Fundamentals of Quality of Service

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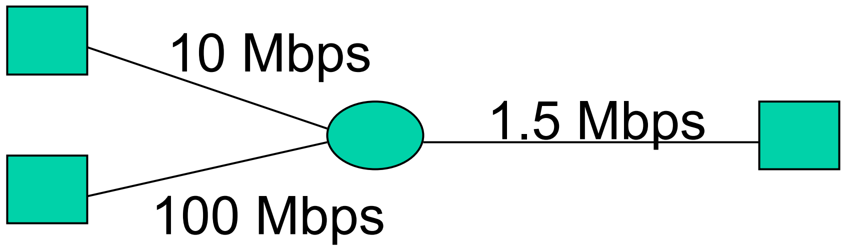
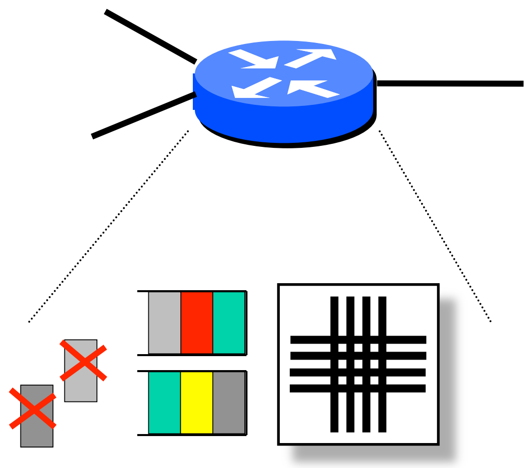
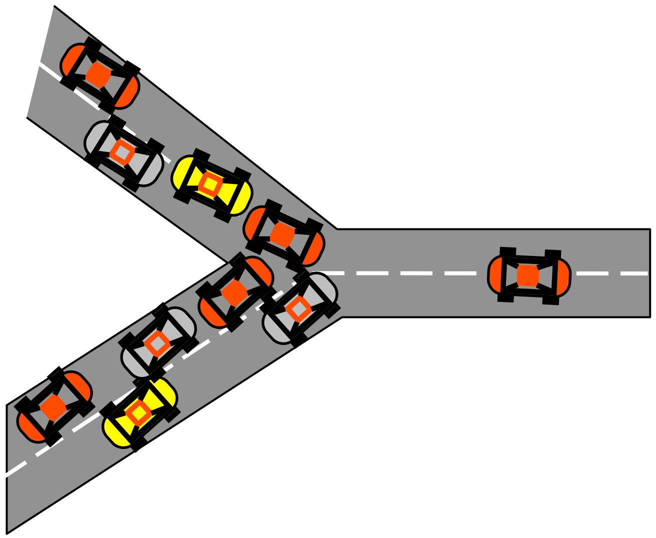
These slides borrow material from various sources which are indicated below each slide when necessary

Slides mostly taken from Shivkumar Kalyanaraman which are mostly based on slides of Ion Stoica, Jim Kurose, Srini Seshan, Srini Keshav

The congestion phenomenon



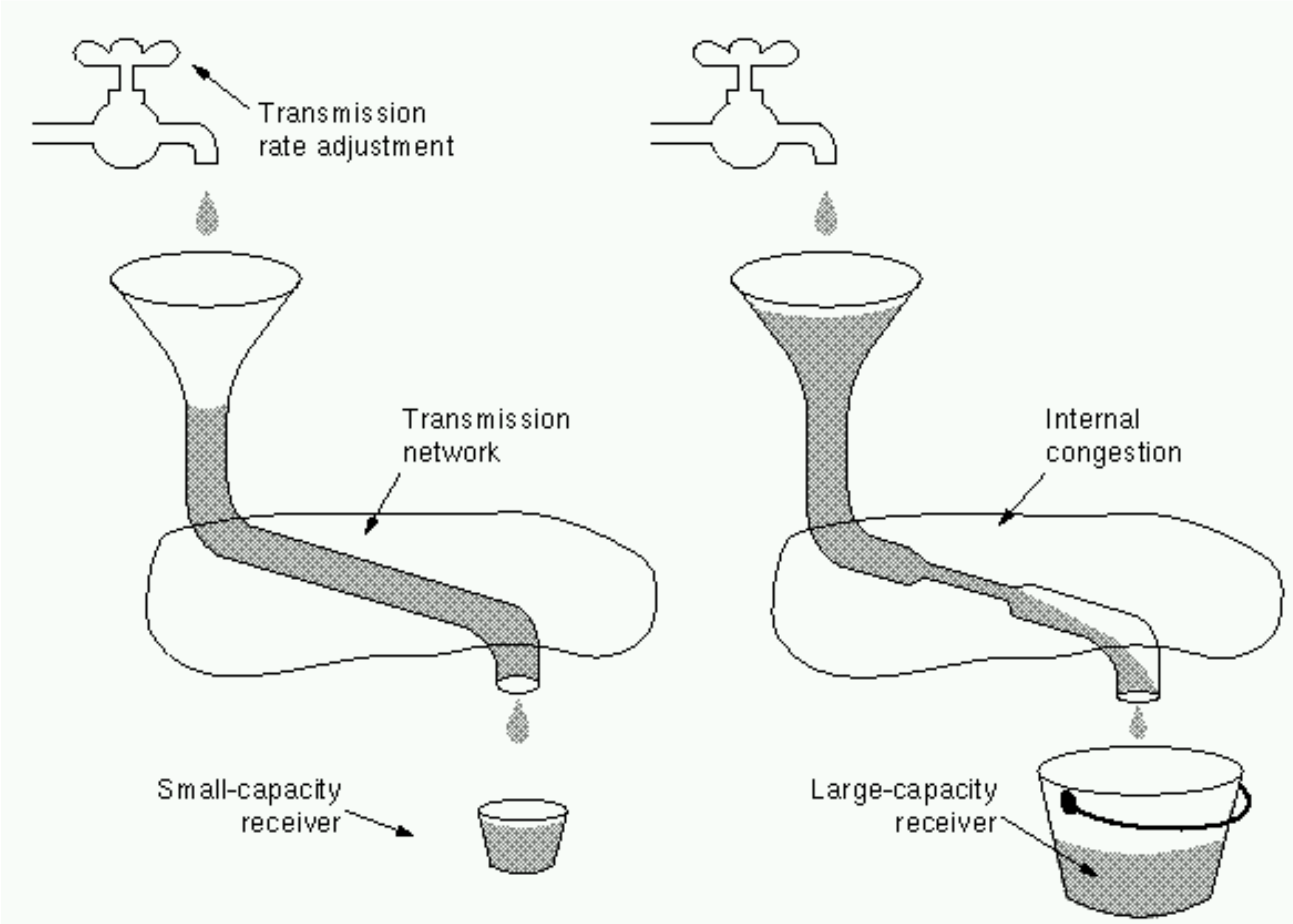




- Too many packets sent to the same interface.
- Difference bandwidth from one network to another

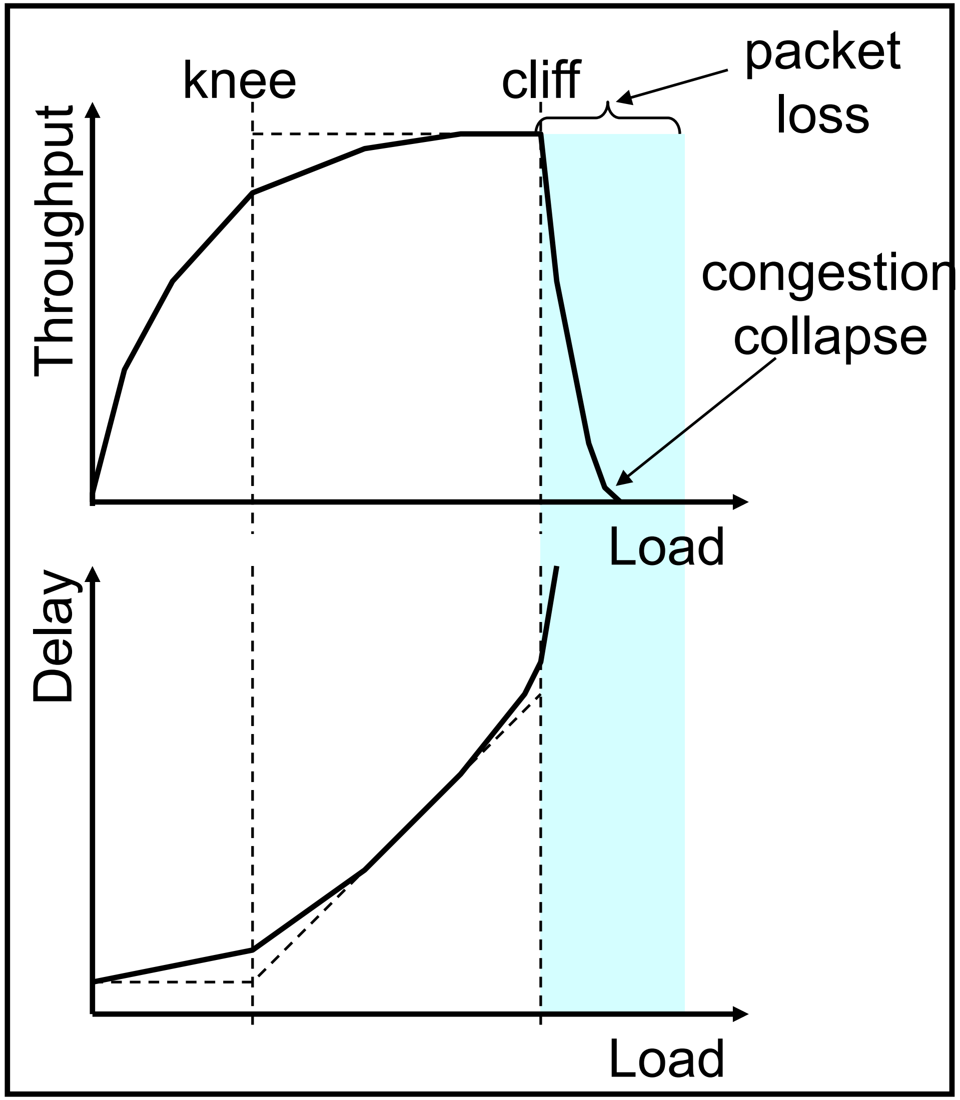
Main consequence: packet losses in routers

The problem of bottlenecks in networks



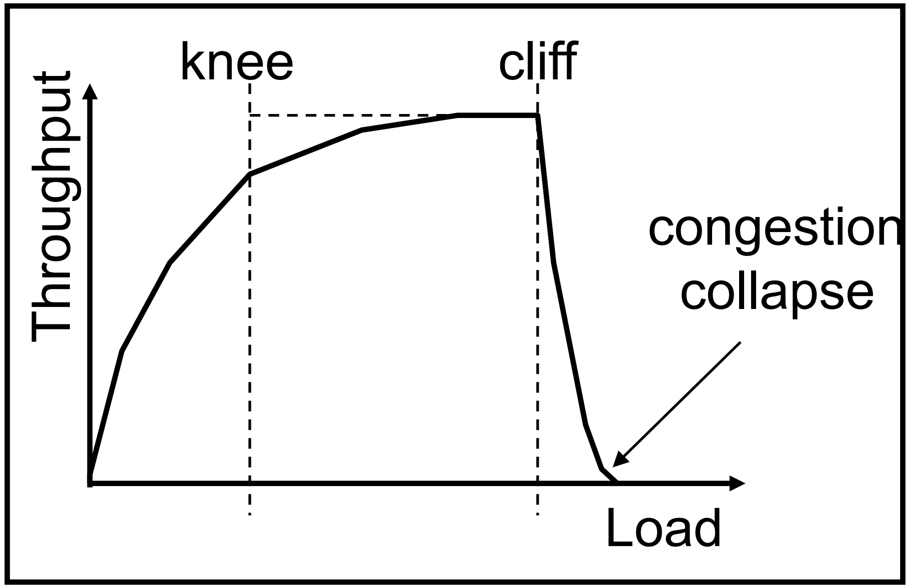
Congestion: A Close-up View

- knee – point after which
  - throughput increases very slowly
  - delay increases fast
- cliff – point after which
  - throughput starts to decrease very fast to zero (congestion collapse)
  - delay approaches infinity
- Note (in an M/M/1 queue)
  - delay = 1/(1 – utilization)

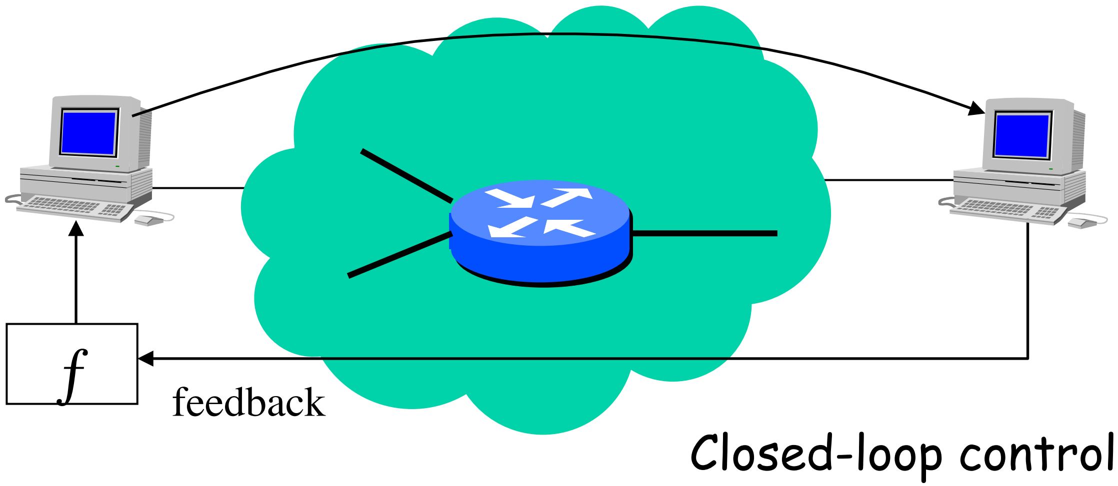


Congestion Control vs. Congestion Avoidance

- Congestion control goal
  - stay left of cliff
- Congestion avoidance goal
  - stay left of knee
- Right of cliff:
  - Congestion collapse



From the control theory point of view

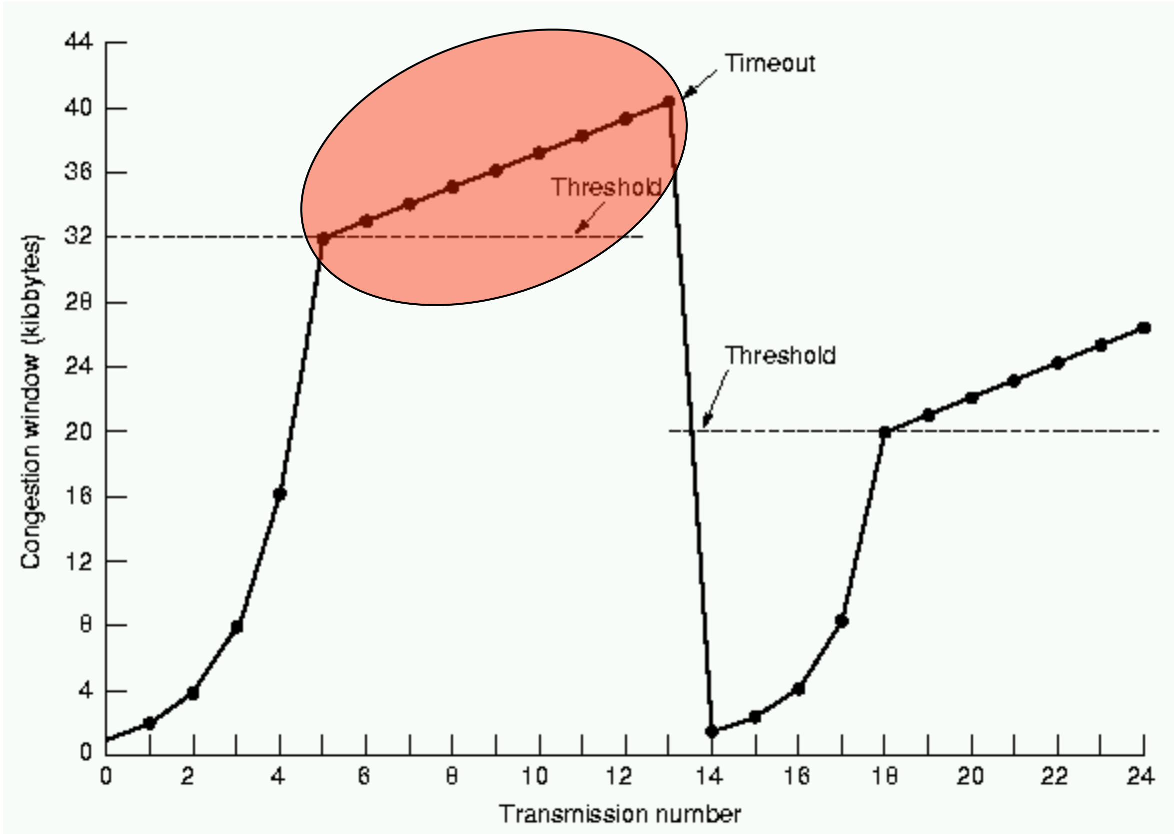


- Feedback should be frequent, but not too much otherwise there will be oscillations
- Can not control the behavior with a time granularity less than the feedback period

Congestion control principles

- Reactive
  - When congestion is detected, inform upstream and downstream nodes,
  - Then, marks, drops and process packets with priority levels
- Preventive
  - Periodical broadcast of node's status (buffer occupancy for instance)
  - Control of the source, traffic shaping (Leacky Bucket, Token Bucket...),
  - Flow control, congestion control, admission control.
- End-to-end
  - No feedback from the networks
  - Congestion is detected by end nodes only, using filters (packet losses, RTT variations...)
- Router-assisted
  - Congestion indication bit (SNA, DECbit, TCP/ECN, FR, ATM)
  - More complex router functionalities (XCP)

Congestion control in TCP: avoidance

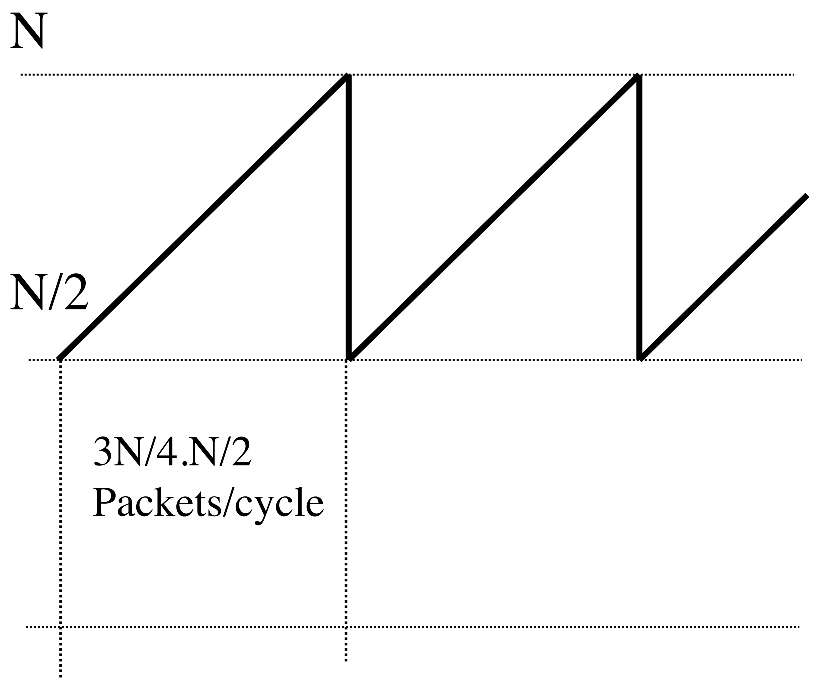


- initial threshold set to 64K, cwnd grows exponentially (slow-start) then linearly (*congestion avoidance*),
- If packet losses, threshold is divided by 2, and cwnd=1

The TCP saw-tooth curve

TCP behavior in steady state

Isolated packet losses trigger the fast recovery procedure instead of the slow-start.



- The TCP steady-state behavior is referred to as the Additive Increase-Multiplicative Decrease process

no loss:

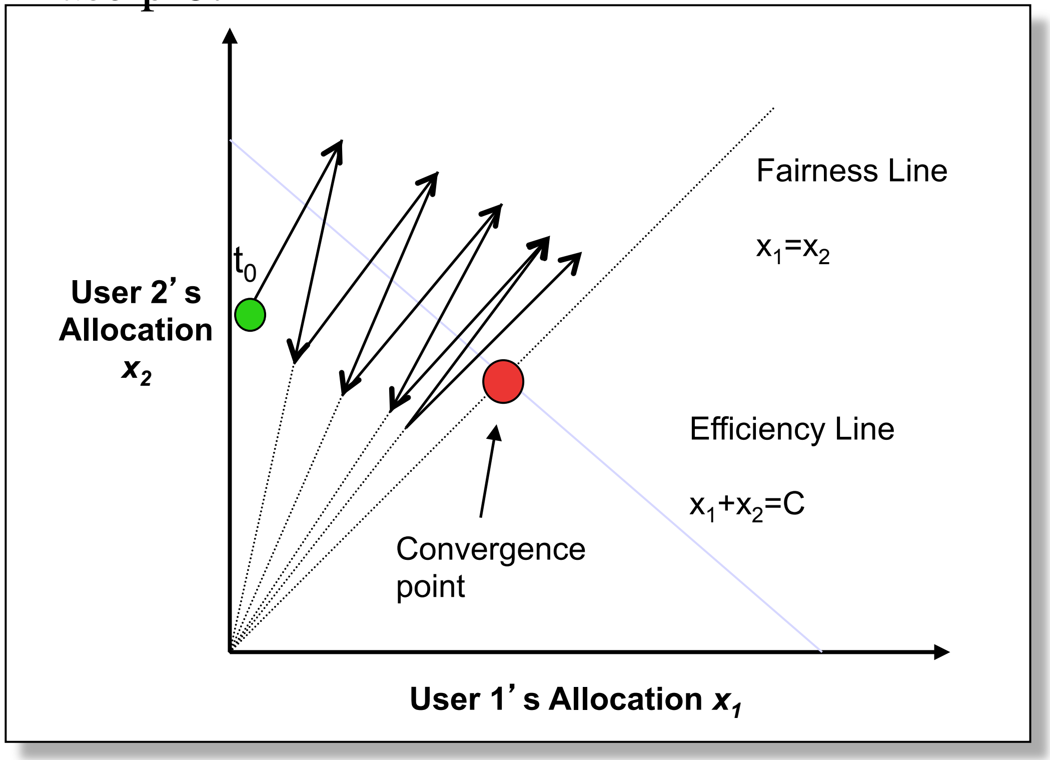
cwnd = cwnd + 1

loss:

cwnd = cwnd*0.5

AIMD

Phase plot



Fairness is preserved under Multiplicative Decrease since the user's allocation ratio remains the same

Ex: $$\frac{x_2}{x_1} = \frac{x_2 b}{x_1 b}$$

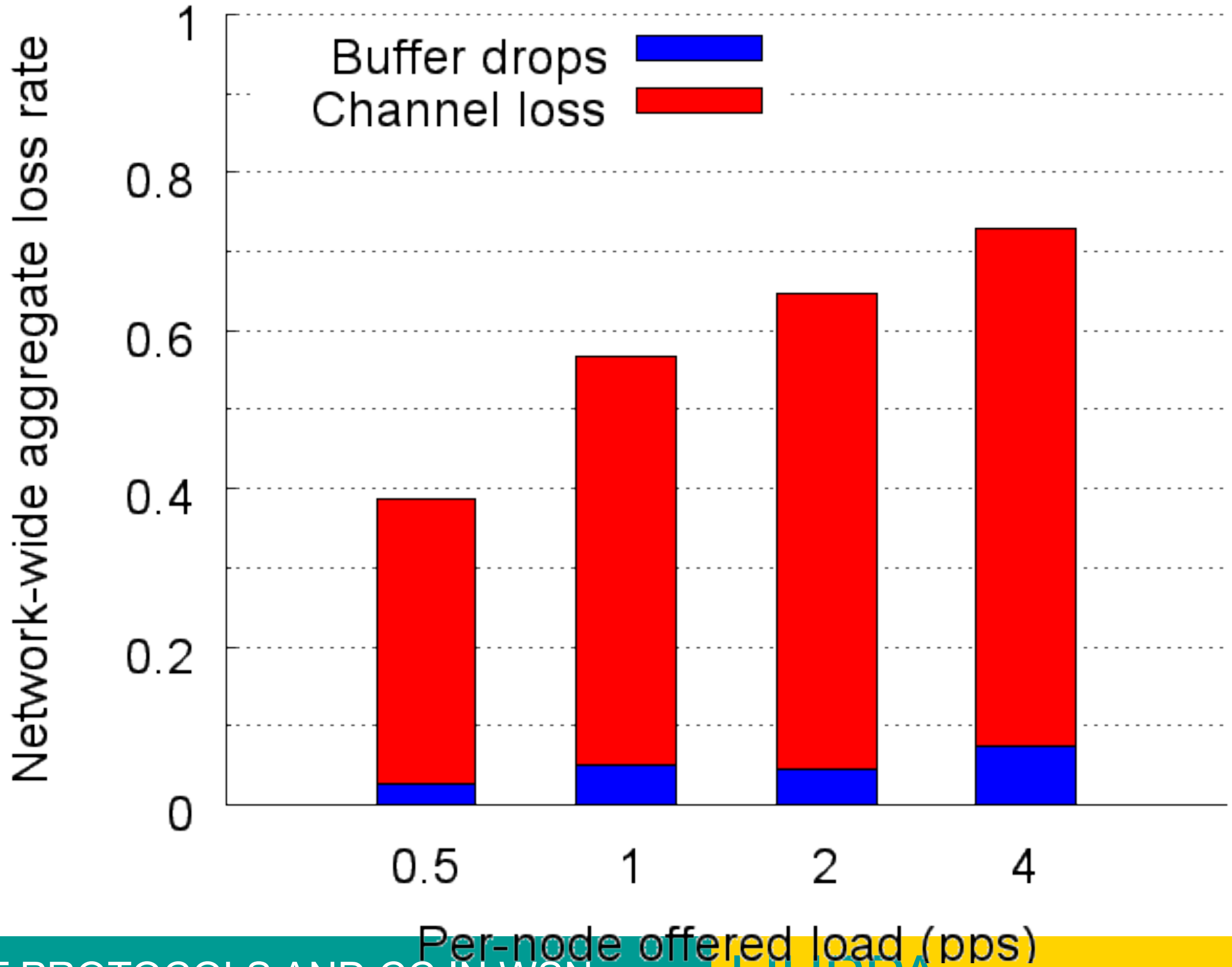
- Assumption: decrease policy must (at minimum) reverse the load increase over-and-above efficiency line
- Implication: decrease factor should be conservatively set to account for any congestion detection lags etc

Congestion in wireless networks

Congestion in wireless env.

- Very lossy environments
- High interferences
- Difficult to distinguish congestions from node failures or bad channel quality
- Input queue occupancy is not a good indicator of congestion level !!

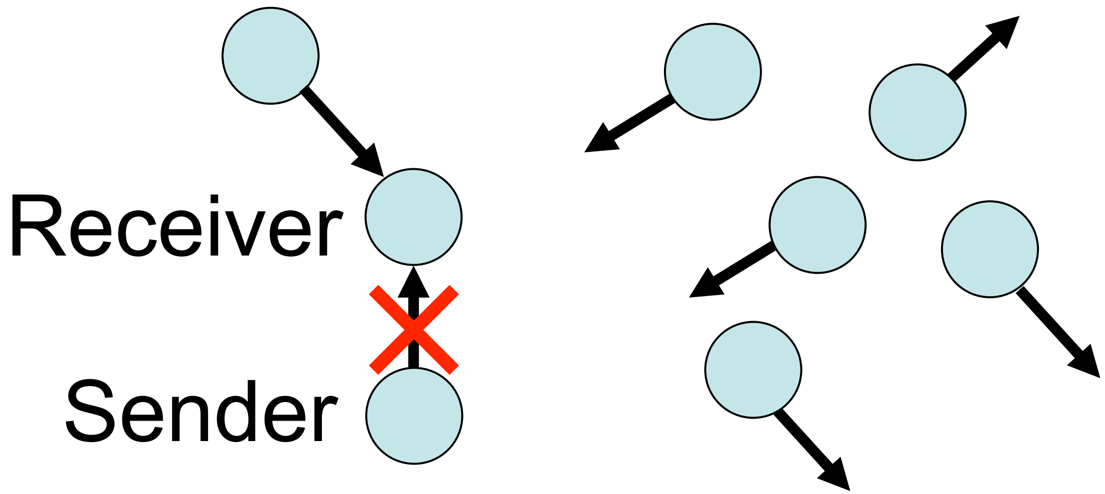
Congestion dramatically degrades channel quality



From "Mitigating Congestion in Wireless Sensor Networks", by Hull et al.

Why does channel quality degrade?

- Wireless is a shared medium
  - Hidden terminal collisions
  - Many far-away transmissions corrupt packets



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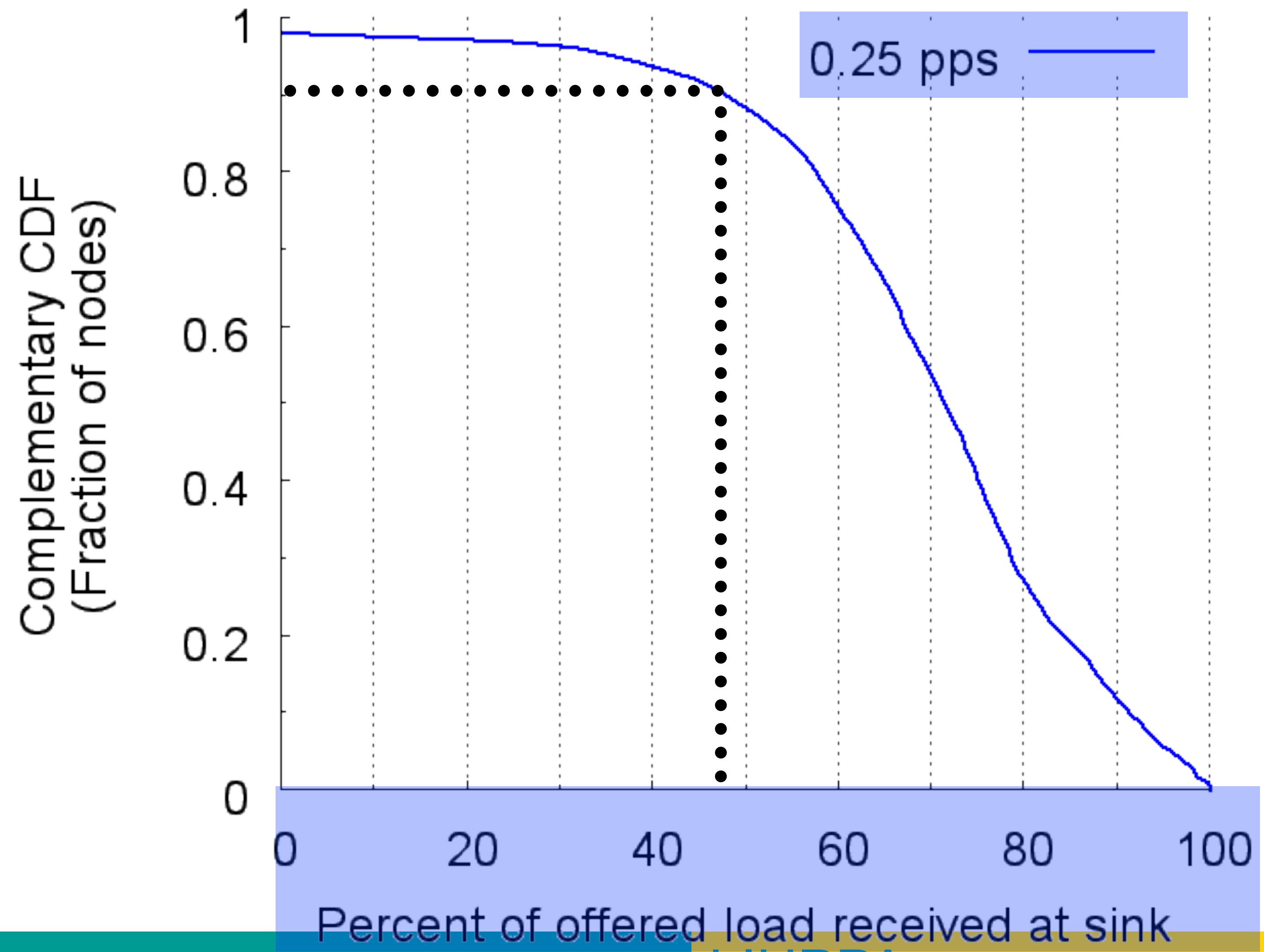
Per-node throughput distribution



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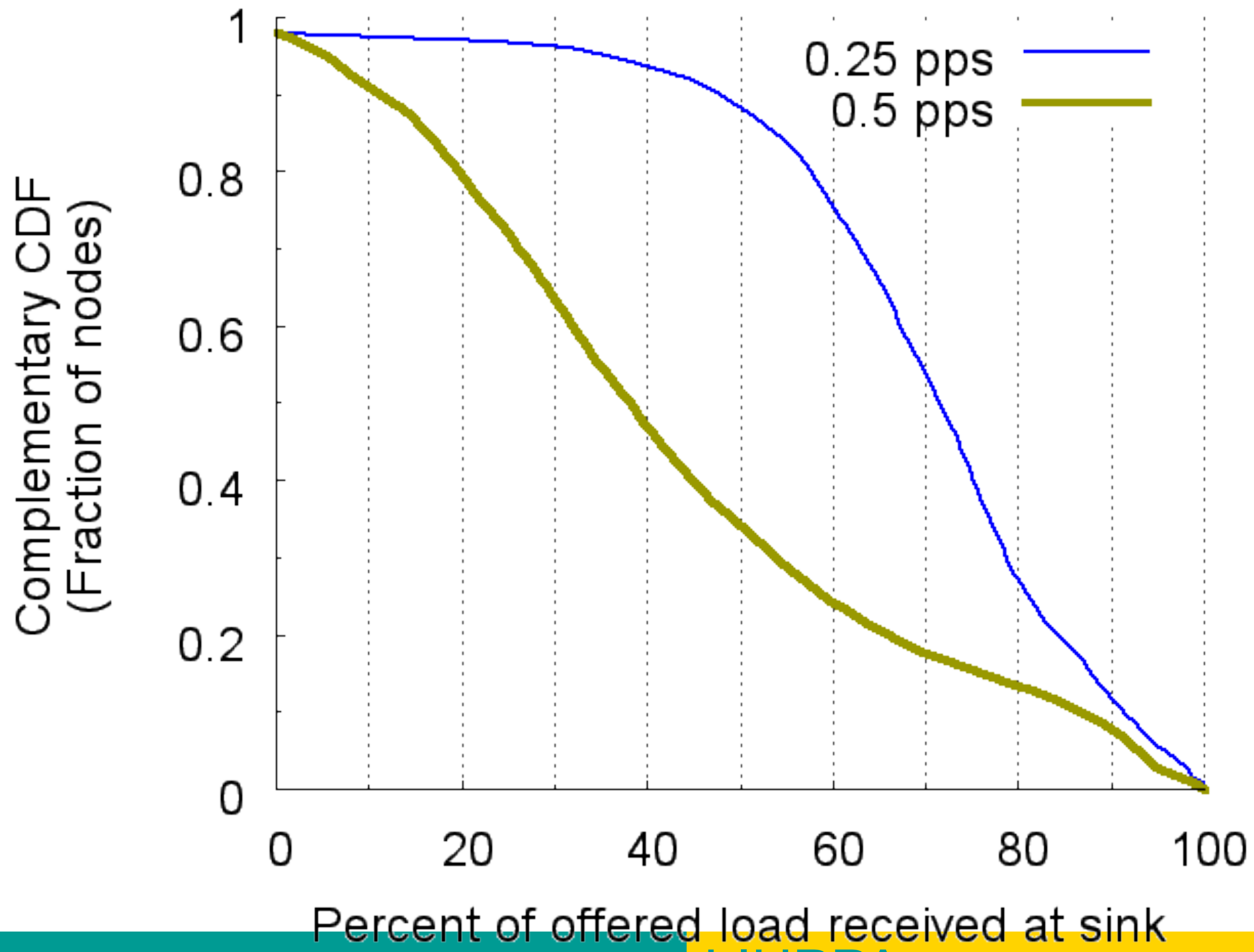

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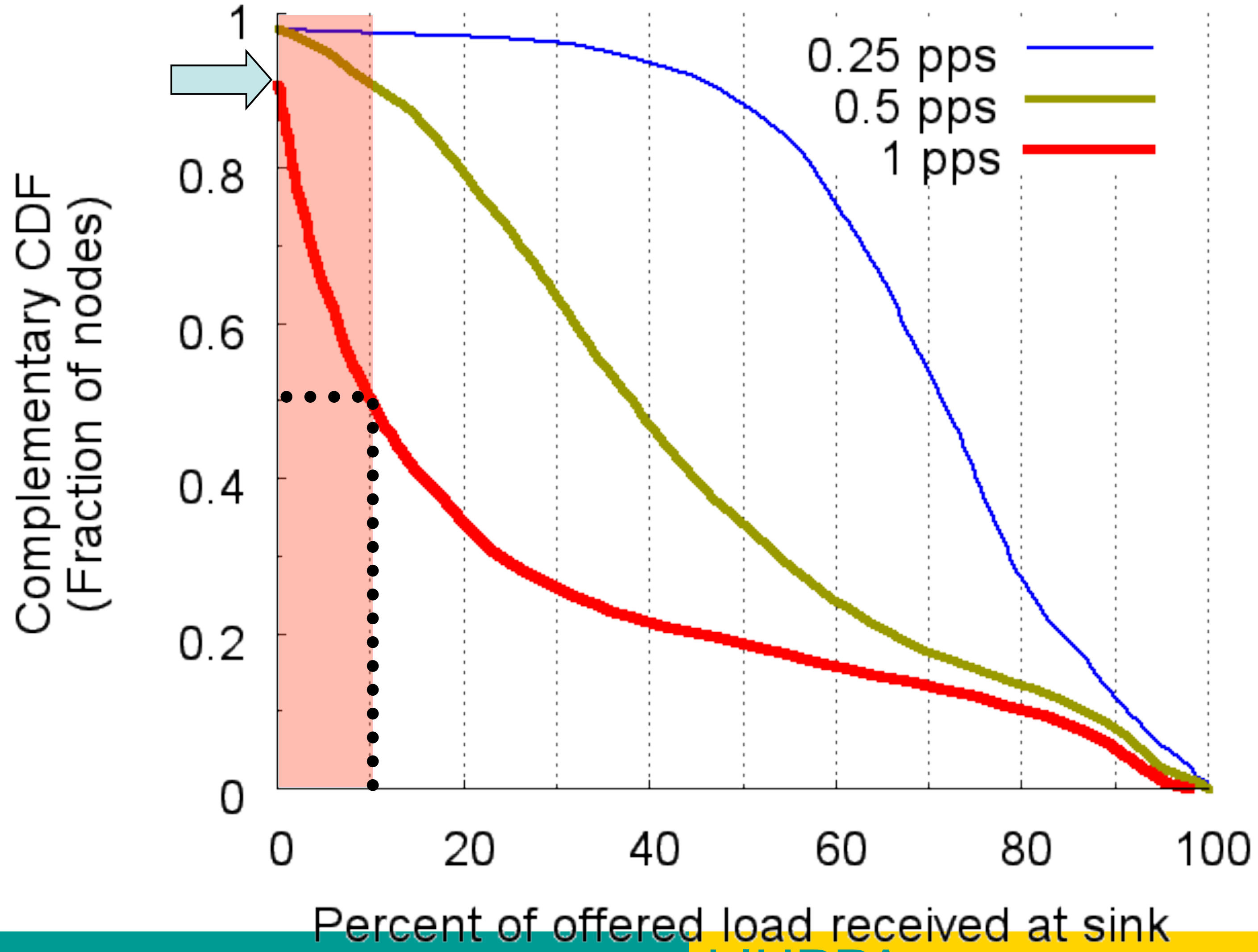

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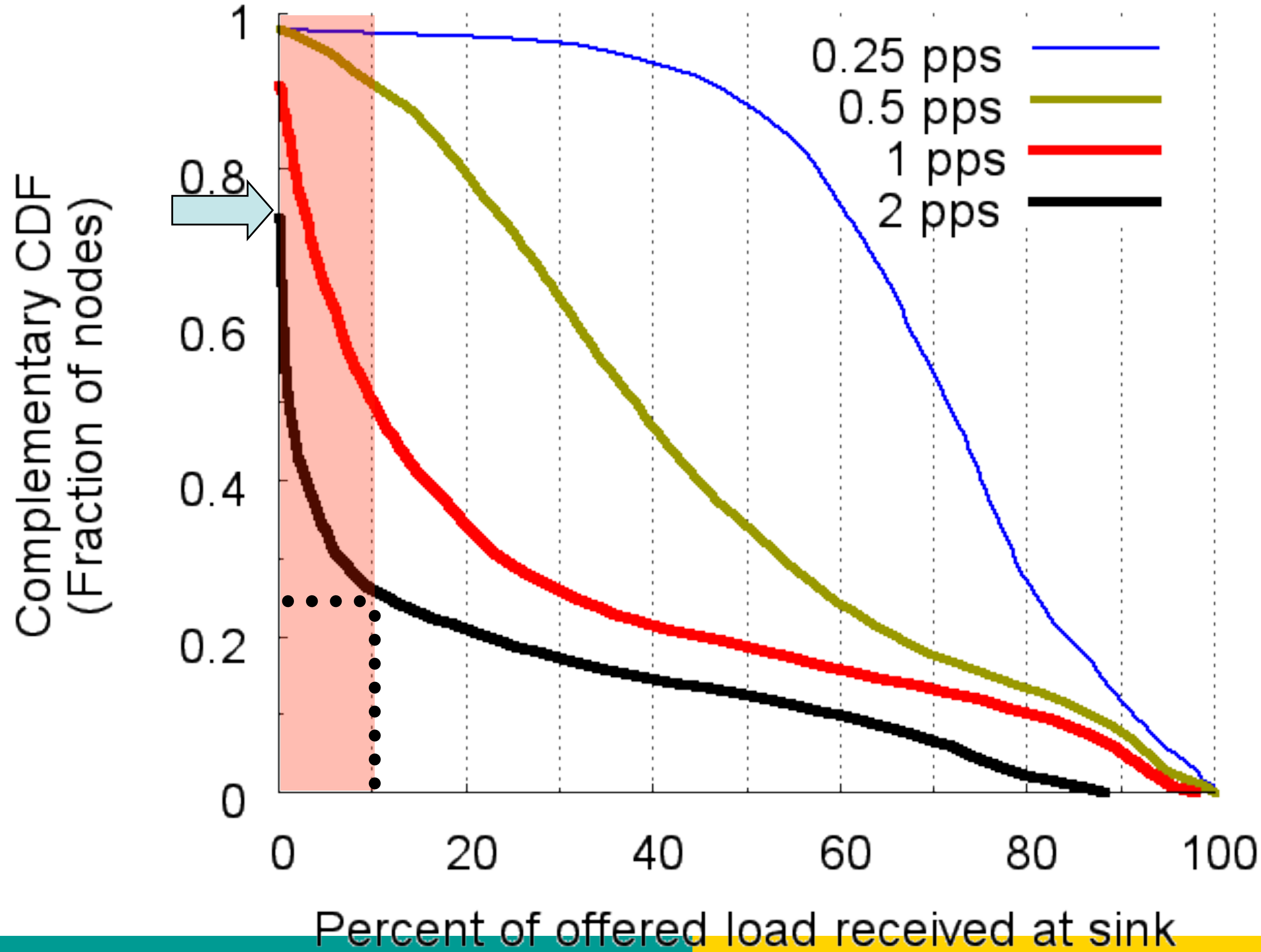
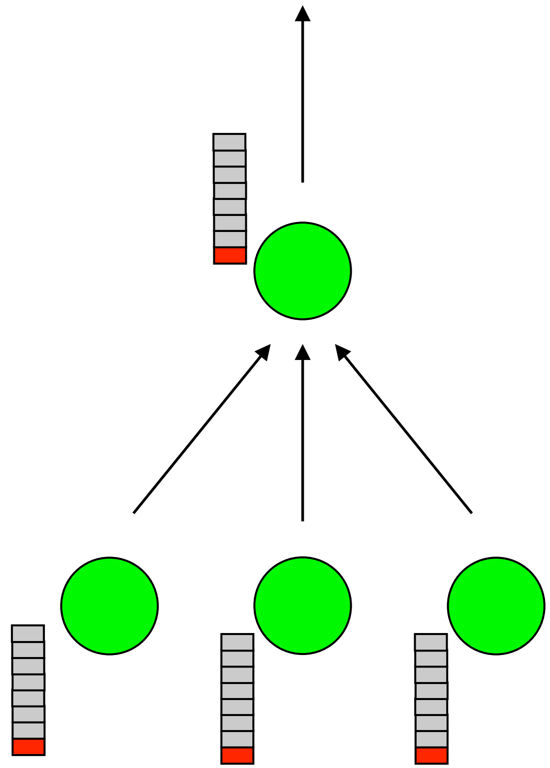


From "Mitigating Congestion in Wireless Sensor Networks", by Hull et al.

Detecting congestion?

- Queue occupancy-based congestion detection
  - Each node has an output packet queue
  - Monitor instantaneous output queue occupancy
  - If queue occupancy exceeds α, indicate *local congestion*



Queue occupancy not enough!

- Channel sampling: sample channel at appropriate time to detect congestion
- Report Rate from sources: Fidelity measurement – observed over a long period

C.-Y. Wan, S. B. Eisenman, and A. T. Campbell, "CODA: Congestion detection and avoidance in sensor networks," in Proceedings of ACM Sensys' 03

Channel sampling

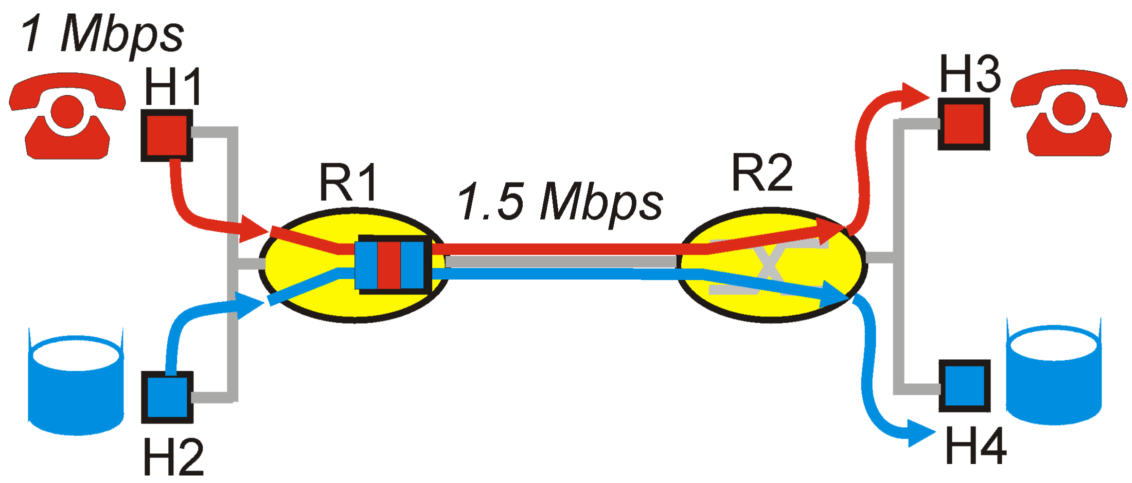
- Channel status (busy/idle) measured for N consecutive sensing epochs of length E with a predefined sampling rate → Φ_n : # of busy(idle) / epoch
- $\Phi_{n+1} = \alpha \, \Phi_n + (1-\alpha) \, \Phi_n$ (EWMA)
- Experimental validation for
  - $N \in \{2,3,4,5\}$
  - $E \in \{100ms, 200ms, 300ms\}$
  - $\alpha \in \{0.75, 0.80, 0.85, 0.95\}$

How to upgrade the Internet for QoS?

- Approach: de-couple end-system evolution from network evolution
- End-to-end protocols: RTP, H.323, etc to spur the growth of adaptive multimedia applications
  - Assume best-effort or better-than-best-effort clouds
- Network protocols: IntServ, DiffServ, RSVP, MPLS, COPS …
  - To support better-than-best-effort capabilities at the network (IP) level

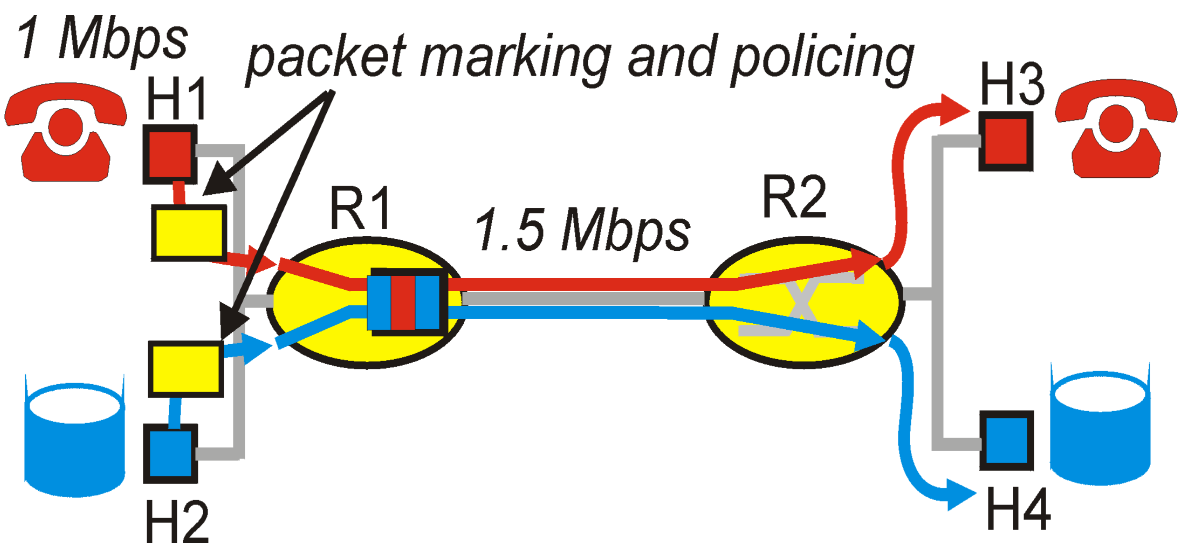
Principles for QOS Guarantees

- Consider a phone application at 1Mbps and an FTP application sharing a 1.5 Mbps link.
  - bursts of FTP can congest the router and cause audio packets to be dropped.
  - want to give priority to audio over FTP
- **PRINCIPLE 1: Marking of packets is needed for router to distinguish between different classes; and new router policy to treat packets accordingly**



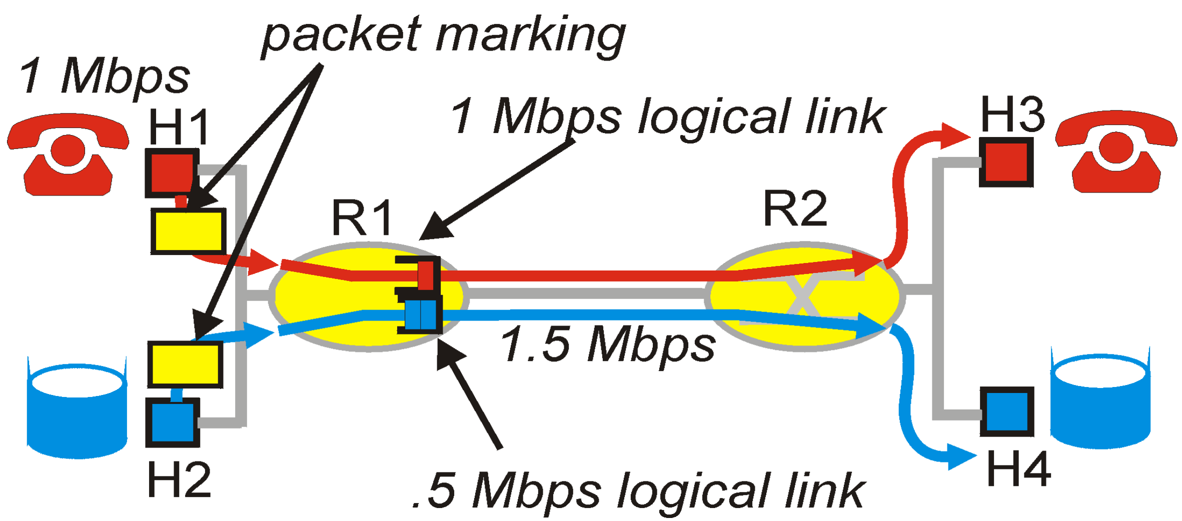
Principles for QOS Guarantees (more)

- Applications misbehave (audio sends packets at a rate higher than 1Mbps assumed above);
- **PRINCIPLE 2: provide protection (isolation) for one class from other classes**
- Require Policing Mechanisms to ensure sources adhere to bandwidth requirements; Marking and Policing need to be done at the edges:



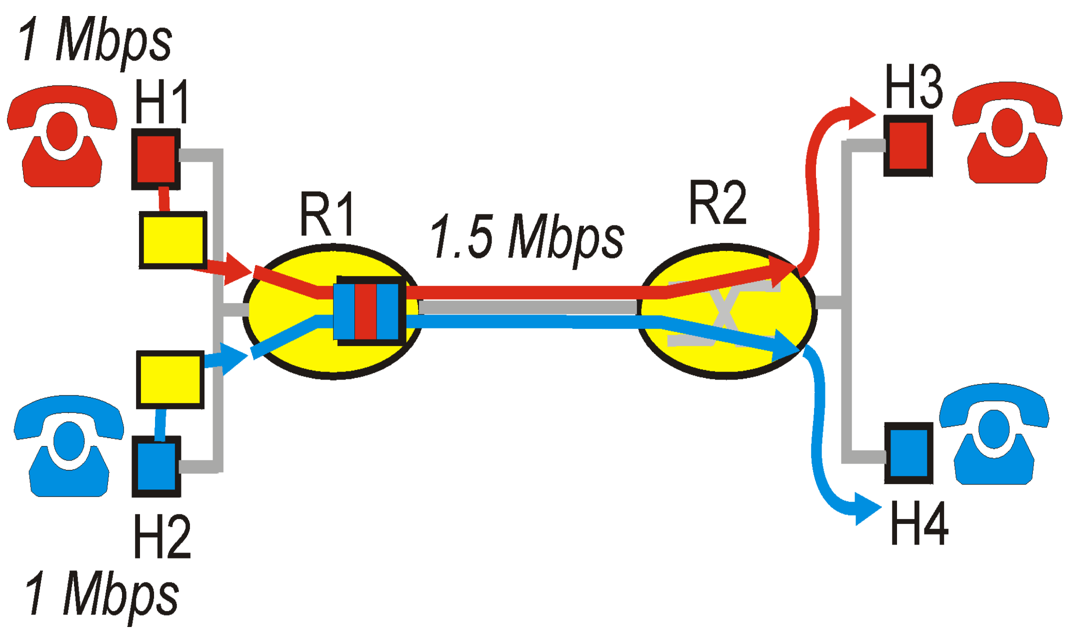
Principles for QOS Guarantees (more)

- Alternative to Marking and Policing: allocate a set portion of bandwidth to each application flow; can lead to inefficient use of bandwidth if one of the flows does not use its allocation
- **PRINCIPLE 3: While providing isolation, it is desirable to use resources as efficiently as possible**

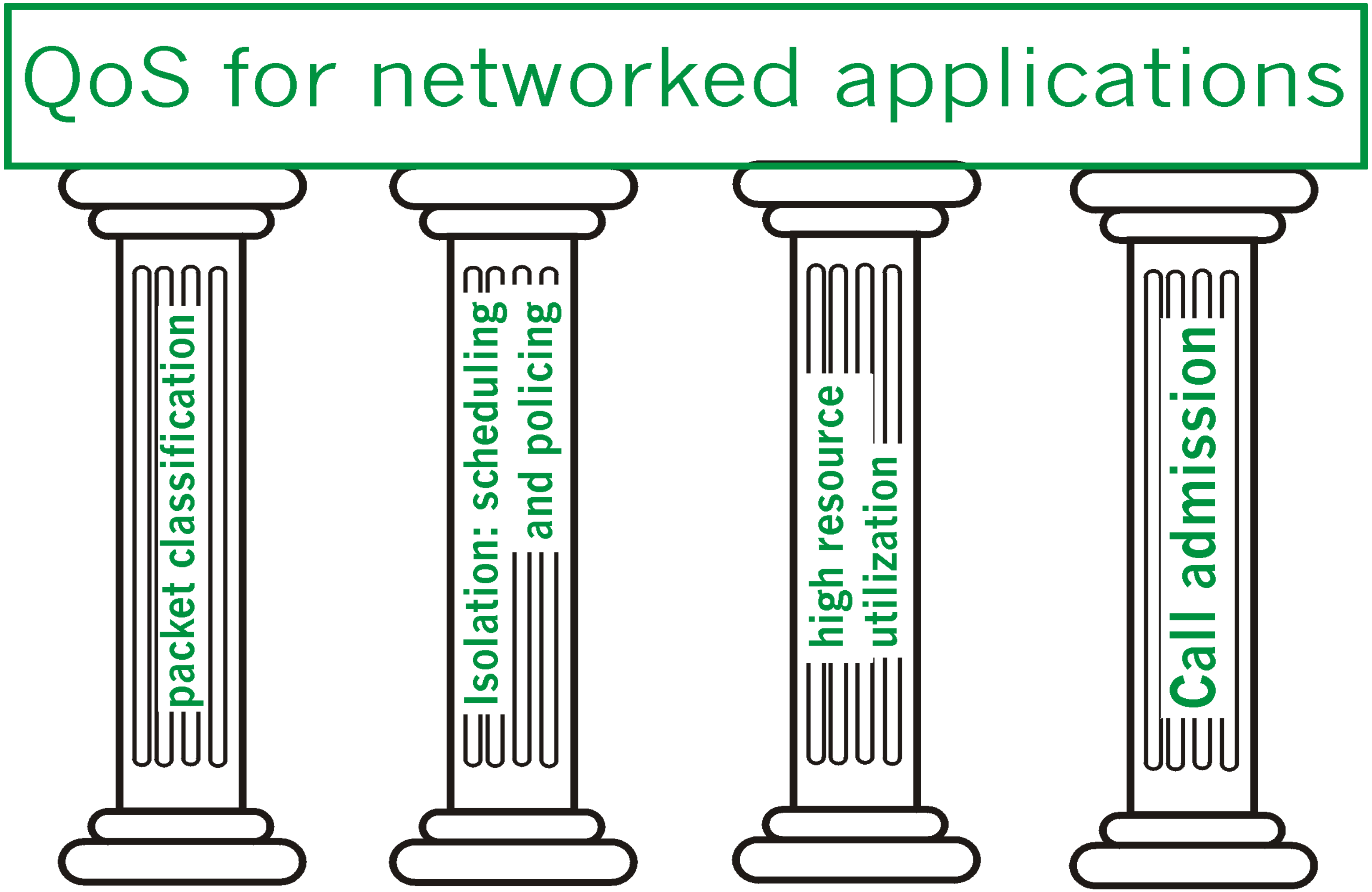


Principles for QOS Guarantees (more)

- Cannot support traffic beyond link capacity
- PRINCIPLE 4: Need a Call Admission Process; application flow declares its needs, network may block call if it cannot satisfy the needs



Summary


QoS for networked applications
packet classification
Isolation: scheduling
and policing
high resource
utilization
Call admission

High Performance Routers

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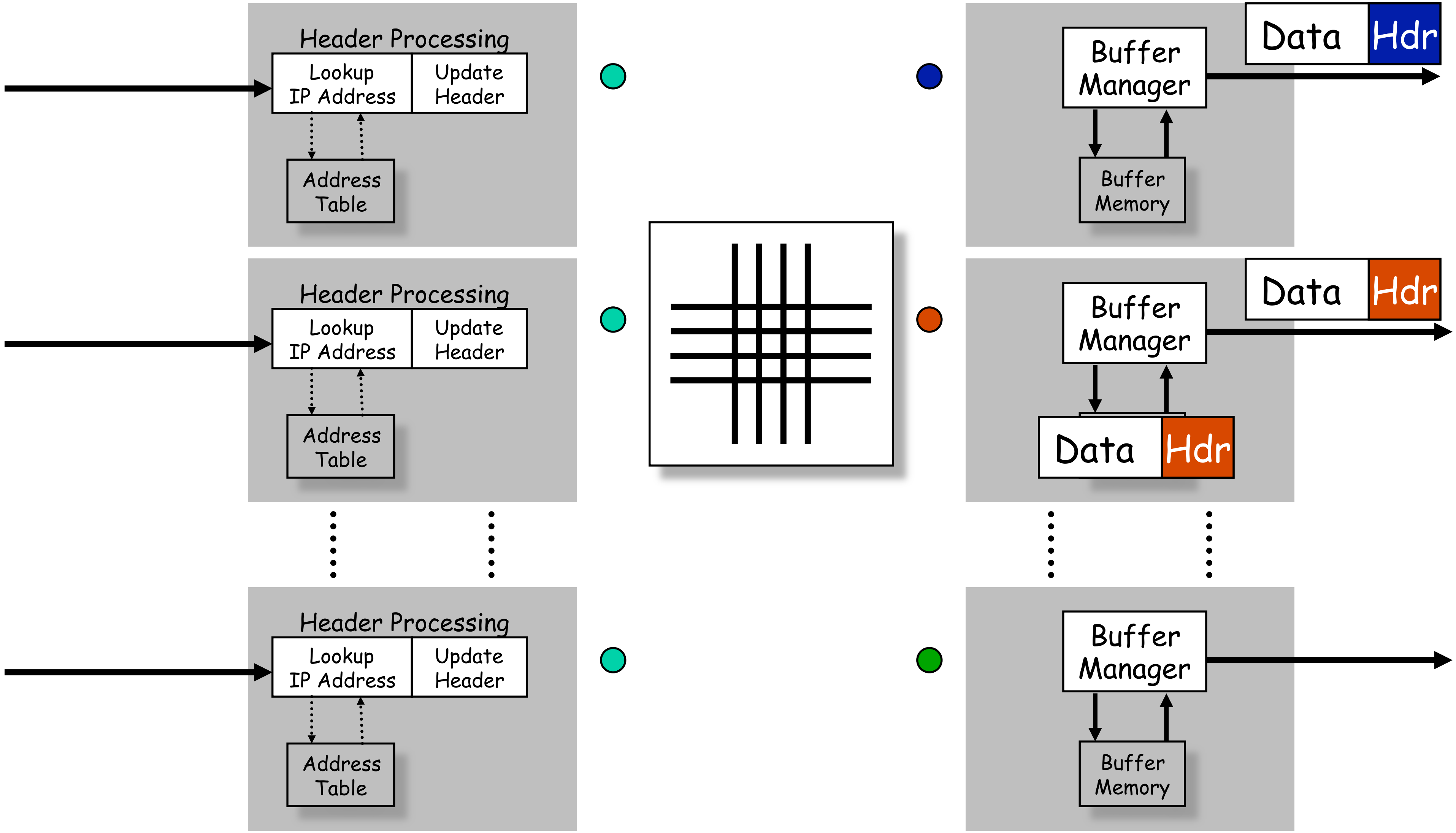
and more…

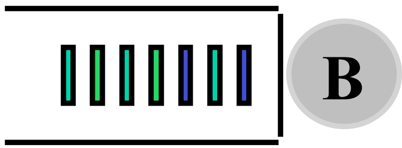
Generic router architecture



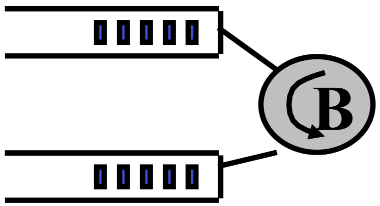
Fundamental Queueing Problems

- In a FIFO service discipline, the performance assigned to one flow is convoluted with the arrivals of packets from all other flows!
  - Cant get QoS with a "free-for-all"
  - Need to use new scheduling disciplines which provide "isolation" of performance from arrival rates of background traffic

FIFO

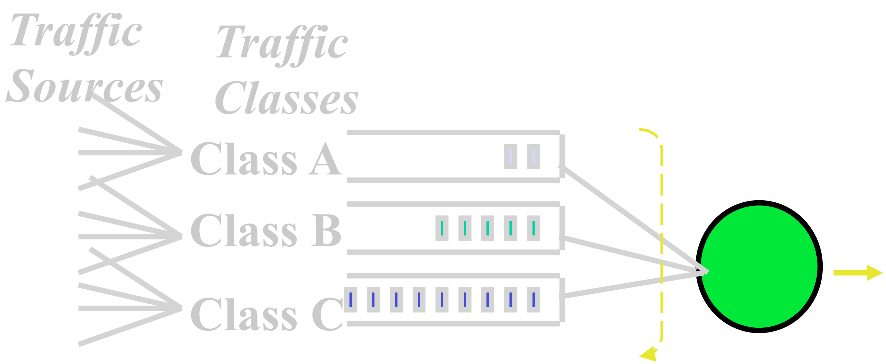


Scheduling Discipline

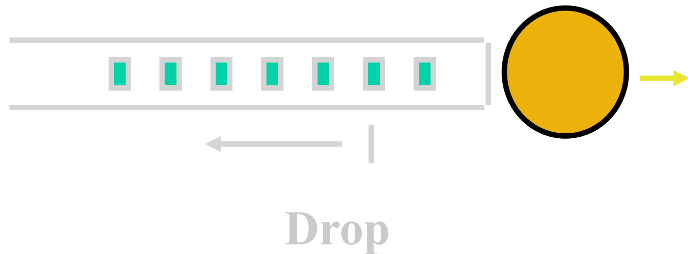


Queuing Disciplines

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



Scheduling



Buffer Management

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 (buffer management) policy

FIFO + Drop-tail Problems

- FIFO Issues: In a FIFO discipline, the service seen by a flow is *convoluted* with the arrivals of packets from all other flows!
  - No isolation between flows: full burden on e2e control
  - No policing: send more packets → get more service
- Drop-tail issues:
  - Routers are forced to have have large queues to maintain high utilizations
  - Larger buffers => larger steady state queues/delays
  - Synchronization: end hosts react to same events because packets tend to be lost in bursts
  - Lock-out: a side effect of burstiness and synchronization is that a few flows can monopolize queue space

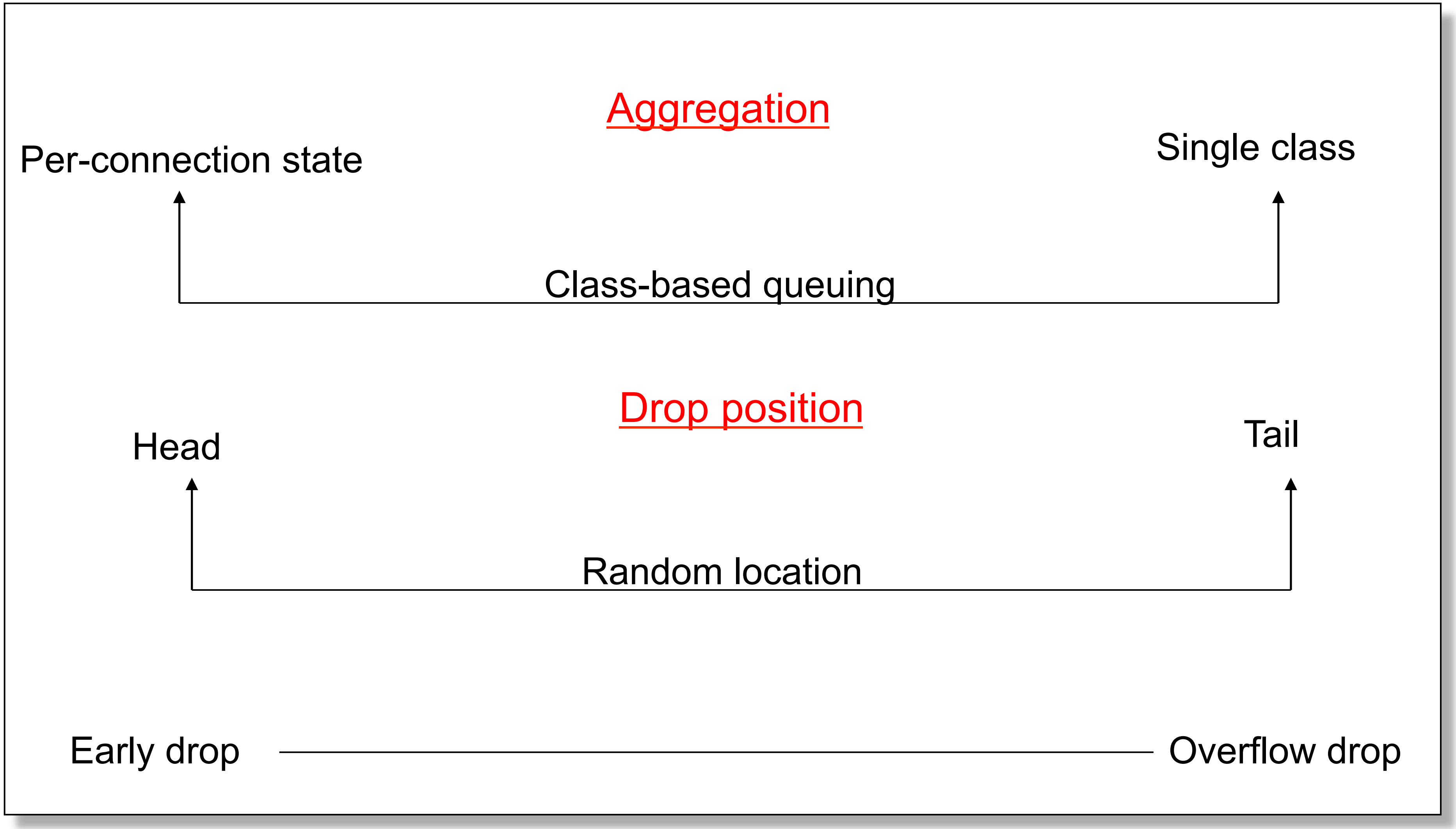
Design Objectives

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

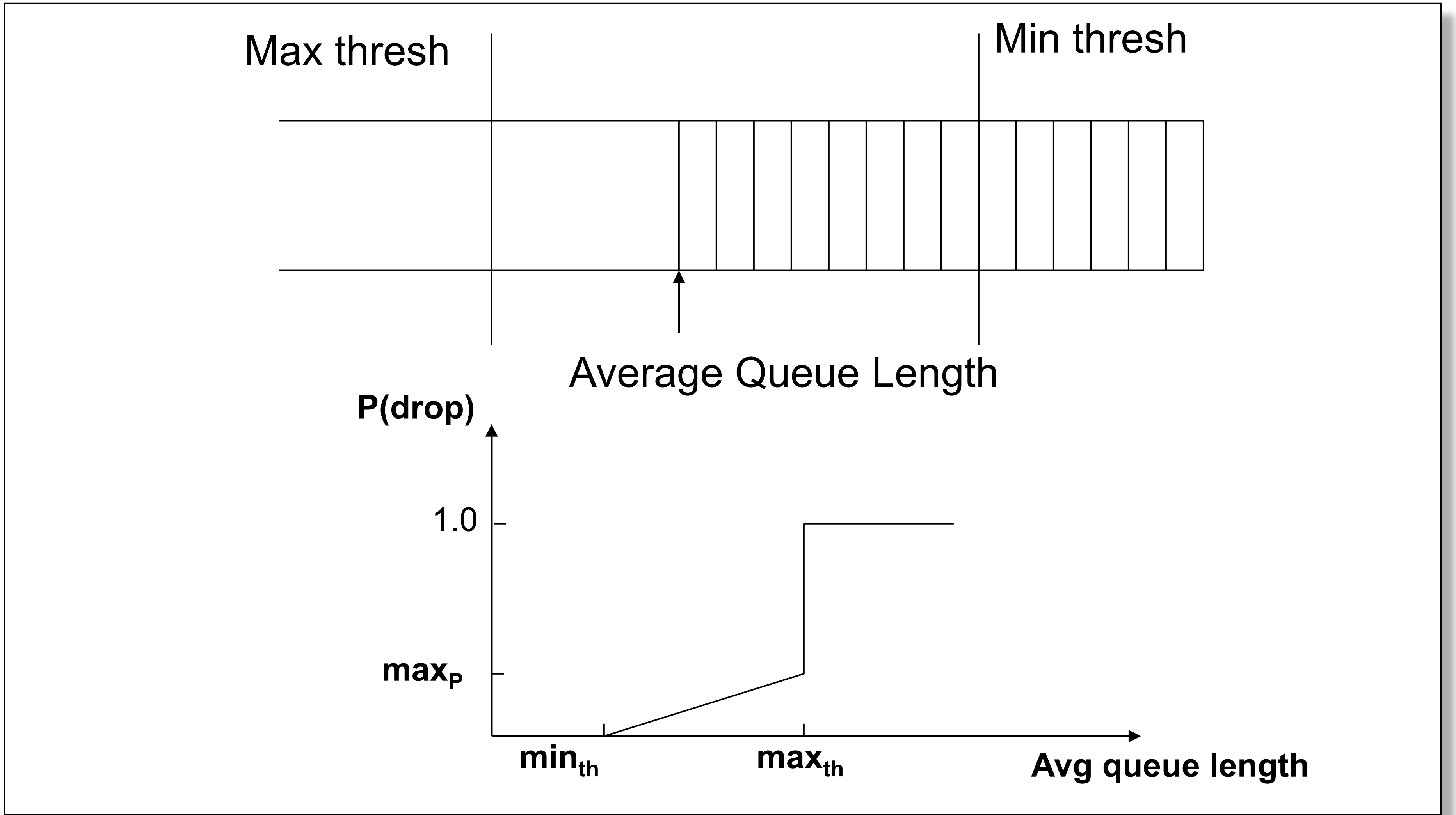
Queue Management Ideas

- Synchronization, lock-out:
  - Random drop: drop a randomly chosen packet
  - Drop front: drop packet from head of queue
- High steady-state queuing vs burstiness:
  - Early drop: Drop packets before queue full
  - Do not drop packets "too early" because queue may reflect only burstiness and not true overload
- Misbehaving vs Fragile flows:
  - Drop packets proportional to queue occupancy of flow
  - Try to protect fragile flows from packet loss (eg: color them or classify them on the fly)
- Drop packets vs Mark packets:
  - Dropping packets interacts w/ reliability mechanisms
  - Mark packets: need to trust end-systems to respond!

Packet Drop Dimensions



Random Early Detection (RED)



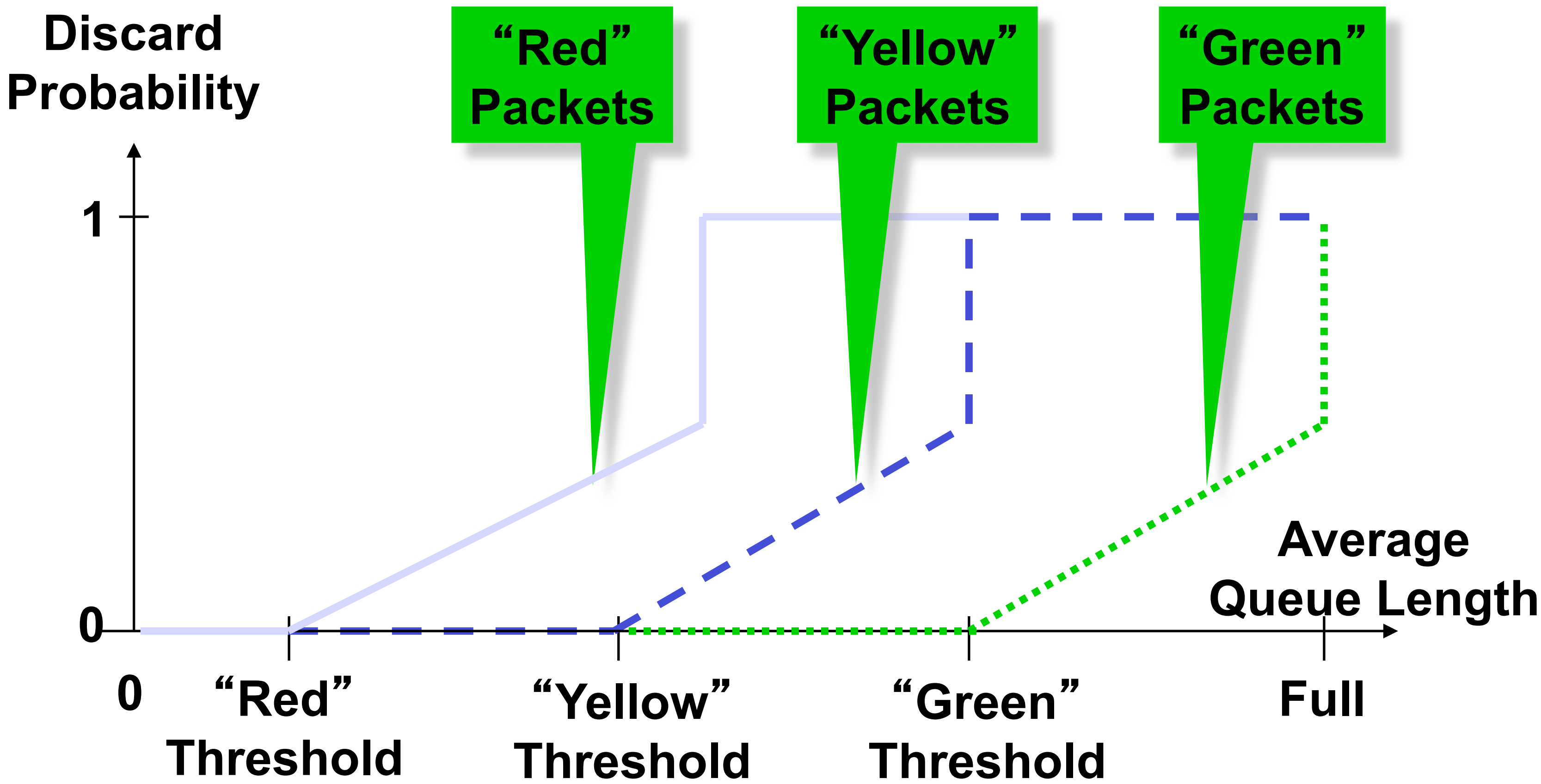
Random Early Detection (RED)

- Maintain running average of queue length
  - Low pass filtering
- If avg Q < min_{th} do nothing
  - Low queuing, send packets through
- If avg Q > max_{th}, drop packet
  - Protection from misbehaving sources
- Else mark (or drop) packet in a manner proportional to queue length & bias to protect against synchronization
  - $P_b = max_p(avg - min_{th}) / (max_{th} - min_{th})$
  - Further, bias P_b by history of unmarked packets
  - $P_a = P_b/(1 - count*P_b)$

RED Issues

- Issues:
  - Breaks synchronization well
  - Extremely sensitive to parameter settings
  - Wild queue oscillations upon load changes
  - Fail to prevent buffer overflow as #sources increases
  - Does not help fragile flows (eg: small window flows or retransmitted packets)
  - Does not adequately isolate cooperative flows from non-cooperative flows
- Isolation:
  - Fair queuing achieves isolation using per-flow state
  - RED penalty box: Monitor history for packet drops, identify flows that use disproportionate bandwidth

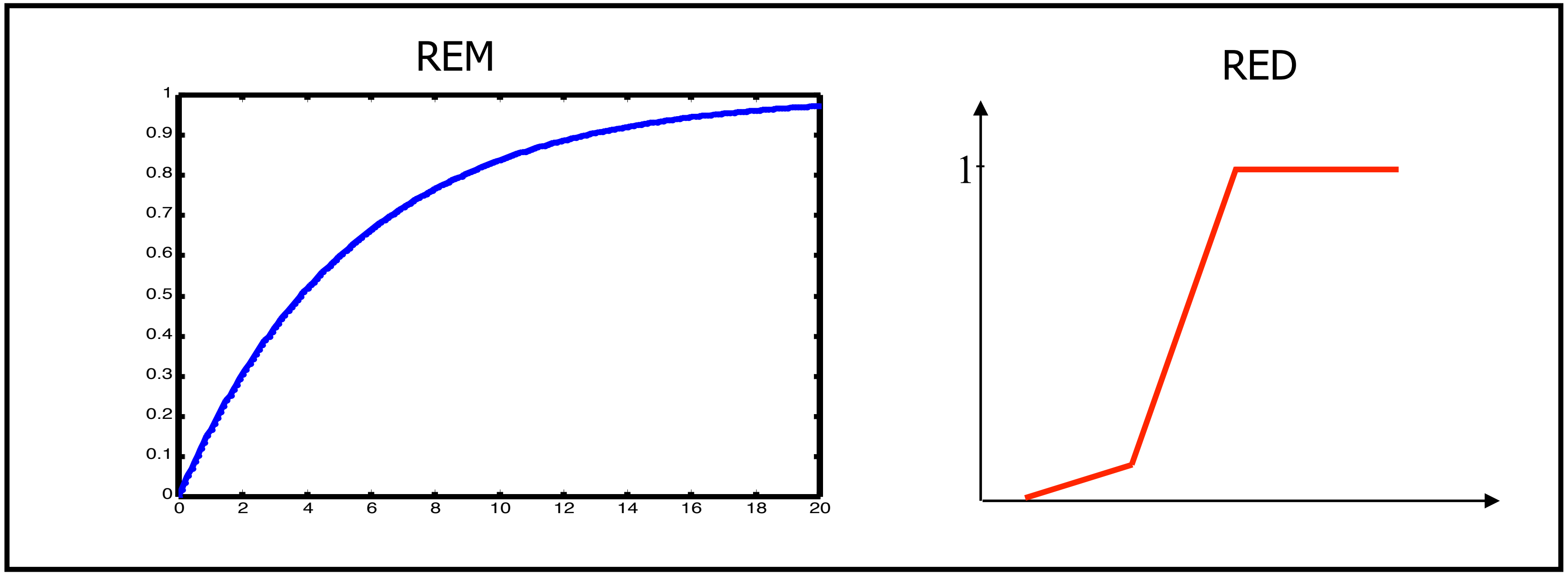
RED with Multiple Thresholds



source Juha Heinänen

REM Athuraliya & Low 2000

- Main ideas
  - Decouple congestion & performance measure
  - "Price" adjusted to match rate and clear buffer
  - Marking probability exponential in `price'



Avg queue

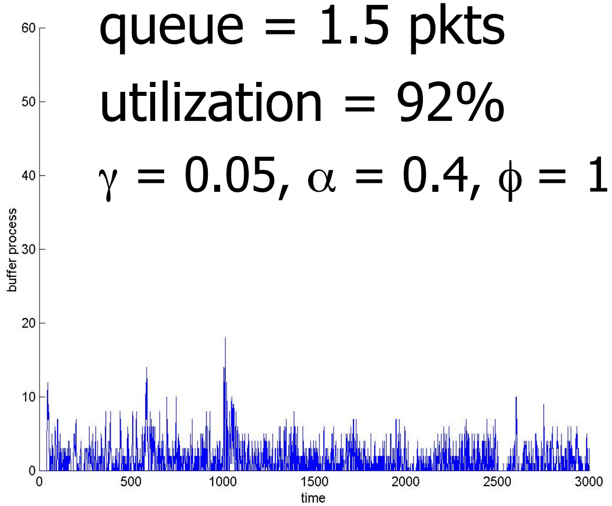
Comparison of AQM Performance

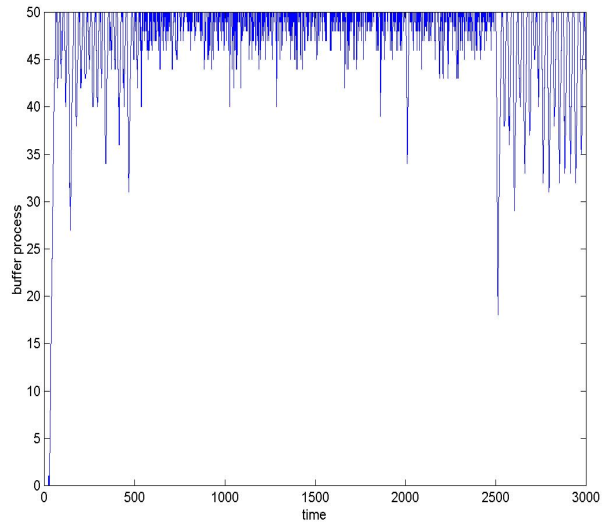
REM

queue = 1.5 pkts

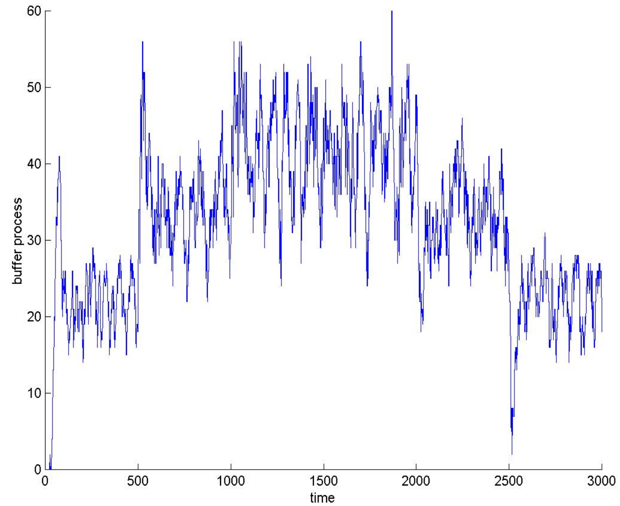
utilization = 92%

$\gamma = 0.05$, $\alpha = 0.4$, $\phi = 1.15$





DropTail



RED

min_th = 10 pkts

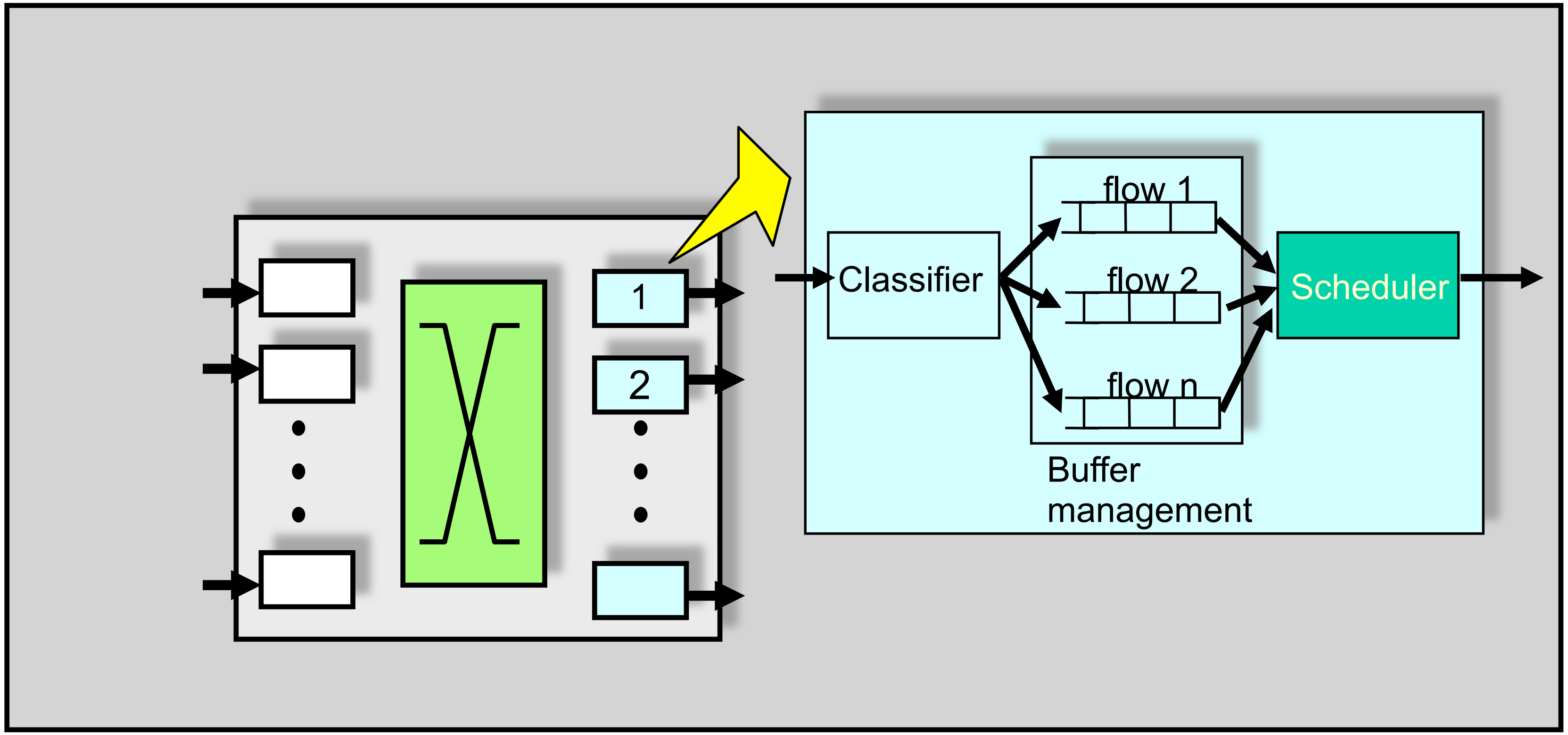
max_th = 40 pkts

max_p = 0.1

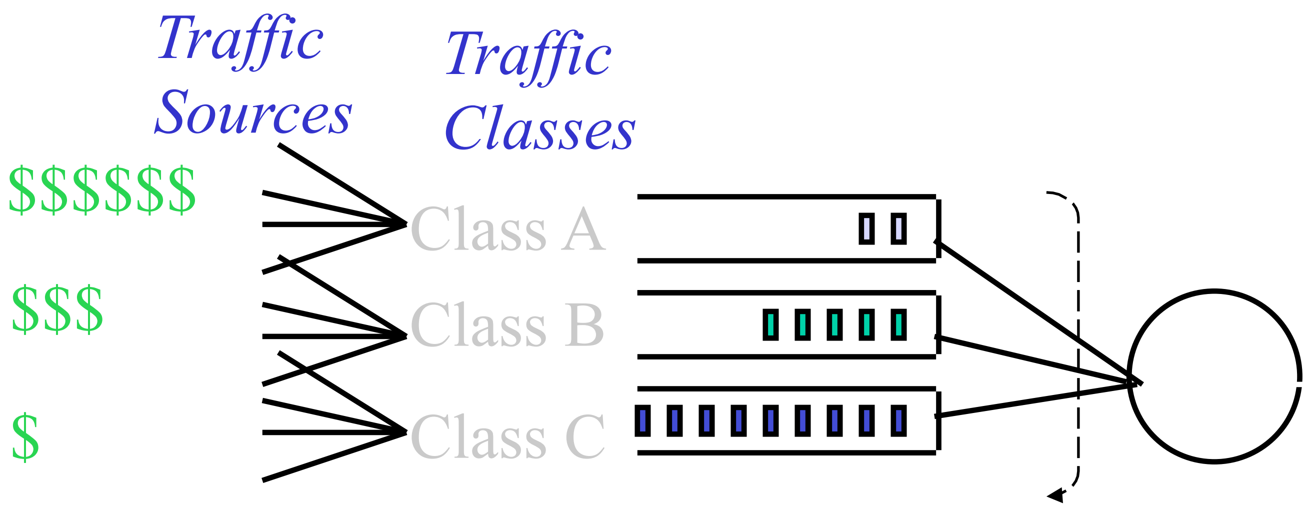
SCHEDULING

Packet Scheduling

- Decide when and what packet to send on output link
  - Usually implemented at output interface



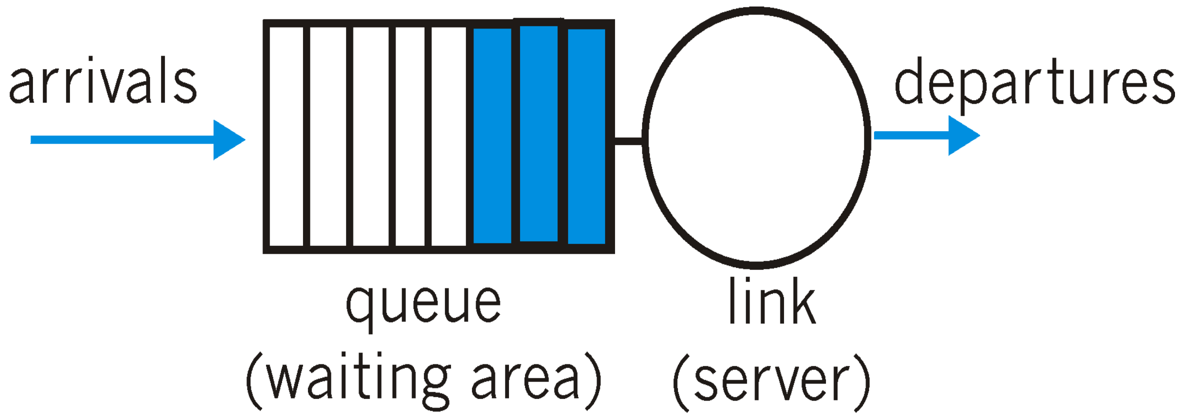
Mechanisms: Queuing/Scheduling



- Use a few bits in header to indicate which queue (class) a packet goes into (also branded as CoS)
- High $$ users classified into high priority queues, which also may be less populated
  - => lower delay and low likelihood of packet drop
- Ideas: priority, round-robin, classification, aggregation, ...

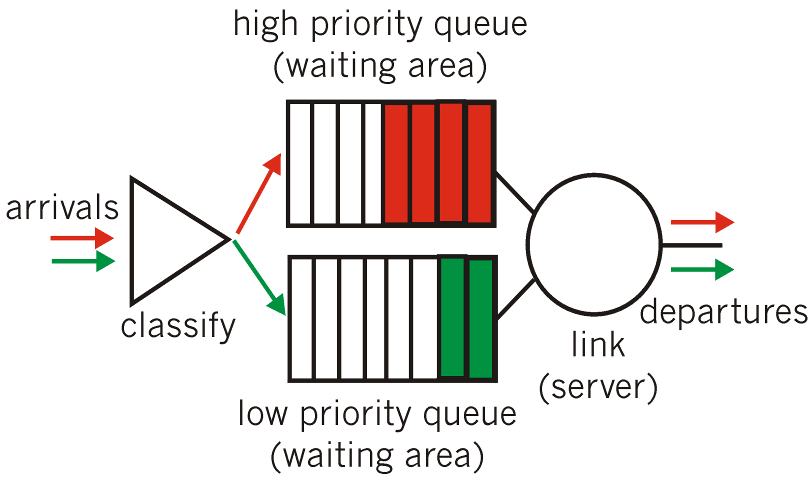
Scheduling And Policing Mechanisms

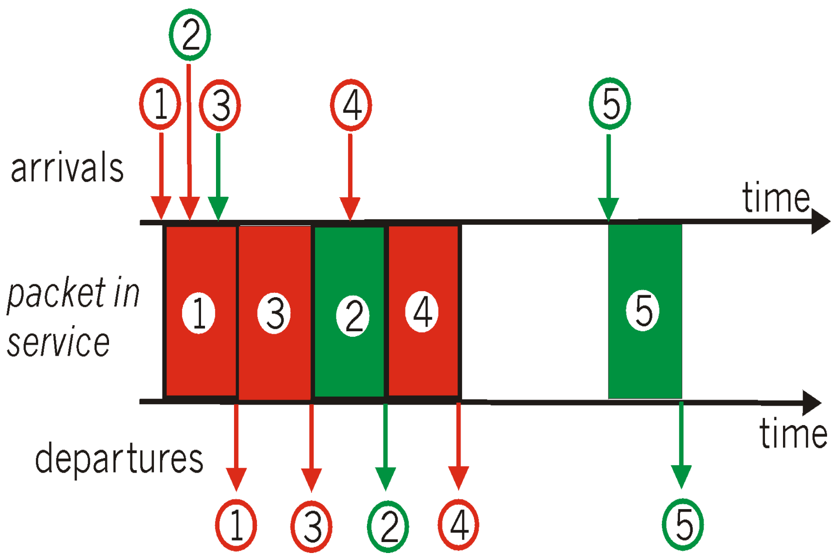
- Scheduling: choosing the next packet for transmission on a link can be done following a number of policies;
- FIFO: in order of arrival to the queue; packets that arrive to a full buffer are either discarded, or a discard policy is used to determine which packet to discard among the arrival and those already queued



Priority Queueing

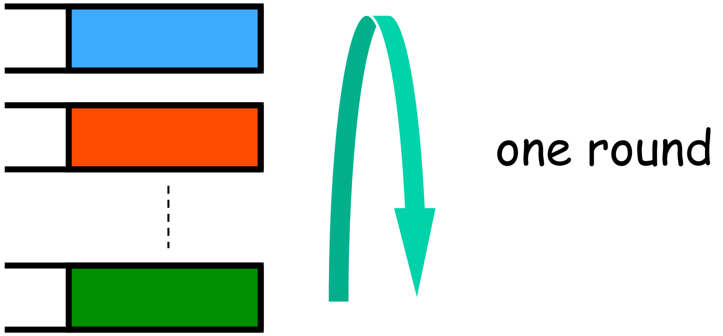
- Priority Queuing: classes have different priorities; class may depend on explicit marking or other header info, eg IP source or destination, TCP Port numbers, etc.
- Transmit a packet from the highest priority class with a non-empty queue
- Preemptive and non-preemptive versions

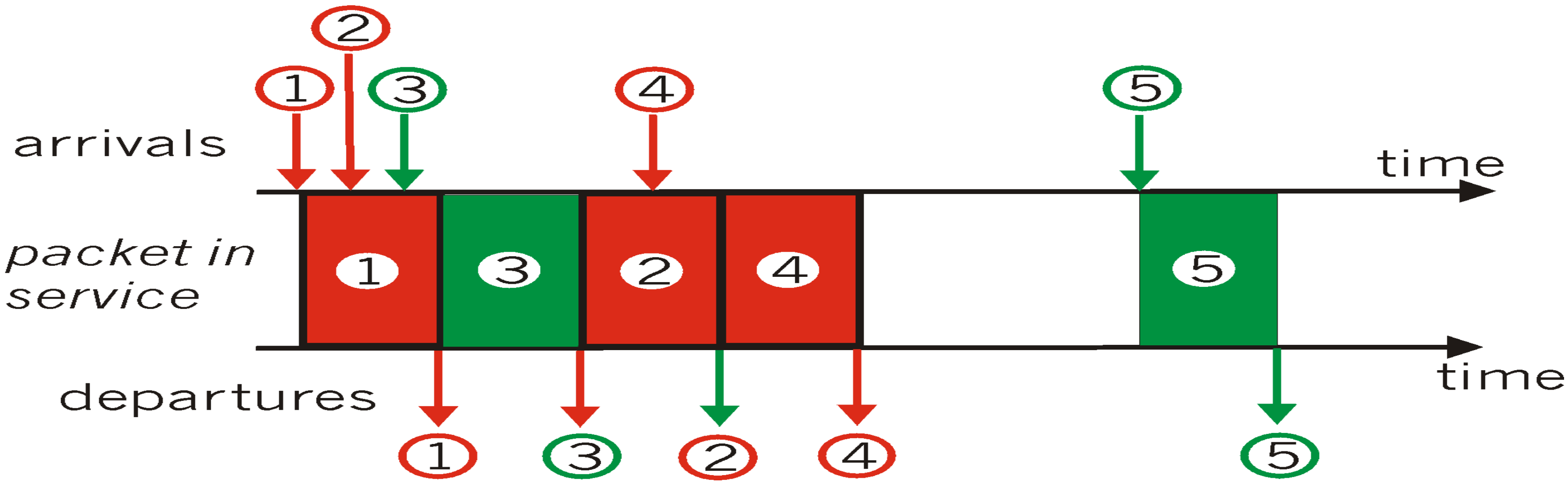




Round Robin (RR)

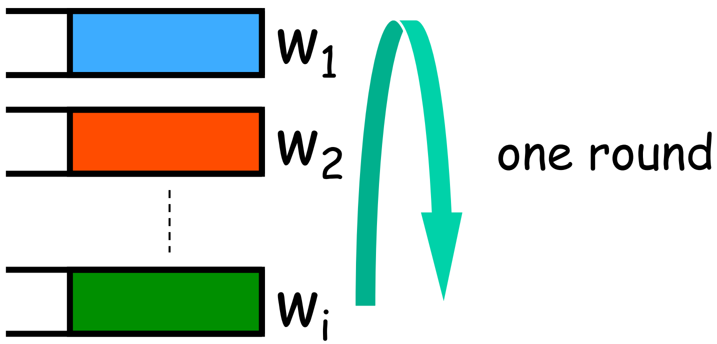
- Round Robin: scan class queues serving one from each class that has a non-empty queue





Weighted Round Robin (WRR)

- Assign a weight to each connection and serve a connection in proportion to its weight
- Ex:
  - Connection A, B and C with same packet size and weight 0.5, 0.75 and 1. How many packets from each connection should a round-robin server serve in each round?
  - Answer: Normalize each weight so that they are all integers: we get 2, 3 and 4. Then in each round of service, the server serves 2 packets from A, 3 from B and 4 from C.

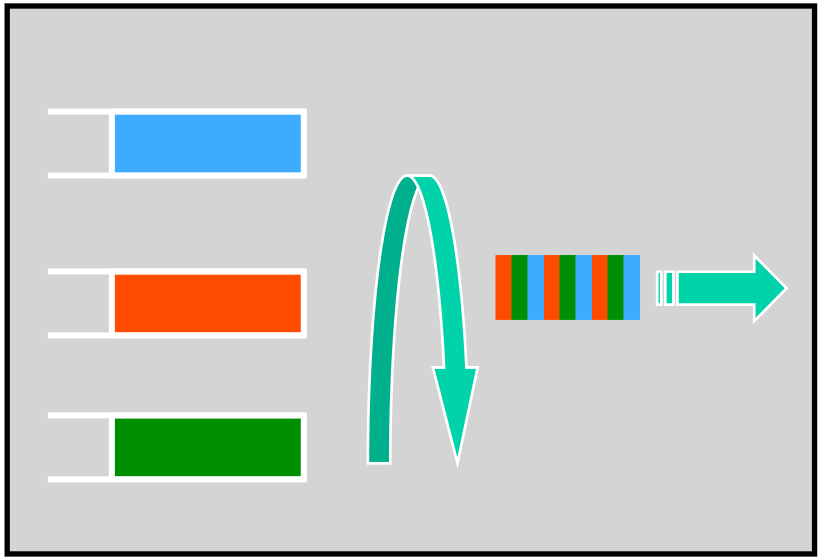


(Weighted) Round-Robin Discussion

- Advantages: protection among flows
  - Misbehaving flows will not affect the performance of well-behaving flows
    - Misbehaving flow – a flow that does not implement any congestion control
  - FIFO does not have such a property
- Disadvantages:
  - More complex than FIFO: per flow queue/state
  - Biased toward large packets (not ATM)– a flow receives service proportional to the number of packets
- If packet size are different, we normalize the weight by the packet size
  - ex: 50, 500 & 1500 bytes with weight 0.5, 0.75 & 1.0

Generalized Processor Sharing (GPS)

- Assume a fluid model of traffic
  - Visit each non-empty queue in turn (like RR)
  - Serve infinitesimal from each
  - Leads to "max-min" fairness
- GPS is un-implementable!
  - We cannot serve infinitesimals, only packets



max-min fairness

Consider n sources 1,..,n requesting resources $x_1,..,x_n$ with $x_1<x_2..<x_n$ for instance.
Link or server capacity is C.

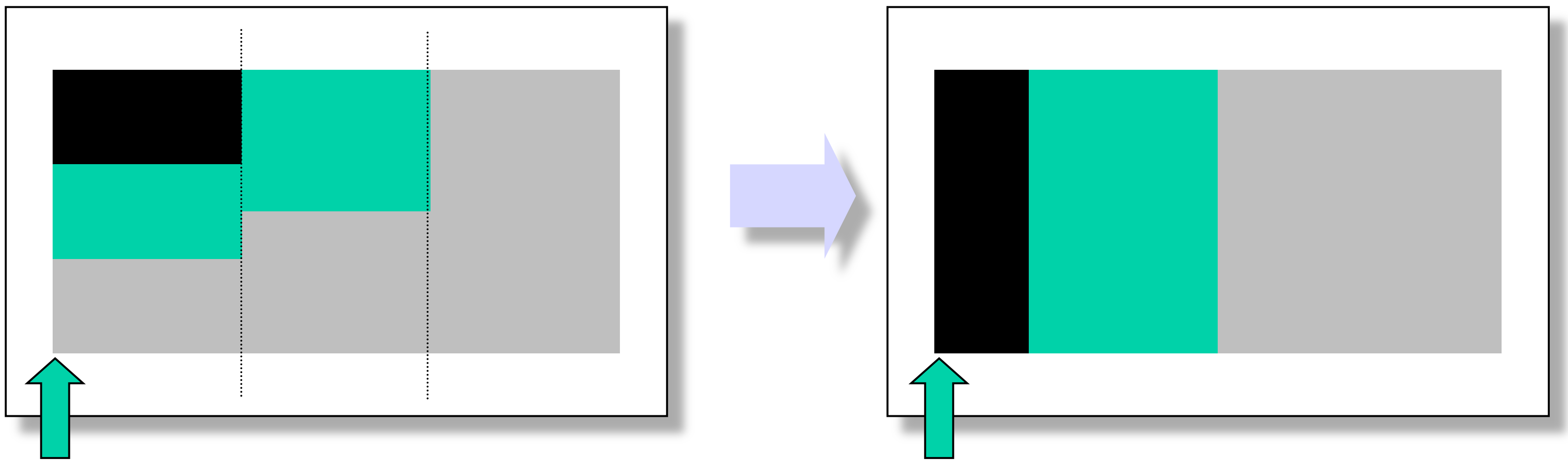
We assign C/n to source 1. If $C/n>x_1$, we give $C/n+(C/n-x_1)/(n-1)$ to the remaining (n-1) sources. If this amount is greater than x_2, we iterate.

Packet Approximation of Fluid System

- GPS un-implementable
- Standard techniques of approximating fluid GPS
  - Select packet that finishes first in GPS assuming that there are no future arrivals (emulate GPS on the side)
- Important properties of GPS
  - Finishing order of packets currently in system independent of future arrivals
- Implementation based on virtual time
  - Assign virtual finish time to each packet upon arrival
  - Packets served in increasing order of virtual times

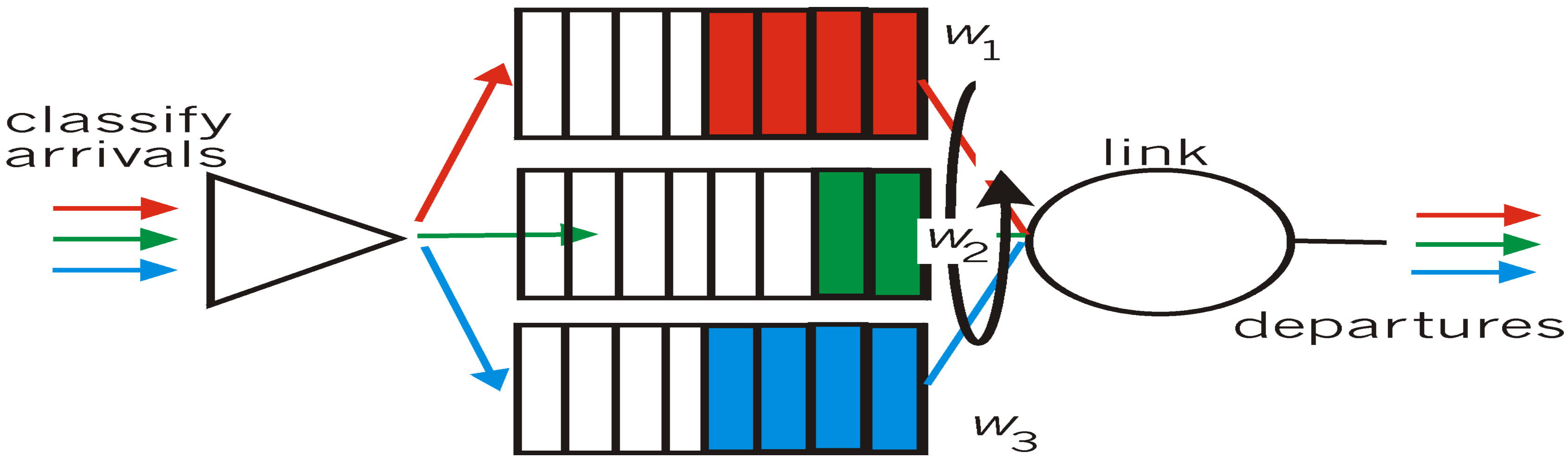
Fair Queuing (FQ)

- Idea: serve packets in the order in which they would have finished transmission in the fluid flow system
- Mapping bit-by-bit schedule onto packet transmission schedule
- Transmit packet with the lowest finish time at any given time



Weighted Fair Queueing

- Variation of FQ: Weighted Fair Queuing (WFQ)
- Weighted Fair Queuing: is a generalized Round Robin in which an attempt is made to provide a class with a differentiated amount of service over a given period of time



Implementing WFQ

- WFQ needs per-connection (or per-aggregate) scheduler state→implementation complexity.
  - complex iterated deletion algorithm
  - complex sorting at the output queue on the service tag
- WFQ needs to know the weight assigned for each queue →manual configuration, signalling.
- WFQ is not perfect…
- Router manufacturers have implemented as early as 1996 WFQ in their products
  - from CISCO 1600 series
  - Fore System ATM switches

Big Picture

- FQ does not eliminate congestion → it just manages the congestion
- You need both end-host congestion control and router support for congestion control
  - end-host congestion control to adapt
  - router congestion control to protect/isolate
- Don't forget buffer management: you still need to drop in case of congestion. Which packet's would you drop in FQ?
  - one possibility: packet from the longest queue

QOS SPECIFICATION, TRAFFIC, SERVICE CHARACTERIZATION, BASIC MECHANISMS

Service Specification

- Loss: probability that a flow's packet is lost
- Delay: time it takes a packet's flow to get from source to destination
- Delay jitter: maximum difference between the delays experienced by two packets of the flow
- Bandwidth: maximum rate at which the soource can send traffic
- QoS spectrum:

Hard Real Time: Guaranteed Services

- Service contract
  - Network to client: guarantee a deterministic upper bound on delay for each packet in a session
  - Client to network: the session does not send more than it specifies
- Algorithm support
  - Admission control based on worst-case analysis
  - Per flow classification/scheduling at routers

Soft Real Time: Controlled Load Service

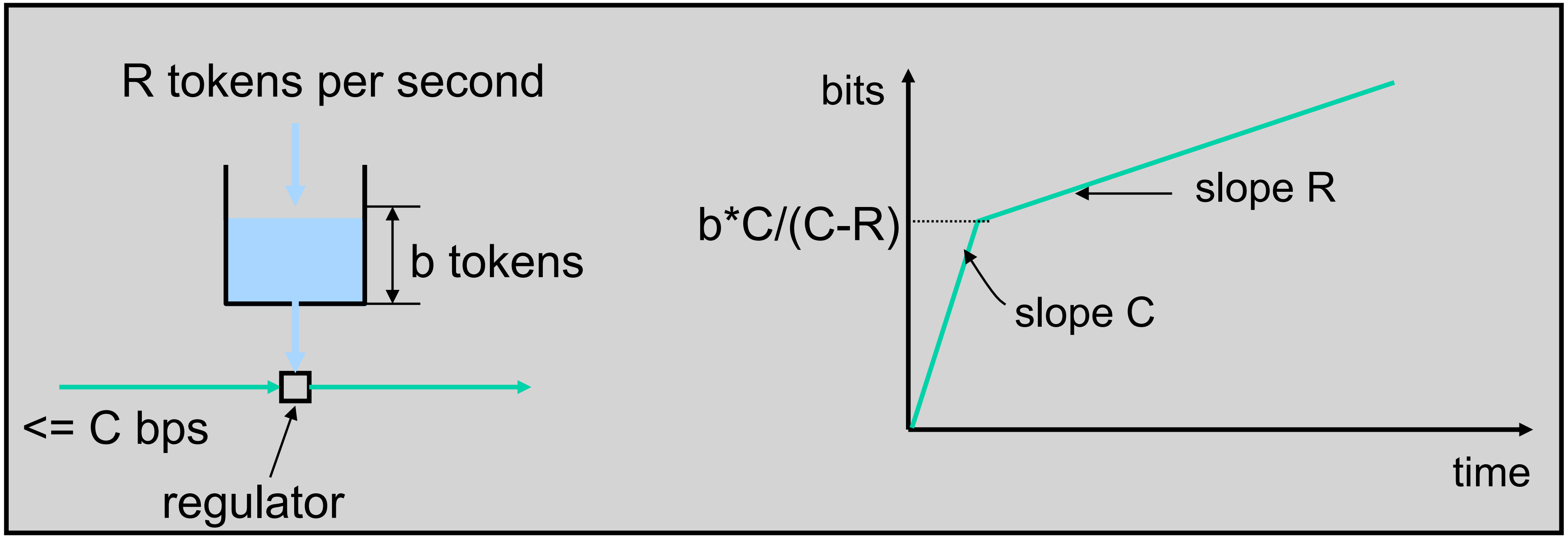
- Service contract:
  - Network to client: similar performance as an unloaded best-effort network
  - Client to network: the session does not send more than it specifies
- Algorithm Support
  - Admission control based on measurement of aggregates
  - Scheduling for aggregate possible

Traffic and Service Characterization

- To quantify a service one has two know
  - Flow's traffic arrival
  - Service provided by the router, i.e., resources reserved at each router
- Examples:
  - Traffic characterization: token bucket
  - Service provided by router: fix rate and fix buffer space
    - Characterized by a service model (service curve framework)

Ex: Token Bucket

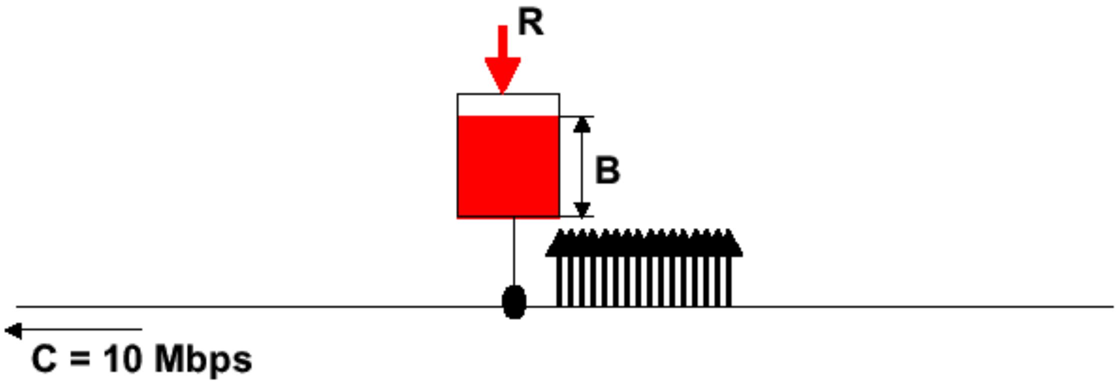
- Characterized by three parameters (b, R, C)
  - b – token depth
  - R – average arrival rate
  - C – maximum arrival rate (e.g., link capacity)
- A bit is transmitted only when there is an available token
  - When a bit is transmitted exactly one token is consumed



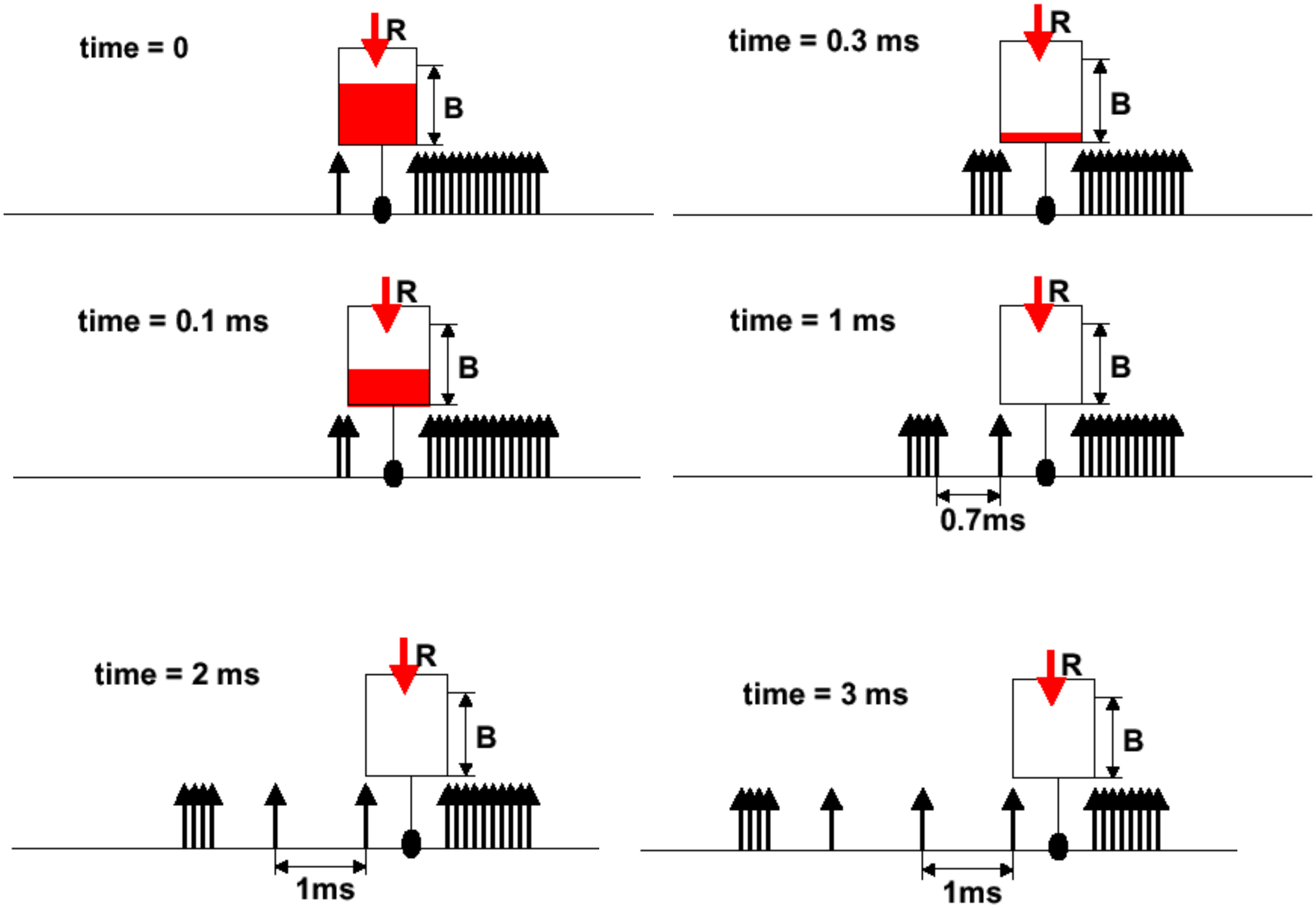
Token Bucket

Example

- B = 4000 bits, R = 1 Mbps, C = 10 Mbps
- Packet length = 1000 bits
- Assume the bucket is initially full and a "large" burst of packets arrives

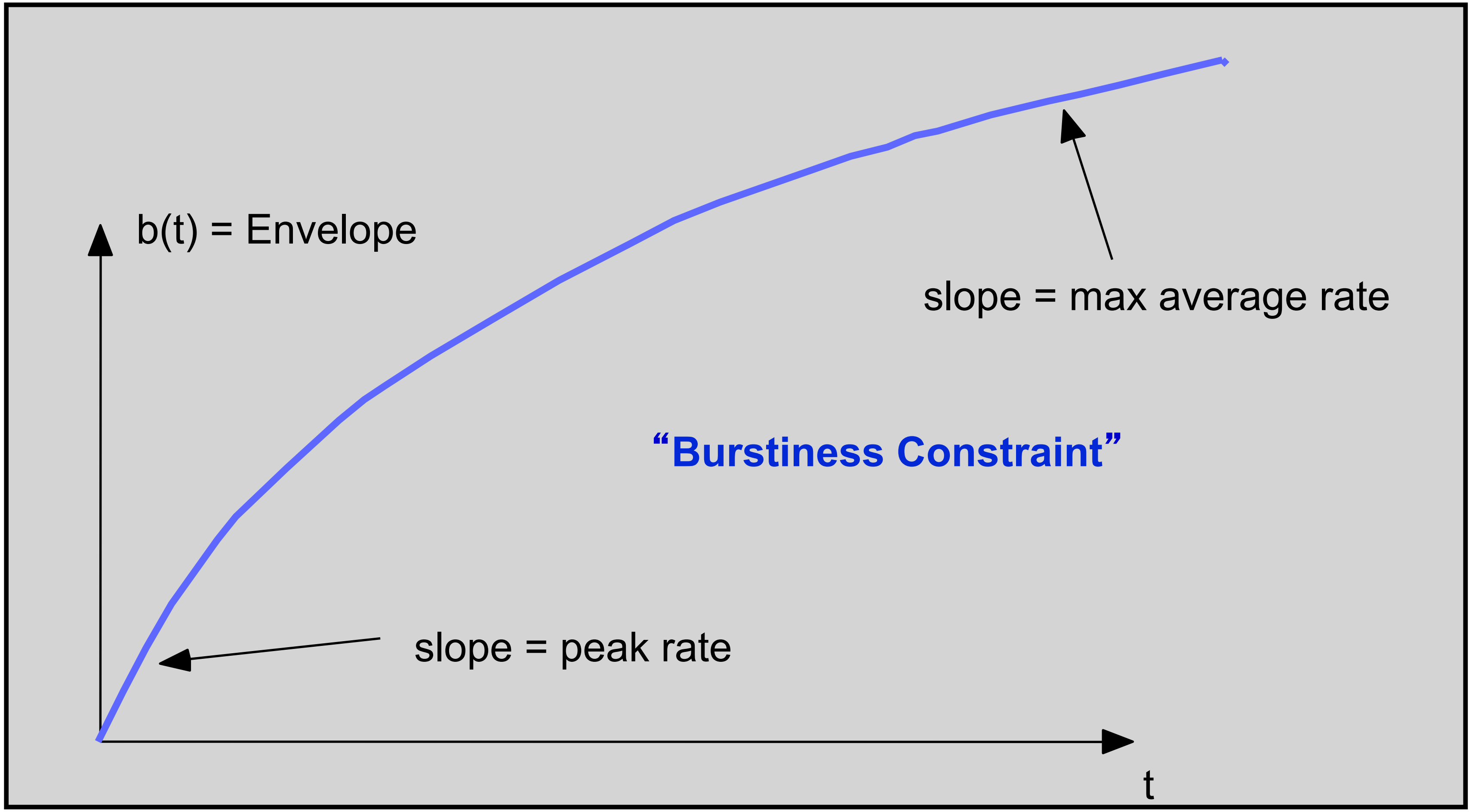


Token Bucket



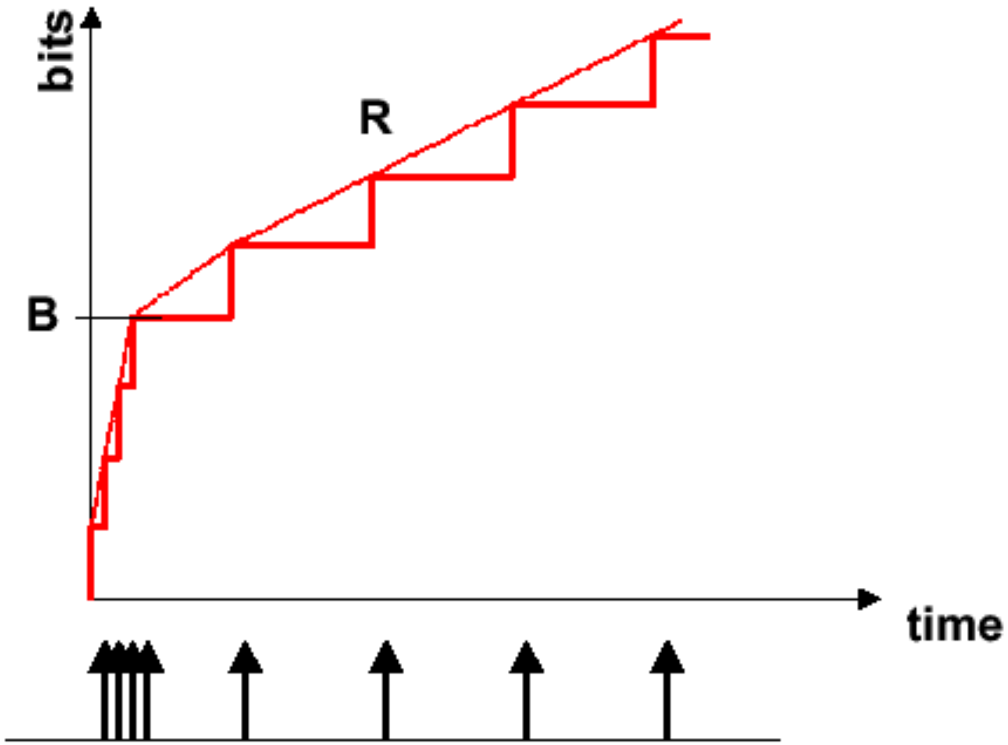
Traffic Envelope (Arrival Curve)

- Maximum amount of service that a flow can send during an interval of time t



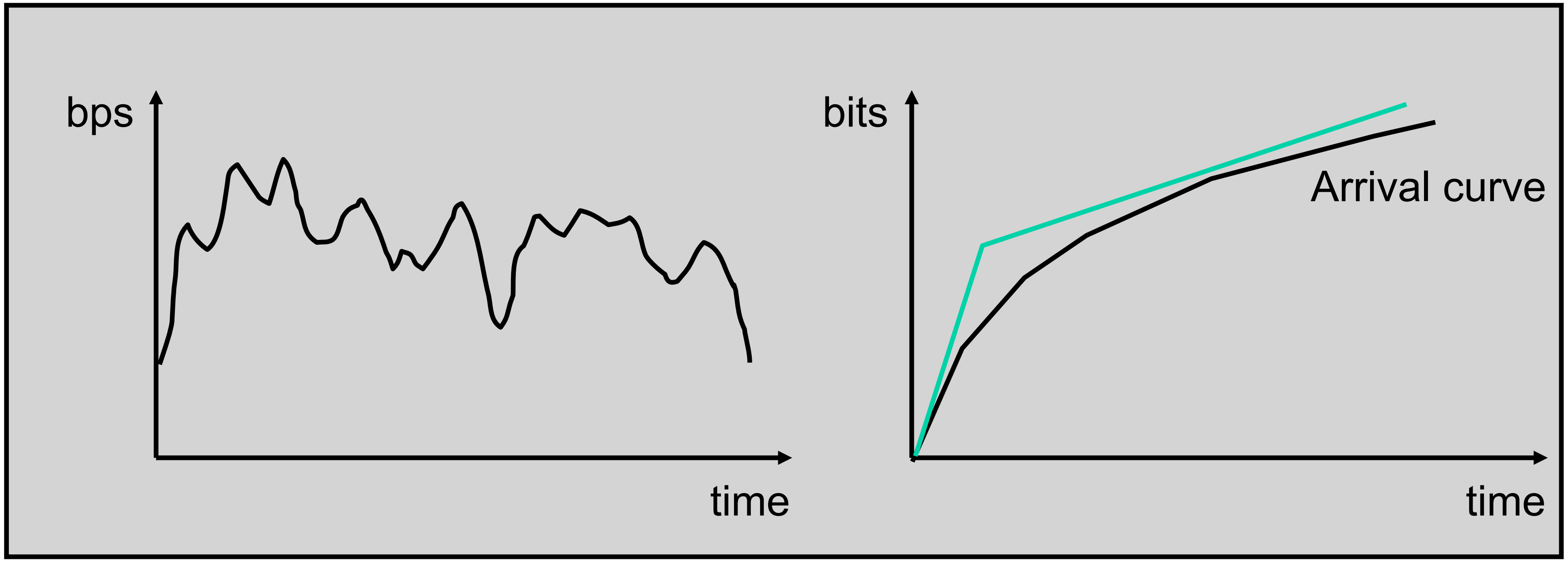
Arrival curve

A(t) – number of bits received up to time t



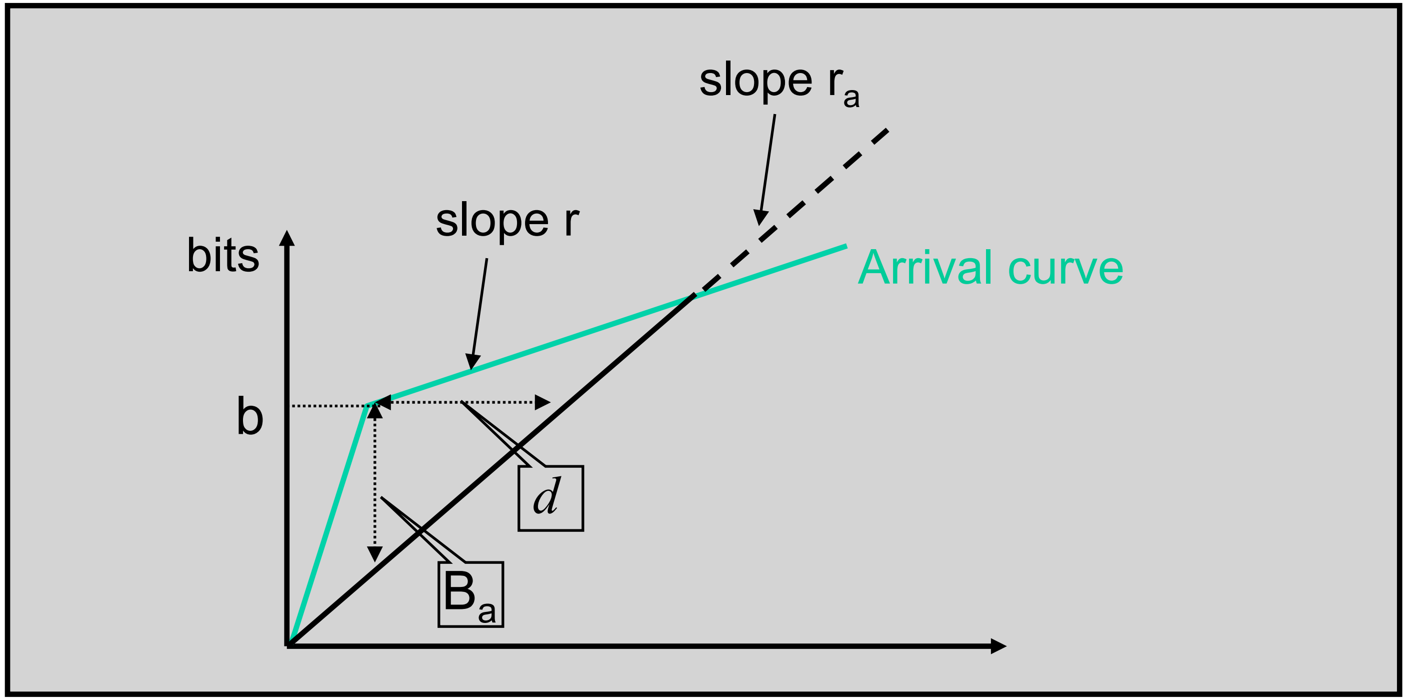
Characterizing a Source by Token Bucket

- Arrival curve – maximum amount of bits transmitted by time t
- Use token bucket to bound the arrival curve

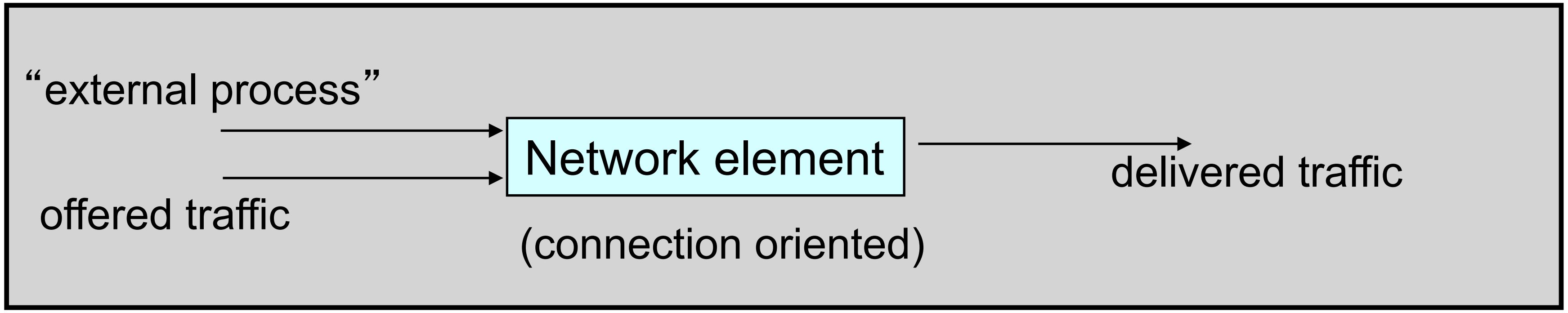


Per-hop Reservation with Token Bucket

- Given b,r,R and per-hop delay d
- Allocate bandwidth r_a and buffer space B_a such that to guarantee d

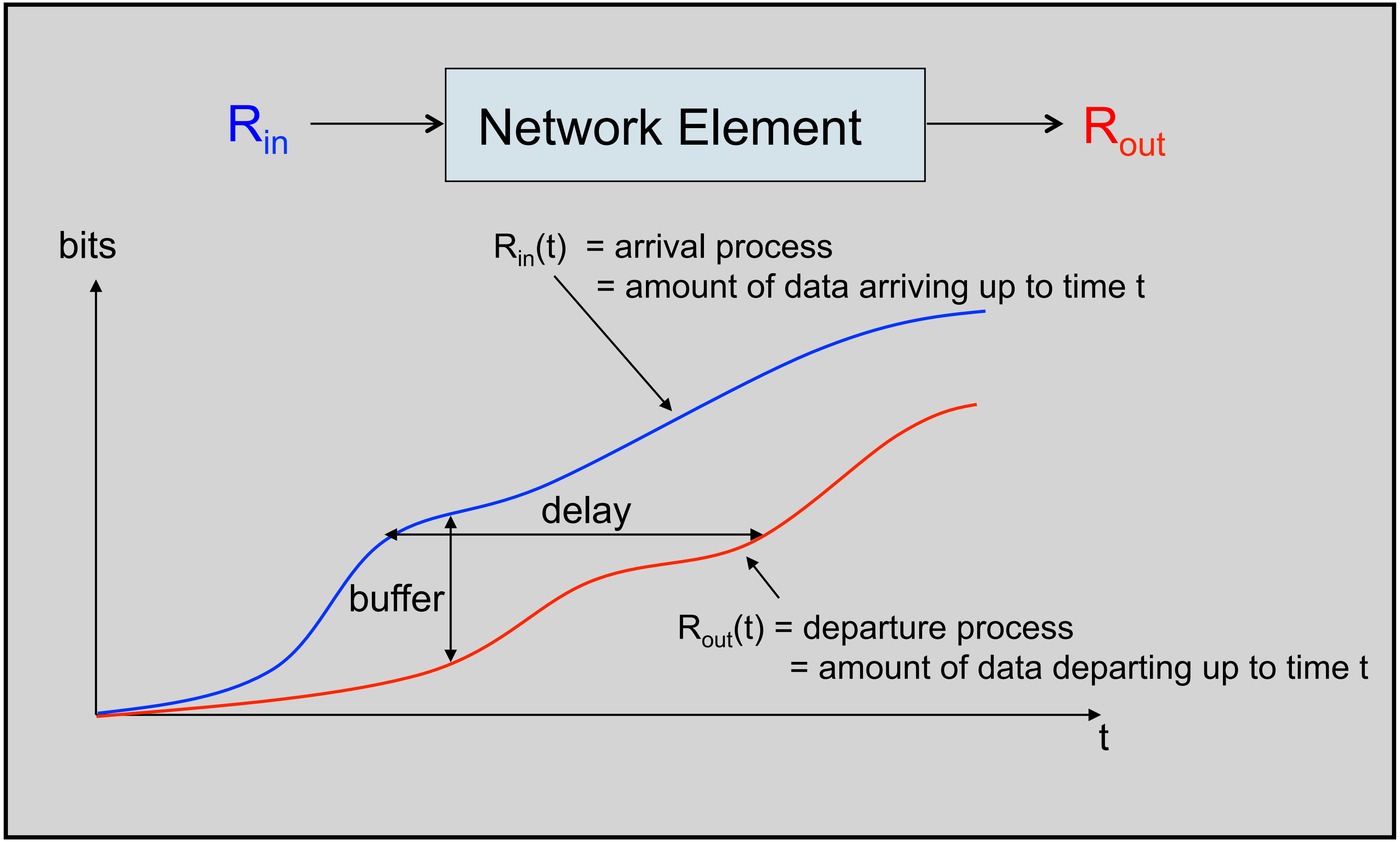


What is a Service Model?

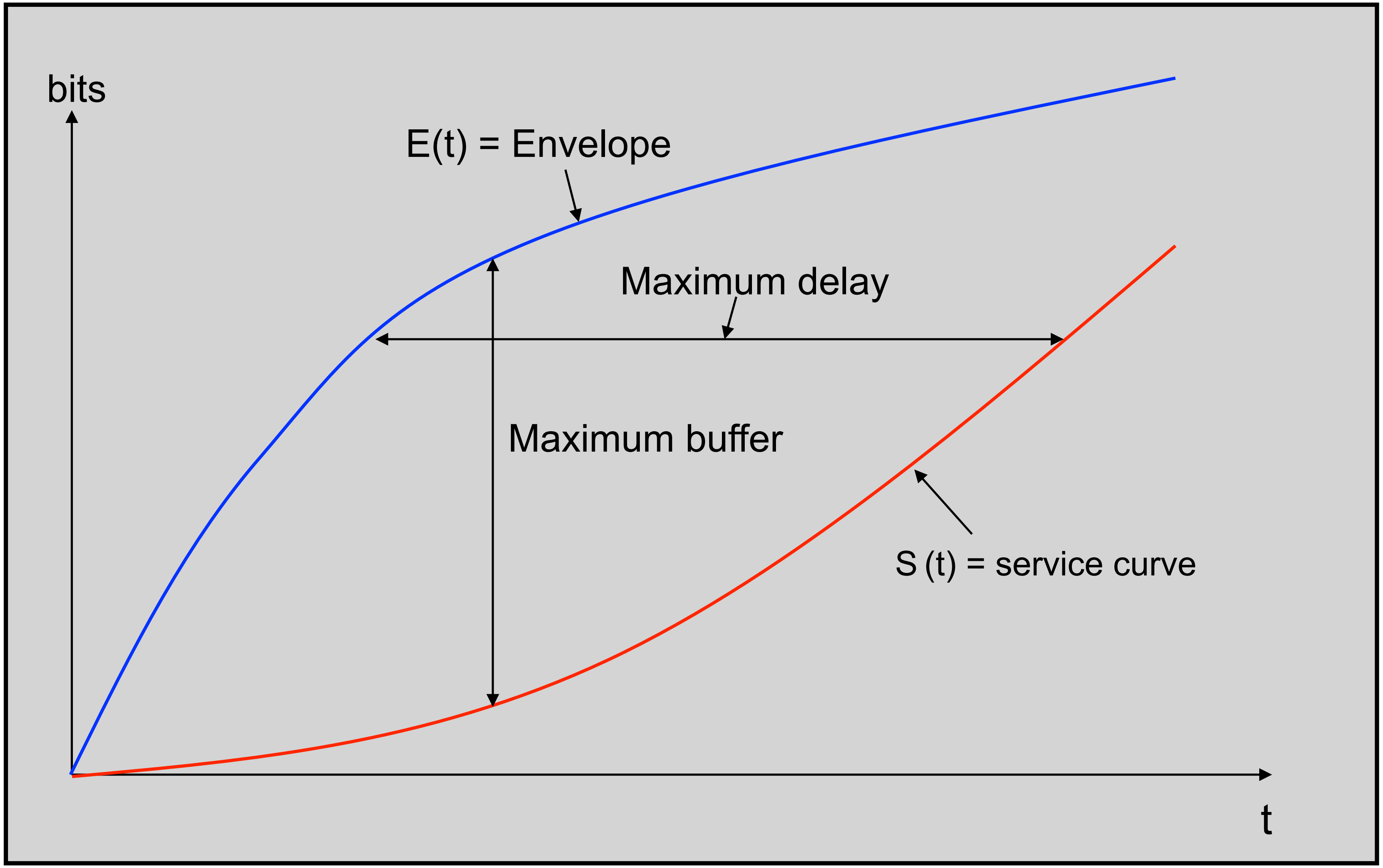


- The QoS measures (delay,throughput, loss, cost) depend on offered traffic, and possibly other external processes.
- A service model attempts to characterize the relationship between offered traffic, delivered traffic, and possibly other external processes.

Arrival and Departure Process



Delay and Buffer Bounds



QoS ARCHITECTURES

Stateless vs. Stateful QoS Solutions

- Stateless solutions – routers maintain no fine grained state about traffic
  - ↑ scalable, robust
  - ↓ weak services
- Stateful solutions – routers maintain per-flow state
  - ↑ powerful services
    - guaranteed services + high resource utilization
    - fine grained differentiation
    - protection
  - ↓ much less scalable and robust

Integrated Services (IntServ)

- An architecture for providing QOS guarantees in IP networks for individual application sessions
- Relies on resource reservation, and routers need to maintain state information of allocated resources (eg: g) and respond to new Call setup requests