
  - Thus ECN is ameliorating a design flaw in REM

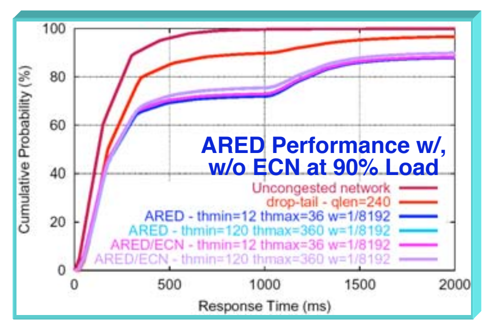
Discussion
Why does ARED not benefit from ECN?



- ARED drops marked packets when average queue size is above max_{th}
- This is done to deal with potentially non-responsive flows
- We believe this policy is a premature optimization

Discussion
Why does ARED perform so poorly?

- PI and REM measure queue length in bytes
- By default RED measures in packets
  - But ARED does have a "byte mode"

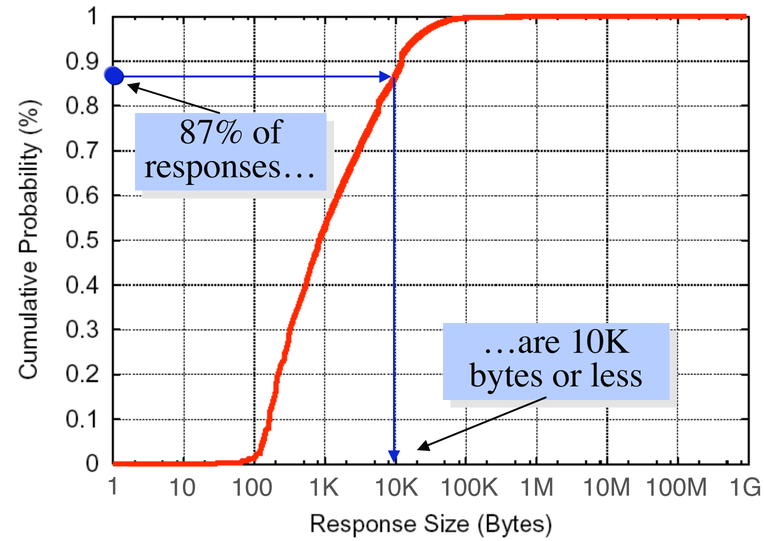


- Drop/Mark probability in PI/REM biased by packet size
  - SYNs and pure ACKs have a lower drop probability in PI/REM
- Differentiating at the packet level is critical
  - Is it enough?

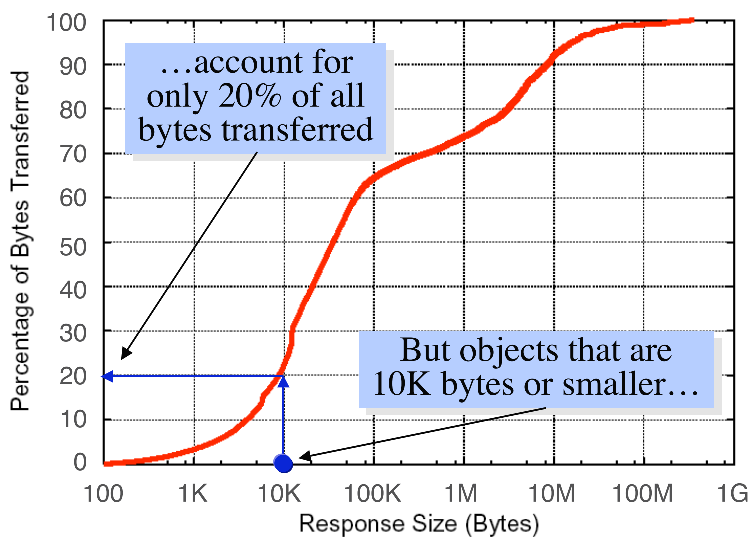
Discussion
Do AQM designs inherently require ECN?

- Claim: Differentiating between flows at the flow-level is important
- ECN is required for good AQM performance because it eliminates the need for short flows to retransmit (a significant fraction of their) data
  - With ECN, short flows (mostly) no longer retransmit data
  - But their performance is still hurt by AQM
- Why signal short flows at all?
  - They have no real transmission rate to adapt
  - Hence signaling these flows provides no benefit to the network and only hurts end-system performance

The Structure of Web Traffic
Distribution of response sizes



The Structure of Web Traffic
Percent of bytes transferred by response sizes



Making AQM Work
Overview

- Background: Router-based congestion control
  - Active Queue Management
  - Explicit Congestion Notification
- State of the art in active queue management (AQM)
  - Control theoretic *v.* traditional randomized dropping AQM
- Do AQM schemes work?
  - An empirical study of the effect of AQM on web performance
- Analysis of AQM performance
  - The case for *differential congestion notification* (DCN)
- A DCN prototype and its empirical evaluation

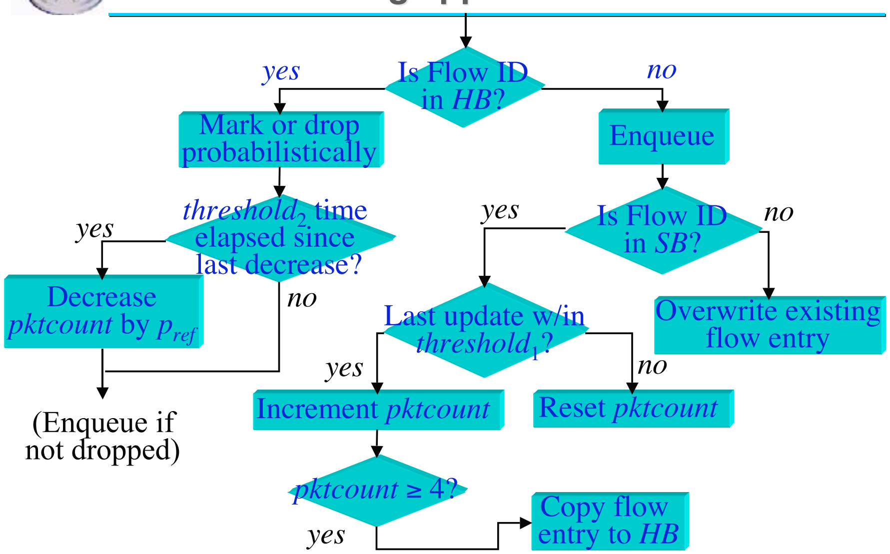
Realizing Differential Notification
Issues and approach

- How to identify packets belonging to long-lived, high bandwidth flows with minimal state?
  - Adopt the Estan, Varghese flow filtering scheme developed for traffic accounting [SIGCOMM 2002]
- How to determine when to signal congestion (by dropping packets)?
  - Use a PI-like scheme
- Differential treatment of flows an old idea:
  - FRED
  - CHOKe
  - AFD
  - RIO-PS
  - SRED
  - SFB
  - RED-PD
  - …

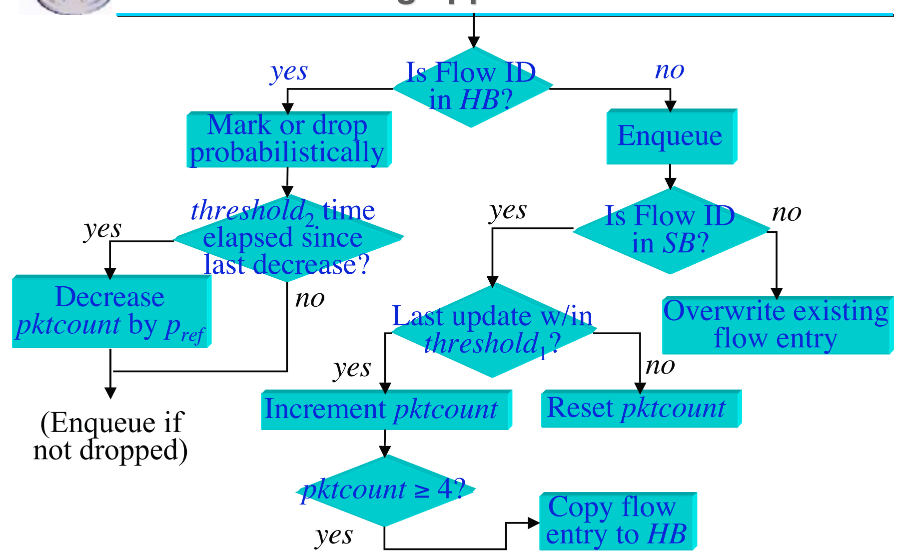
Classifying Flows
A score-boarding approach

- Use two hash tables:
  - A "suspect" flow table HB ("high-bandwidth") and
  - A per-flow packet count table SB ("scoreboard")
  - Hash on IP addressing 4-tuple plus protocol number
- Arriving packets from flows in HB are subject to dropping
- Arriving packets from other flows are inserted into SB and tested to determine if the flow should be considered high-bandwidth
  - Use a simple packet count threshold for this determination

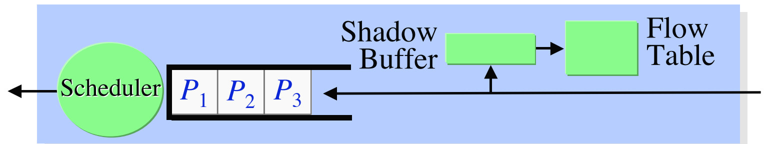
Classifying Flows
A score-boarding approach



Classifying Flows
A score-boarding approach



An Alternate Approach
AFD [Pan *et al.* 2003]



"Approximate Fairness through Differential Dropping"

- Sample 1 out of every *s* packets and store in a *shadow buffer* of size *b*
- Estimate flow's rate as $r_{est} = R \frac{\#\ matches}{b}$
- Drop packet with probability $p = 1 - \frac{r_{fair}}{r_{est}}$

DCN Evaluation
Experimental plan

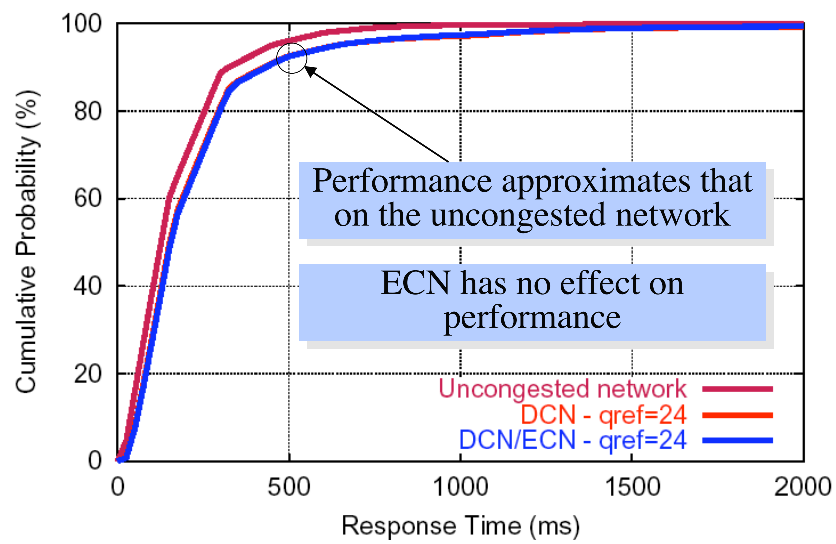
80% 90% 98% 105%

uncongested
drop-tail
DCN
AFD
PI

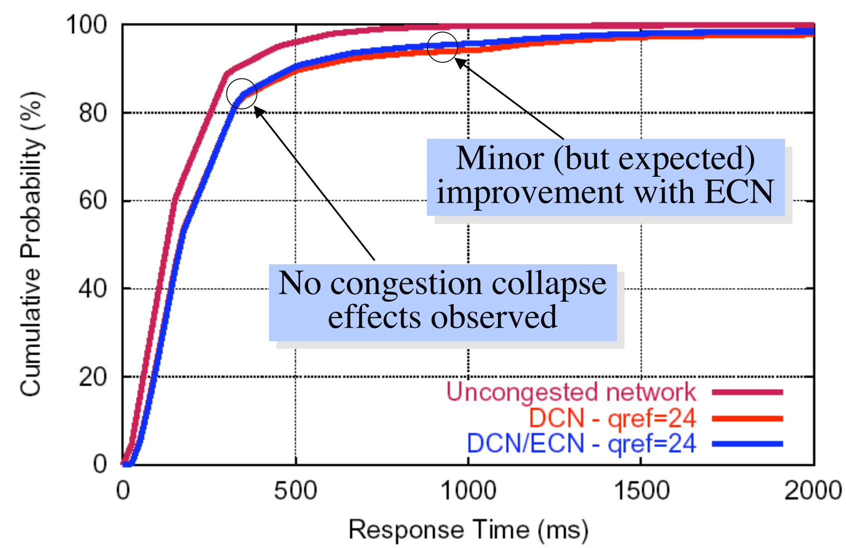
loss rate
utilization
response times
completed requests

- Run experiments with DCN, AFD, and PI at same offered loads as before
  - PI always uses ECN, test AFD with and without ECN
  - DCN always signals congestion via drops
- Compare DCN results against…
  - The better of PI or AFD (the performance to beat)
  - The uncongested network (the performance to approximate)

Experimental Results — 90% Load
DCN performance

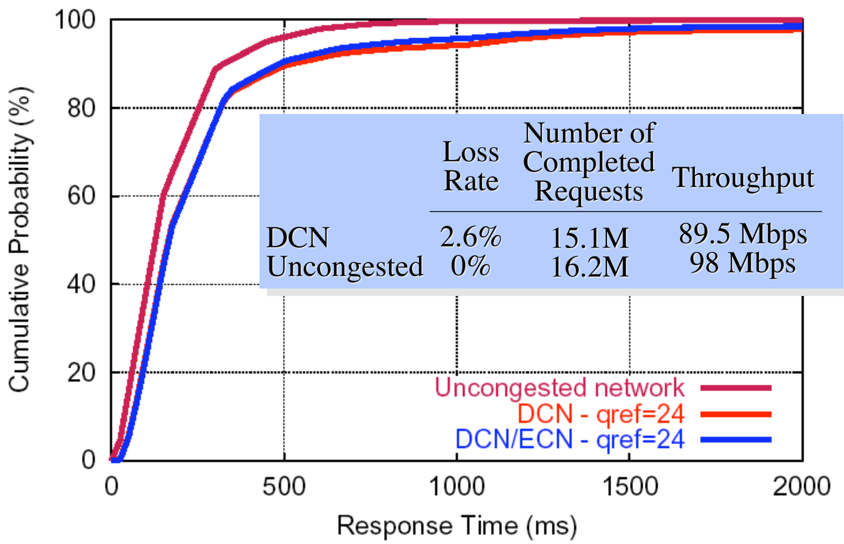


Experimental Results — 98% Load
DCN performance



Experimental Results — 98% Load

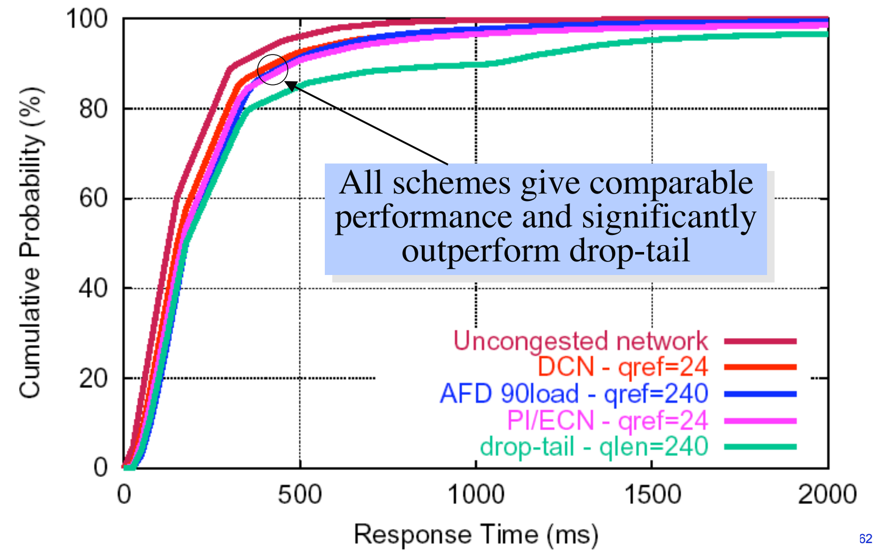
DCN performance



	Loss Rate	Number of Completed Requests	Throughput
DCN	2.6%	15.1M	89.5 Mbps
Uncongested	0%	16.2M	98 Mbps

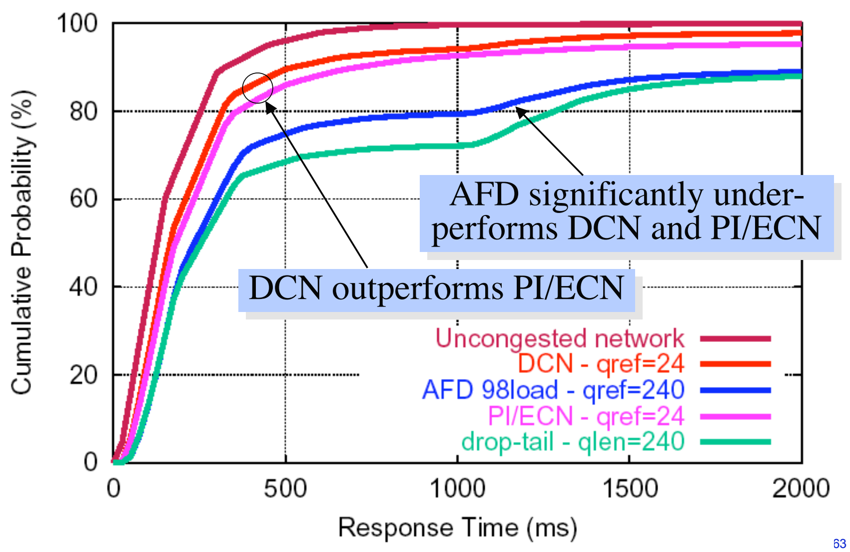
Experimental Results — 90% Load

Comparison of all schemes



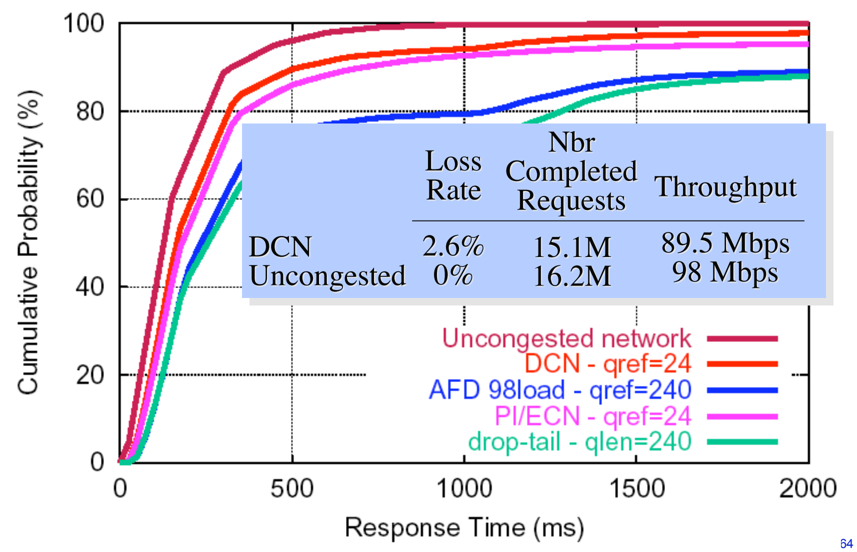
Experimental Results — 98% Load

Comparison of all schemes



Experimental Results — 98% Load

Comparison of all schemes



	Loss Rate	Nbr Completed Requests	Throughput
DCN	2.6%	15.1M	89.5 Mbps
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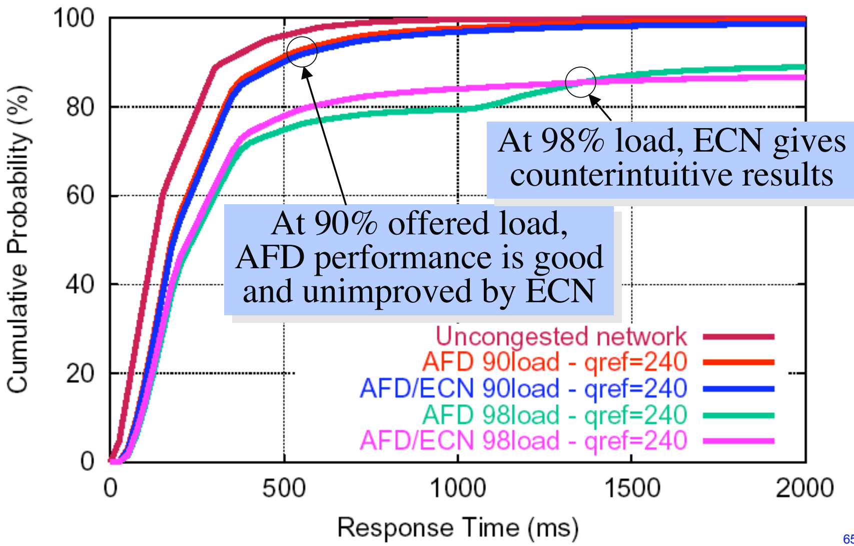
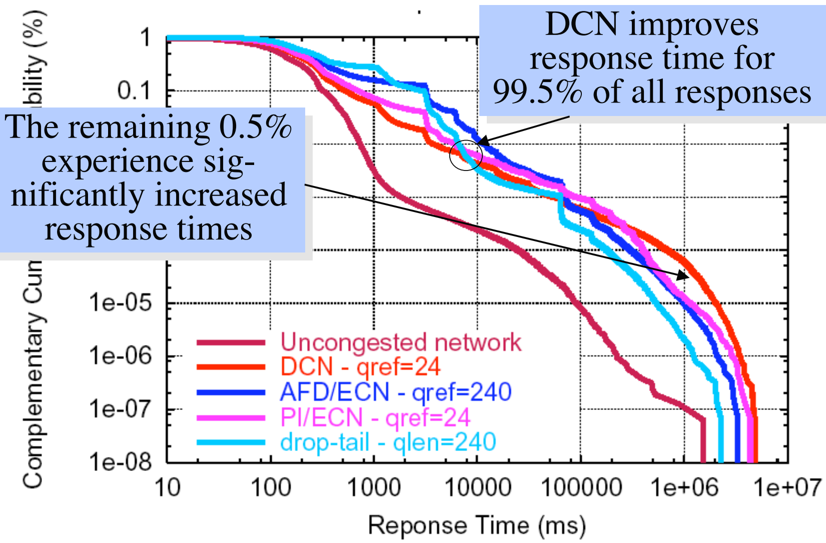
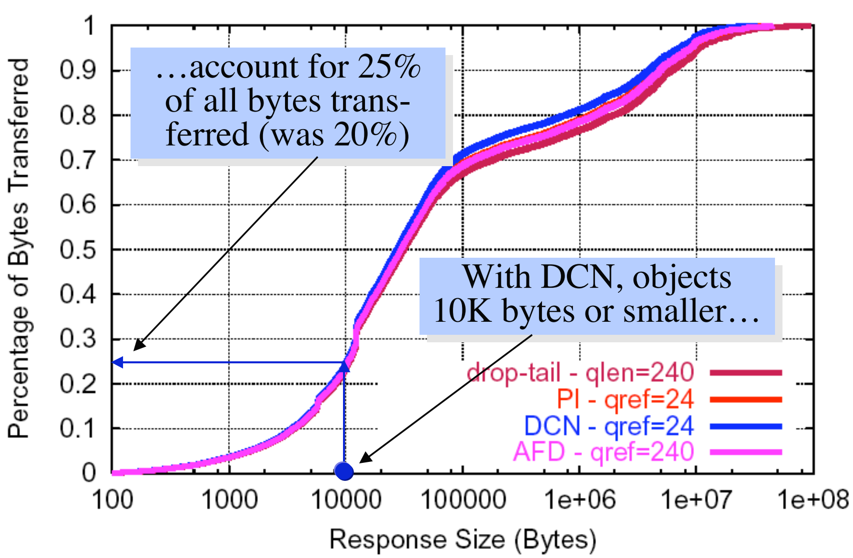
Experimental Results
AFD Performance with & without ECN



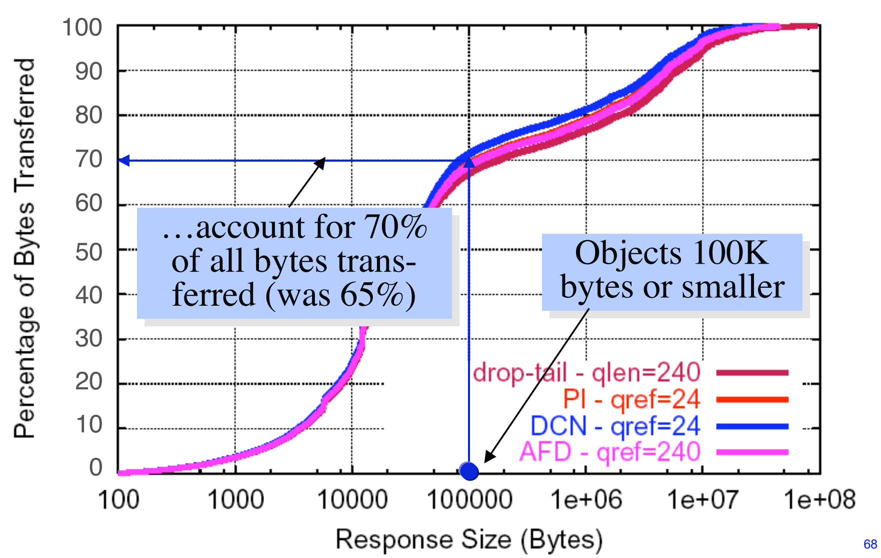
Experimental Results — 98% Load
Tail of the response time distribution



Experimental Results — 98% Load
Percentage of bytes transferred by response size



Experimental Results — 98% Load
Percentage of bytes transferred by response size



DCN Evaluation
Summary

- DCN uses a simple, tunable two-tiered classification scheme with:
  - Tunable storage overhead
  - *O*(1) complexity with high probability
- DCN, without ECN, meets or exceeds the performance of the best performing AQM designs with ECN
  - The performance of 99+% of flows is improved
  - More small and "medium" flows complete per unit time
- On heavily congested networks, DCN closely approximates the performance achieved on an uncongested network

Making AQM Work
Summary and Conclusions

- We emulated a peering point between two ISPs and applied AQM in ISP border routers
- We emulated the browsing behaviors of tens of thousands of users in a laboratory testbed
- No AQM scheme with or without ECN is better than drop-tail FIFO for offered loads up to 80% of link capacity
- For offered loads of 90% or greater there is benefit to control theoretic AQM but only when used with ECN

Making AQM Work
Summary and Conclusions

- The reliance on ECN is required to "improve" (hurt less) the performance of short flows
  - 90% of the flows in our HTTP model
- But in the absolute, ECN is not helping their performance
- Heuristically signaling only long-lived, high-bandwidth flows improves the performance of most flows and eliminates the requirement for ECN
  - One can operate links carrying HTTP traffic at near saturation levels with performance approaching an achieved on an uncongested network
- Identification of short flows can effectively be performed with tunable state and complexity

Making AQM Work
Future work

- More of the same…
  - Tuning, tuning, tuning…
  - Re-evaluate DCN (and other AQM schemes) with more diverse traffic models

    (But where do we get these models?)
  - Study the effect of non-responsive and malicious flows
- New and improved…
  - Deconstruct AQM and study performance contribution of constituent components
  - Understand the interplay between ECN and AQM components