15-744: Computer Networking

L-5 Fair Queuing

Announcements

- Project proposals: please e-mail!
  - Before/during/after class is fine
- Bin Fan will likely be back next week
- Change in lecture schedule:
  - Friday: Router design
  - Monday: Router algorithms
    - Another volunteer for presentation?

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Fair Queuing

- Fair Queuing
- Core-stateless Fair queuing
- Assigned reading
  - Analysis and Simulation of a Fair Queueing Algorithm, Internetworking: Research and Experience
  - Congestion Control for High Bandwidth-Delay Product Networks (XTP - 2 sections)

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Overview

- TCP and queues
- Queuing disciplines
- RED
- Fair-queuing
- Core-stateless FQ
- XCP

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Example

- 10Gb/s linecard
  - Requires 300Mbytes of buffering.
  - Read and write 40 byte packet every 32ns.
- Memory technologies
  - DRAM: require 4 devices, but too slow.
  - SRAM: require 80 devices, 1kW, $2000.
- Problem gets harder at 40Gb/s
  - Hence RLDRAM, FCRAM, etc.

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Rule-of-thumb

- Rule-of-thumb makes sense for one flow
- Typical backbone link has > 20,000 flows
- Does the rule-of-thumb still hold?

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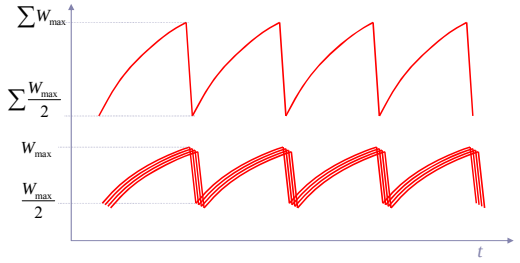
If flows are synchronized



- Aggregate window has same dynamics
- Therefore buffer occupancy has same dynamics
- Rule-of-thumb still holds.

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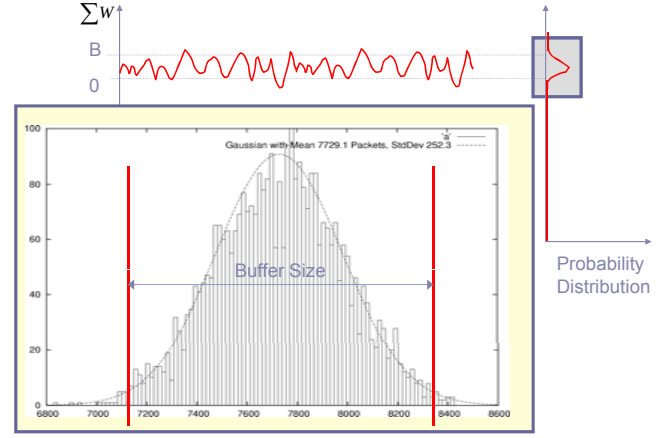
If flows are not synchronized



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Central Limit Theorem

- CLT tells us that the more variables (Congestion Windows of Flows) we have, the narrower the Gaussian (Fluctuation of sum of windows)
  - Width of Gaussian decreases with $\frac{1}{\sqrt{n}}$
  - Buffer size should also decreases with $\frac{1}{\sqrt{n}}$

$$B \rightarrow \frac{B_{n=1}}{\sqrt{n}} = \frac{2T \times C}{\sqrt{n}}$$

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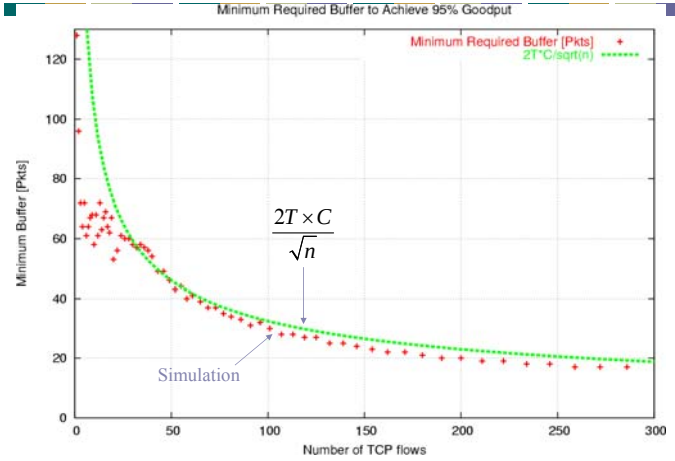
Required buffer size



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Queuing Disciplines

- Each router must implement some queuing discipline
- Queuing allocates both bandwidth and buffer space:
  - Bandwidth: which packet to serve (transmit) next
  - Buffer space: which packet to drop next (when required)
- Queuing also affects latency

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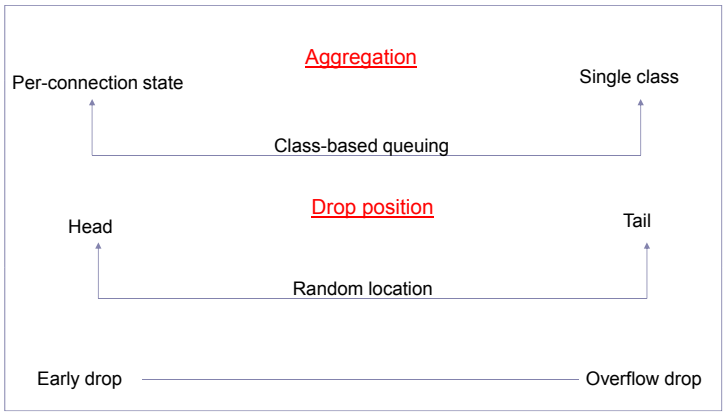
Packet Drop Dimensions



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Typical Internet Queuing

- FIFO + drop-tail
  - Simplest choice
  - Used widely in the Internet
- FIFO (first-in-first-out)
  - Implies single class of traffic
- Drop-tail
  - Arriving packets get dropped when queue is full regardless of flow or importance
- Important distinction:
  - FIFO: scheduling discipline
  - Drop-tail: drop policy

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FIFO + Drop-tail Problems

- Leaves responsibility of congestion control to edges (e.g., TCP)
- Does not separate between different flows
- No policing: send more packets → get more service
- Synchronization: end hosts react to same events

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Active Queue Management

- Design active router queue management to aid congestion control
- Why?
  - Routers can distinguish between propagation and persistent queuing delays
  - Routers can decide on transient congestion, based on workload

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Active Queue Designs

- Modify both router and hosts
  - DECbit – congestion bit in packet header
- Modify router, hosts use TCP
  - Fair queuing
    - Per-connection buffer allocation
  - RED (Random Early Detection)
    - Drop packet or set bit in packet header as soon as congestion is starting

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Internet Problems

- Full queues
  - Routers are forced to have have large queues to maintain high utilizations
  - TCP detects congestion from loss
    - Forces network to have long standing queues in steady-state
- Lock-out problem
  - Drop-tail routers treat bursty traffic poorly
  - Traffic gets synchronized easily → allows a few flows to monopolize the queue space

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Design Objectives

- Keep throughput high and delay low
- Accommodate bursts
- Queue size should reflect ability to accept bursts rather than steady-state queuing
- Improve TCP performance with minimal hardware changes

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Lock-out Problem

- Random drop
  - Packet arriving when queue is full causes some random packet to be dropped
- Drop front
  - On full queue, drop packet at head of queue
- Random drop and drop front solve the lock-out problem but not the full-queues problem

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Full Queues Problem

- Drop packets before queue becomes full (early drop)
- Intuition: notify senders of incipient congestion
  - Example: early random drop (ERD):
    - If qlen > drop level, drop each new packet with fixed probability *p*
    - Does not control misbehaving users

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Random Early Detection (RED)

- Detect incipient congestion, allow bursts
- Keep power (throughput/delay) high
  - Keep average queue size low
  - Assume hosts respond to lost packets
- Avoid window synchronization
  - Randomly mark packets
- Avoid bias against bursty traffic
- Some protection against ill-behaved users

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RED Algorithm

- Maintain running average of queue length
- If avgq < min_{th} do nothing
  - Low queuing, send packets through
- If avgq > max_{th}, drop packet
  - Protection from misbehaving sources
- Else mark packet in a manner proportional to queue length
  - Notify sources of incipient congestion

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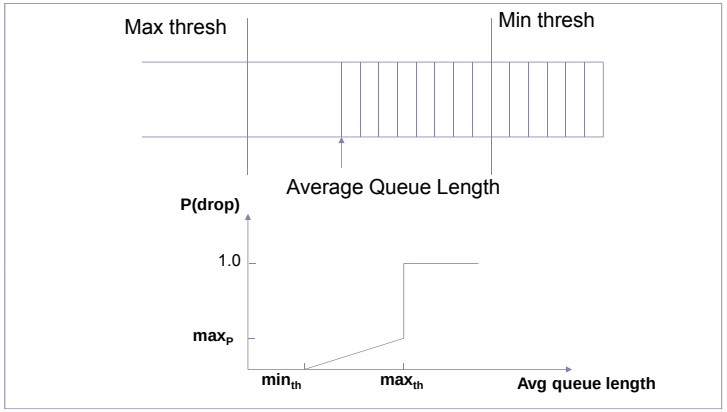
RED Operation



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RED Algorithm

- Maintain running average of queue length
  - Byte mode vs. packet mode – why?
- For each packet arrival
  - Calculate average queue size (avg)
  - If $min_{th} \leq avgq < max_{th}$
    - Calculate probability P_a
    - With probability P_a
      - Mark the arriving packet
    - Else if $max_{th} \leq avg$
      - Mark the arriving packet

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Queue Estimation

- Standard EWMA: $avgq = (1-w_q)\ avgq + w_q qlen$
  - Special fix for idle periods – why?
- Upper bound on w_q depends on min_{th}
  - Want to ignore transient congestion
  - Can calculate the queue average if a burst arrives
    - Set w_q such that certain burst size does not exceed min_{th}
- Lower bound on w_q to detect congestion relatively quickly
- Typical $w_q = 0.002$

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Thresholds

- min_{th} determined by the utilization requirement
  - Tradeoff between queuing delay and utilization
- Relationship between max_{th} and min_{th}
  - Want to ensure that feedback has enough time to make difference in load
  - Depends on average queue increase in one RTT
  - Paper suggest ratio of 2
    - Current rule of thumb is factor of 3

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Packet Marking

- max_p is reflective of typical loss rates
- Paper uses 0.02
  - 0.1 is more realistic value
- If network needs marking of 20-30% then need to buy a better link!
- Gentle variant of RED (recommended)
  - Vary drop rate from max_p to 1 as the avgq varies from max_{th} to 2* max_{th}
  - More robust to setting of max_{th} and max_p

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Extending RED for Flow Isolation

- Problem: what to do with non-cooperative flows?
- Fair queuing achieves isolation using per-flow state – expensive at backbone routers
  - How can we isolate unresponsive flows without per-flow state?
- RED penalty box
  - Monitor history for packet drops, identify flows that use disproportionate bandwidth
  - Isolate and punish those flows

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Fairness Goals

- Allocate resources fairly
- Isolate ill-behaved users
  - Router does not send explicit feedback to source
  - Still needs e2e congestion control
- Still achieve statistical muxing
  - One flow can fill entire pipe if no contenders
  - Work conserving → scheduler never idles link if it has a packet

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What is Fairness?

- At what granularity?
  - Flows, connections, domains?
- What if users have different RTTs/links/etc.
  - Should it share a link fairly or be TCP fair?
- Maximize fairness index?
  - Fairness = $(\Sigma x_i)^2/n(\Sigma x_i^2)$ 0<fairness<1
- Basically a tough question to answer – typically design mechanisms instead of policy
  - User = arbitrary granularity

Max-min Fairness

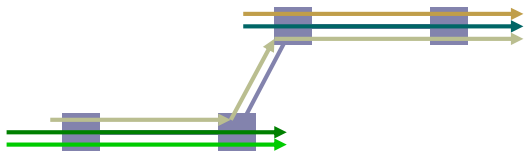
- Allocate user with "small" demand what it wants, evenly divide unused resources to "big" users
- Formally:
  - Resources allocated in terms of increasing demand
  - No source gets resource share larger than its demand
  - Sources with unsatisfied demands get equal share of resource

Max-min Fairness Example

- Assume sources 1..n, with resource demands X1..Xn in ascending order
- Assume channel capacity C.
  - Give C/n to X1; if this is more than X1 wants, divide excess (C/n - X1) to other sources: each gets C/n + (C/n - X1)/(n-1)
  - If this is larger than what X2 wants, repeat process

Max-Min Fair Sharing Example

$$r_{fair} = \frac{C - \sum_{else} r_i}{n_{here}}$$



Assume 10 Mbs links

Implementing max-min Fairness

- Generalized processor sharing
  - Fluid fairness
  - Bitwise round robin among all queues
- Why not simple round robin?
  - Variable packet length → can get more service by sending bigger packets
  - Unfair instantaneous service rate
    - What if arrive just before/after packet departs?

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Bit-by-bit RR

- Single flow: clock ticks when a bit is transmitted. For packet i:
  - P_i = length, A_i = arrival time, S_i = begin transmit time, F_i = finish transmit time
  - $F_i = S_i + P_i = \max(F_{i-1}, A_i) + P_i$
- Multiple flows: clock ticks when a bit from all active flows is transmitted → round number
  - Can calculate F_i for each packet if number of flows is know at all times
    - This can be complicated

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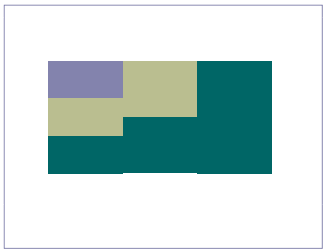
Bit-by-bit RR Illustration

- Not feasible to interleave bits on real networks
  - FQ simulates bit-by-bit RR



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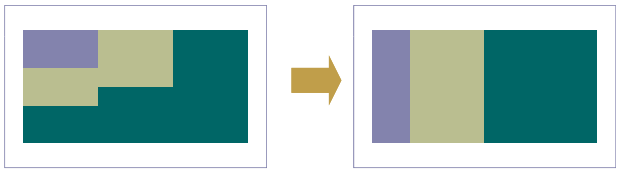
Fair Queuing

- Mapping bit-by-bit schedule onto packet transmission schedule
- Transmit packet with the lowest F_i at any given time
  - How do you compute F_i?



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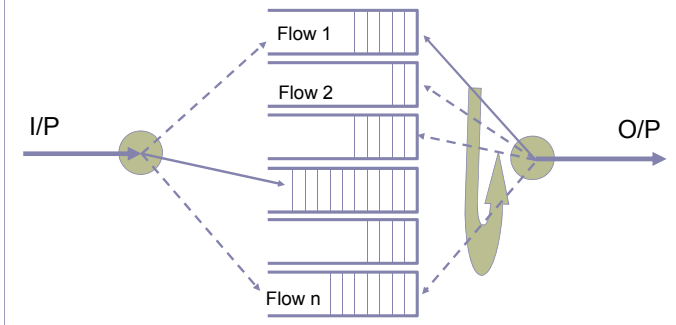
FQ Illustration



Variation: Weighted Fair Queuing (WFQ)

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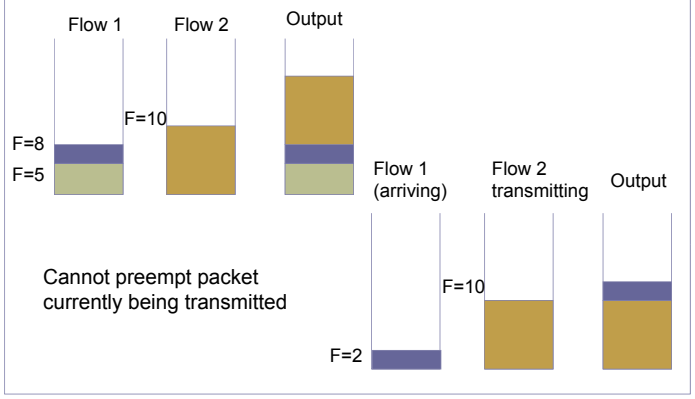
Bit-by-bit RR Example



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Fair Queuing Tradeoffs

- FQ can control congestion by monitoring flows
  - Non-adaptive flows can still be a problem – why?
- Complex state
  - Must keep queue per flow
    - Hard in routers with many flows (e.g., backbone routers)
    - Flow aggregation is a possibility (e.g. do fairness per domain)
- Complex computation
  - Classification into flows may be hard
  - Must keep queues sorted by finish times
  - Finish times change whenever the flow count changes

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- Core-stateless FQ
  - Not discussed in class – FYI only
- XCP

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Core-Stateless Fair Queuing

- Key problem with FQ is core routers
  - Must maintain state for 1000's of flows
  - Must update state at Gbps line speeds
- CSFQ (Core-Stateless FQ) objectives
  - Edge routers should do complex tasks since they have fewer flows
  - Core routers can do simple tasks
    - No per-flow state/processing → this means that core routers can only decide on dropping packets not on order of processing
    - Can only provide max-min bandwidth fairness not delay allocation

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Core-Stateless Fair Queuing

- Edge routers keep state about flows and do computation when packet arrives
- DPS (Dynamic Packet State)
  - Edge routers label packets with the result of state lookup and computation
- Core routers use DPS and local measurements to control processing of packets

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Edge Router Behavior

- Monitor each flow i to measure its arrival rate (r_i)
  - EWMA of rate
  - Non-constant EWMA constant
    - $e^{-T/K}$ where T = current interarrival, K = constant
    - Helps adapt to different packet sizes and arrival patterns
- Rate is attached to each packet

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Core Router Behavior

- Keep track of fair share rate α
  - Increasing α does not increase load (F) by N * α
  - $F(\alpha) = \Sigma_i \min(r_i, \alpha)$ → what does this look like?
  - Periodically update α
  - Keep track of current arrival rate
    - Only update α if entire period was congested or uncongested
- Drop probability for packet = max(1- α/r, 0)

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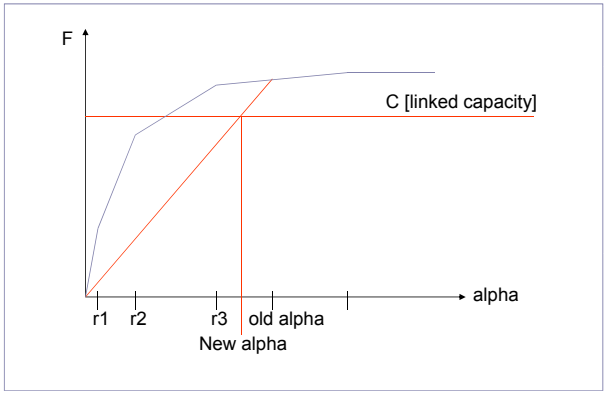
F vs. Alpha



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Estimating Fair Share

- Need F(α) = capacity = C
  - Can't keep map of F(α) values → would require per flow state
  - Since F(α) is concave, piecewise-linear
    - F(0) = 0 and F(α) = current accepted rate = F_c
    - $F(\alpha) = F_c / \alpha$
    - $F(\alpha_{new}) = C \rightarrow \alpha_{new} = \alpha_{old} * C/F_c$
- What if a mistake was made?
  - Forced into dropping packets due to buffer capacity
  - When queue overflows α is decreased slightly

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Other Issues

- Punishing fire-hoses – why?
  - Easy to keep track of in a FQ scheme
- What are the real edges in such a scheme?
  - Must trust edges to mark traffic accurately
  - Could do some statistical sampling to see if edge was marking accurately

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  - See also slides by Nicolas Feltman

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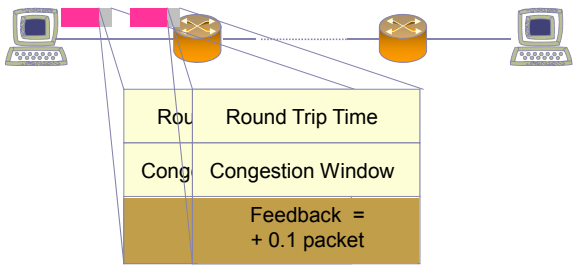
How does XCP Work?



Congestion Header

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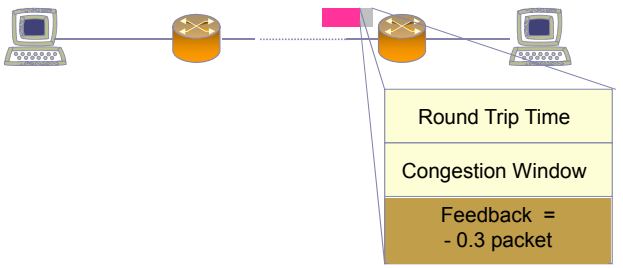
How does XCP Work?



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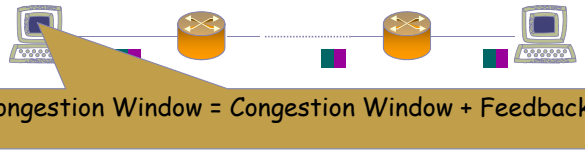

XCP extends ECN and CSFQ

Routers compute feedback without any per-flow state

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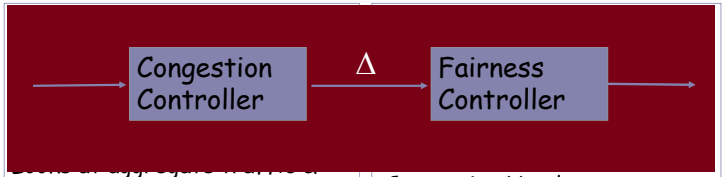
How Does an XCP Router Compute the Feedback?



queue

MIMD

Algorithm:

Aggregate traffic changes by Δ

Δ ~ Spare Bandwidth

Δ ~ - Queue Size

So, $\Delta = \alpha\, d_{avg}\, Spare - \beta\, Queue$

Congestion He

AIMD

Algorithm:

If Δ > 0 ⇒ Divide Δ equally between flows

If Δ < 0 ⇒ Divide Δ between flows proportionally to their current rates

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Getting the devil out of the details …

Congestion Controller

$\Delta = \alpha\, d_{avg}\, Spare - \beta\, Queue$

Theorem: System converges to optimal utilization (i.e., stable) for any link bandwidth, delay, number of sources if:

$$0 < \alpha < \frac{\pi}{4\sqrt{2}} \quad and \quad \beta = \alpha^2\sqrt{2}$$

No Parameter Tuning

Fairness Controller

Algorithm:

If $\Delta > 0 \Rightarrow$ Divide Δ equally between flows

If $\Delta < 0 \Rightarrow$ Divide Δ between flows proportionally to their current rates

Need to estimate number of flows N

$$N = \sum_{pkts\ in\ T} \frac{1}{T \times (Cwnd_{pkt} / RTT_{pkt})}$$

RTT_{pkt}: Round Trip Time in header

No Per-Flow State

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Discussion

- RED
  - Parameter settings
- RED vs. FQ
  - How much do we need per flow tracking? At what cost?
- FQ vs. XCP/CSFQ
  - Is coarse-grained fairness sufficient?
  - Misbehaving routers/trusting the edge
  - Deployment (and incentives)
  - How painful is FQ
- XCP vs CSFQ
  - What are the key differences
- Granularity of fairness
  - Mechanism vs. policy → will see this in QoS

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Important Lessons

- How does TCP implement AIMD?
  - Sliding window, slow start & ack clocking
  - How to maintain ack clocking during loss recovery → fast recovery
- How does TCP fully utilize a link?
  - Role of router buffers
- TCP alternatives
  - TCP being used in new/unexpected ways
  - Key changes needed

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