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Advanced Networking and Future Internet

II. Queue Management

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Advanced Networking and Future Internet: Introduction

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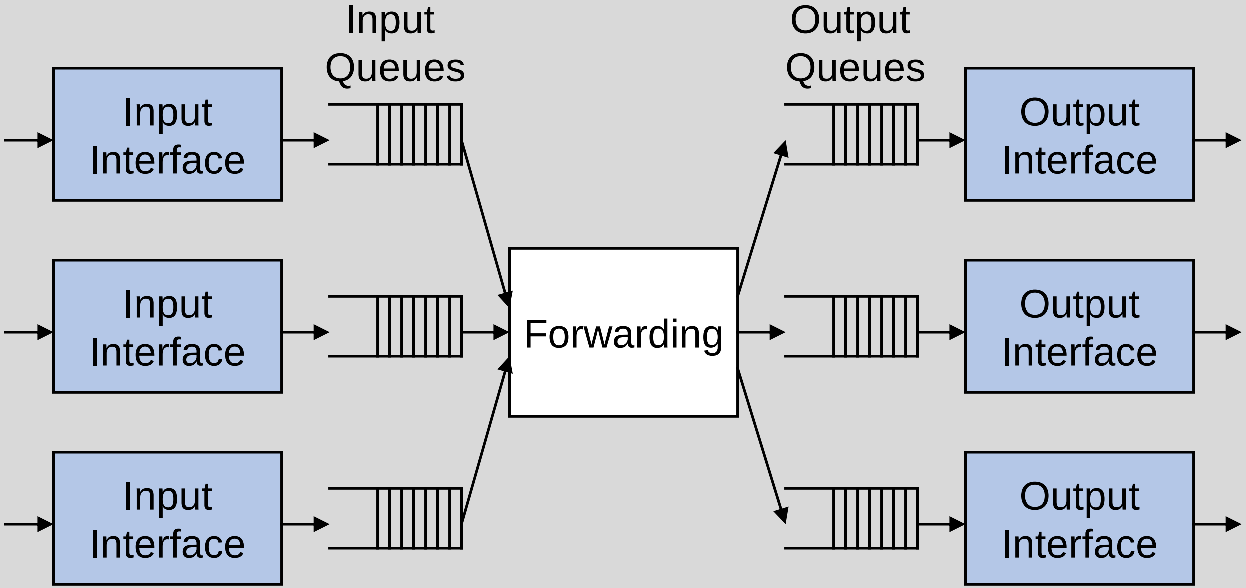
1. Introduction

1. Router Architecture



A packet scheduler at the output port must select one packet among those queued for transmission.

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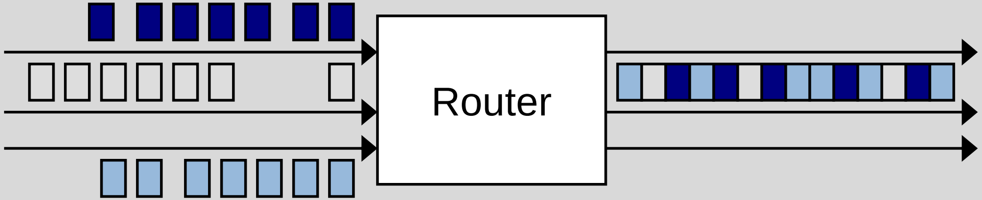
1. Introduction

2. Congestion in the Internet



- Congestion in the Internet is still common.
  - Backbones, e.g., transatlantic links
  - Edge routers aggregating traffic
  - Access networks,
    e.g., modem lines, wireless links

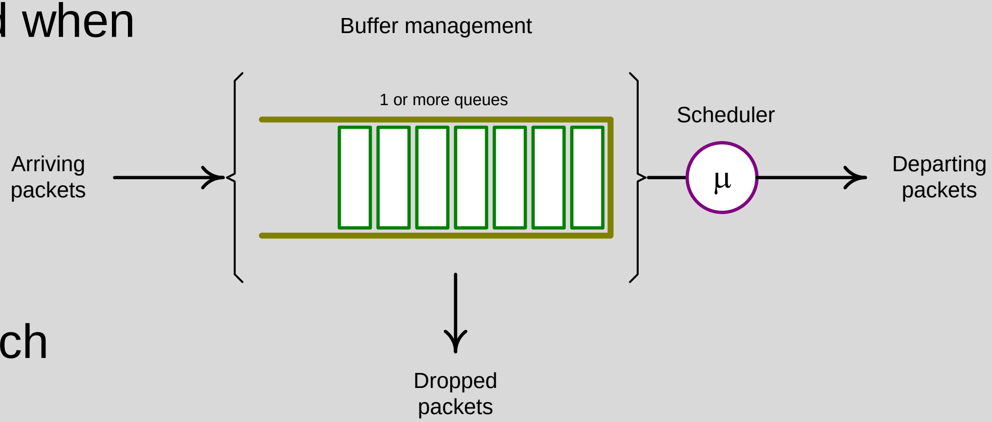
→ Output interfaces might be overloaded.

- Congestion (not transmission errors) is the main reason for packet loss in the Internet.

2. Queue Management

Components

- Scheduling disciplines
  - Which packet to serve next, and when
- Dropping mechanism
  - How and when to drop packets under varying load conditions
- Buffer management
  - How many queues and how much buffer space to use



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2. Queue Management

1. Why Queue Management in IP Routers?

Best-Effort (BE) applications

– e.g., elastic applications such as e-mail or file transfer that can adapt to available resources
– Resources (bandwidth, buffers etc.) should be shared in a fair way among users / applications.
– Protection of connections from misbehaving connections

Non-BE applications
(some form of QoS guarantee)

– e.g., real-time applications, e.g., audio conferencing, video retrieval, transactions, interactive games, cloud computing (partially), that might require performance bounds (bandwidth, delay, jitter)
– Performance guarantees for applications by resource reservations

2. Queue Management

2. Requirements for Queue Management

- Ease of implementation
- Fairness and Protection (for BE)
  - Fairness: The allocation of a link capacity satisfies the max-min fair share allocation criterion.
  - Protection: Misbehavior of one connection does not affect performance of other connections.
- Performance bounds (for non-BE)
  - Arbitrary connection performance bounds, limited by the conservation law only.
- Ease and efficiency of admission control (for non-BE)
  - Limitation of number of connections

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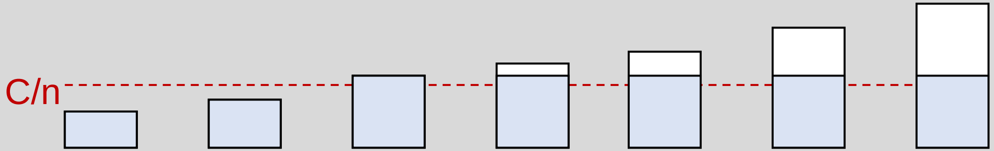
2. Queue Management

3. Max-Min Fair Share

Problem

- Dividing resources among a set of users
- Some users demand fewer resources than others.
- How to divide the resources left by these users ?



Max-Min Fair Share Allocation

- Resources are allocated in the order of increasing demand.
- No source gets a resource share larger than its demand.
- Sources with unsatisfied demands get an equal share of the resource.
- Allocation algorithm
  - Divide capacity C by n: C/n resources for each connection
  - Connection 1 needs x_1 resources ($x_1 < C/n$)
  - Distribute exceeding resources $C/n-x_1$ equally among other connections, so that each connection gets $C/n + (C/n - x_1)/(n-1)$ resources allocated
  - Continue process if resource allocation is larger than x_2

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2. Queue Management

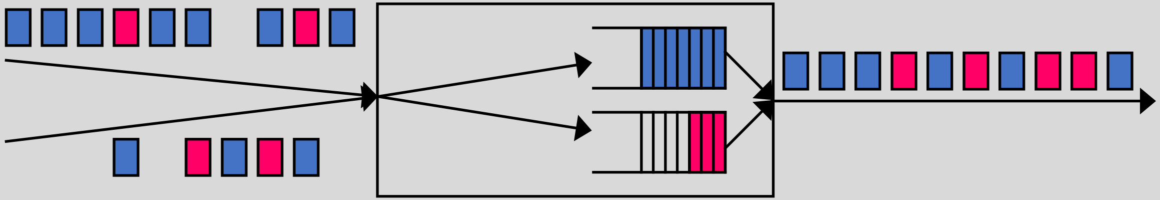
4. FIFO Scheduling

– First In First Out (FIFO) / First Come First Serve (FCFS)
– Packet transmission in the same order as packet arrival
– Packets are dropped if insufficient buffer space.
+ Simple implementation
+ Low packet processing delay

- No service differentiation
  - High-priority and/or delay-sensitive flows may be ‘trapped’ behind generic flows.
- Small packets can undergo large delays if they get behind big packets.
  - In general, flows with larger packets get better service.
- Greedy flows can overload the buffer.
  - Congestion-reactive flows get less and less bandwidth.

2. Queue Management

5. Priority Scheduling



- Priority levels with buffers
- Priority may depend on protocol type, application, IP addresses etc.
- Scheduler selects packet with highest priority.
- Packets with lower priority are selected only if there are no packets with higher priority. → starvation of low priority flows

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2. Queue Management

6.1 Conservation Law

- A work-conserving scheduler is idle only if its queue is empty.
- FCFS is work-conserving
- Conservation Law:

$$\sum_{i=1}^{N} \rho_i \cdot q_i = const$$

- ρ_i: mean utilization of a link due to connection i
- q_i: connection i's mean waiting time at the queue
- If a particular connection receives a lower delay than with FCFS, it must be at the expense of another connection.

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2. Queue Management

6.2 Example: Conservation Law

2 connections A (10 Mbps) and B (25 Mbps) share a 155 Mbps link and each having a mean queuing delay with FCFS: 0.5 ms

New scheduling mechanism reduces A‘s queuing delay to 0.1 ms

- $10 / 155 \cdot 0.5 + 25 / 155 \cdot 0.5 = 10 / 155 \cdot 0.1 + 25 / 155 \cdot B$
- B = 0.66 ms

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2. Queue Management

7. (Non-)Work-Conserving Scheduling Disciplines

- Non-work-conserving scheduling disciplines may be idle, even if there are packets to serve.
- A packet is only sent if it is eligible. Otherwise it is delayed until it becomes eligible.

- Are non-work-conserving scheduling disciplines useful ?
  - Downstream traffic can be made more predictable reducing buffer sizes (important in routers) and jitter.
  - Bursts are eliminated and traffic becomes smoother.
    But jitter can also be compensated by playback buffers in end systems!
- Today‘s routers implement work-conserving schedulers mainly.

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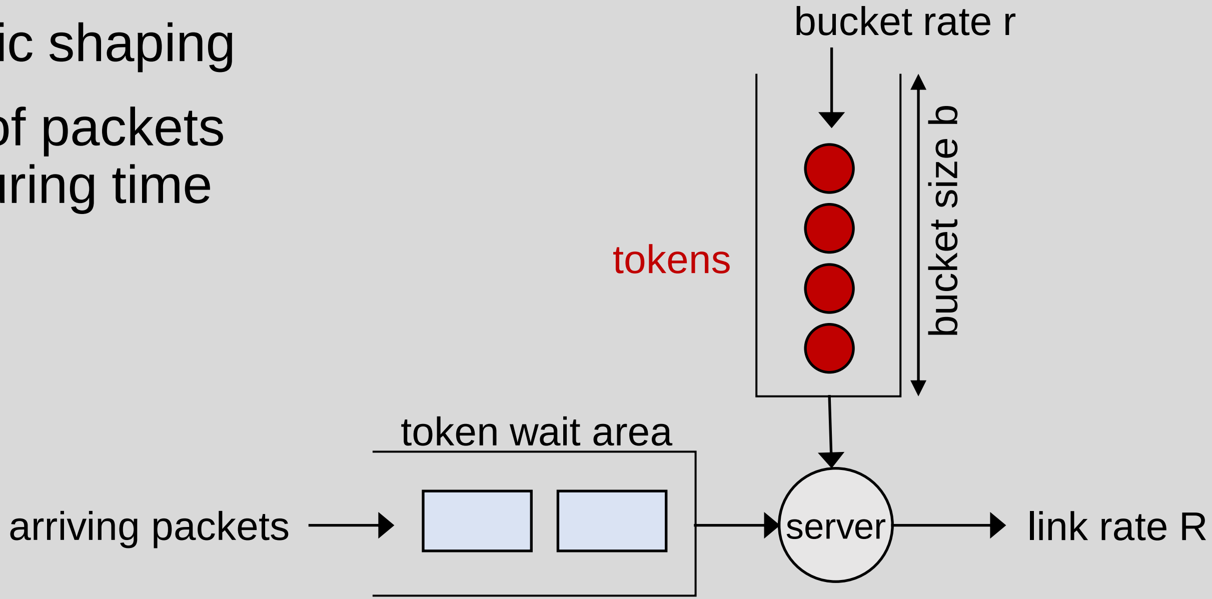
2. Queue Management

8. Token Bucket

- Mechanism for traffic shaping
- Maximum number of packets entering network during time interval t: $r \cdot t + b$



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3. Scheduling Disciplines

For Best-Effort

- Generalized Processor Sharing (GPS)
- Round-Robin (RR)
- Weighted Round-Robin (WRR)
- Deficit Round-Robin (DRR)
- Weighted Fair Queuing (WFQ)

For Guaranteed Service

- Weighted Fair Queuing (WFQ)
- Delay Earliest Due Date (EDD)
- Jitter Earliest Due Date (J-EDD)
- Rate-Controlled Scheduling

(non-work-conserving)

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3. Scheduling Disciplines

1. Generalized Processor Sharing

– serves packets as if they are in separate logical queues.

– visits each non-empty queue in turn.

– serves an infinitesimally small amount of data in each queue so that it can visit each queue at least once in any finite time interval.

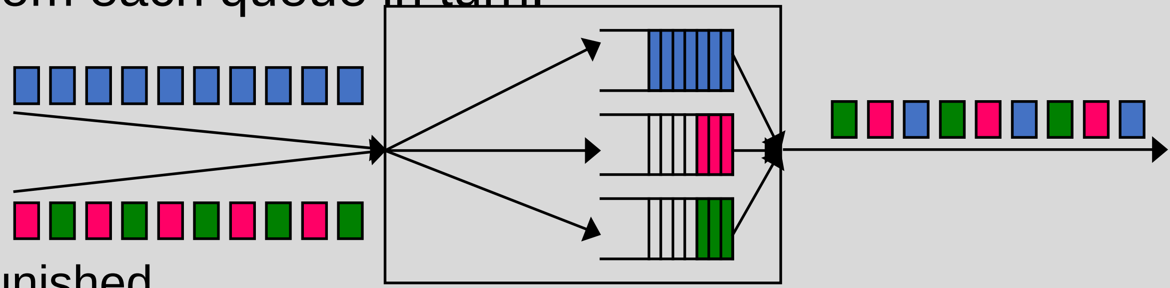
Characteristics

+ Fair
+ Ideal
- Not implementable
- Work-conserving

3. Scheduling Disciplines

2. (Weighted) Round Robin

- Several queues per output, e.g., 1 queue per sender or flow
- RR: Packets are taken from each queue in turn.
- WRR: Queues have different weights.



- Characteristics
  - \+ Aggressive flows get punished.
  - – Mean packet sizes must be known in advance.
  - – Fairness over a time interval much longer than a round time

3. Scheduling Disciplines

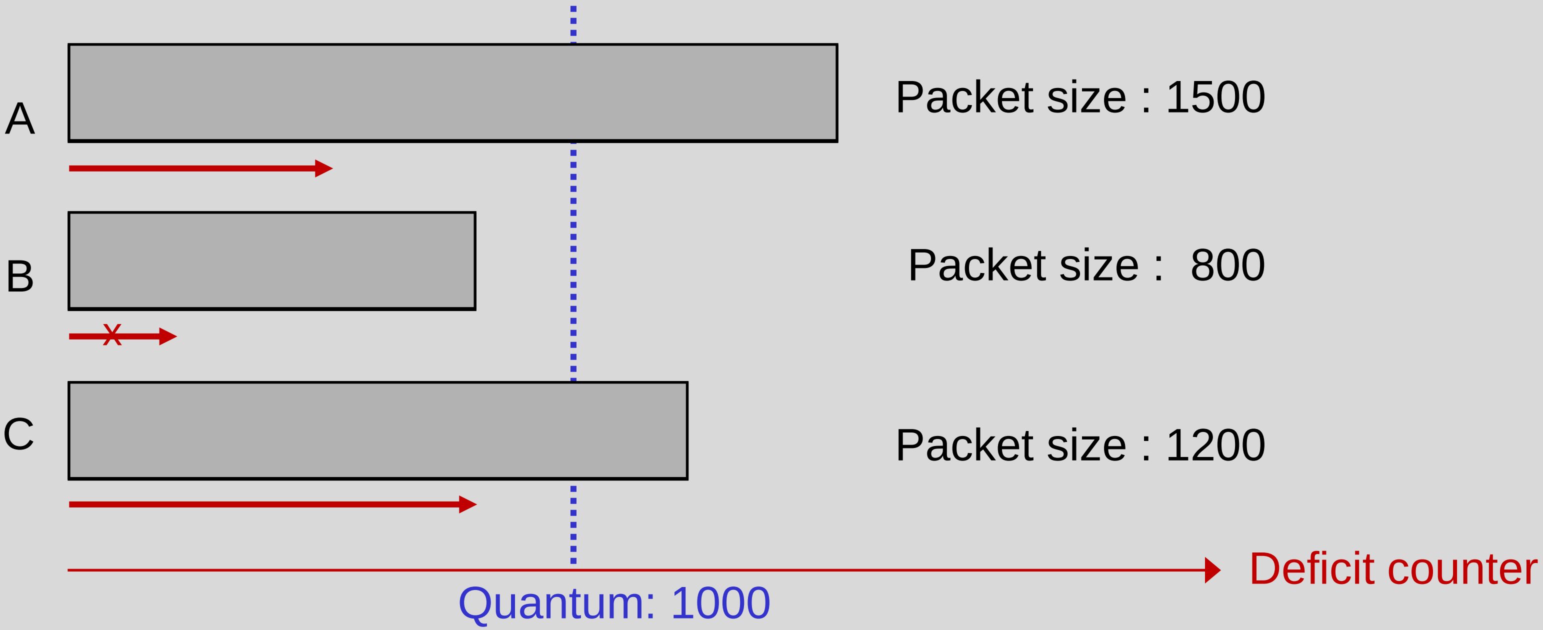
3.1 Deficit Round Robin

- DRR supports variable packet sizes.
- Each queue has a deficit counter initialized by 0.
- Scheduler visits each queue in turn and tries to serve 1 quantum of bits.

```
if (there is a packet to be served)
   if (packet_length <
   (quantum + deficit_counter)){
          serve packet;
          deficit_counter +=
              (quantum - packet_length)}
   else
          deficit_counter += quantum;
else
   deficit_counter := 0;
```

3. Scheduling Disciplines

3.2 Example: DRR



3. Scheduling Disciplines

4. Weighted Fair Queuing

Approximation of GPS

- emulates a weighted bit-by-bit round-robin discipline, i.e., generalised processor sharing
- Virtual starting and finishing ‘times’ are calculated as if GPS would be used.
- The next packet to be served is the one with the smallest finishing time (at the time of calculation).

Implementable GPS version providing different amounts of capacity to different flows.

- WFQ closely approximates the properties of GPS.
- WFQ provides uniform and appropriate level of service to each flow.

3. Scheduling Disciplines

4.1 WFQ: Finish Number

- Calculation of a finish number ($\neq$ finish time !) indicating the order, in which packets are served assuming a bit-by-bit service
- Round number = number of rounds a bit-by-bit RR scheduler has completed at a given time (variable duration of rounds !)
- A connection is active if (largest finish number in the connection‘s queue or of the packet last served) > current round number

- Finish number
  - of a packet arriving at an inactive connection = current round number + packet size [bits]
  - of a packet arriving at an active connection = largest finish number in the queue or of the packet last served + packet size [bits]
  - $F(i, k, t) = \max \{F(i, k - 1, t'), R(t)\} + P(i , k, t) / \phi(i)$
    - $F(i, k, t)$: finish number of k^{th} packet of connection i arriving at time t
    - $P(i, k, t)$: packet length of k^{th} packet of connection i arriving at time t
    - $R(t)$: number of the round at time t
    - $\phi(i)$: weight of connection i
- Packets are ordered by their finish number and are served in that order.

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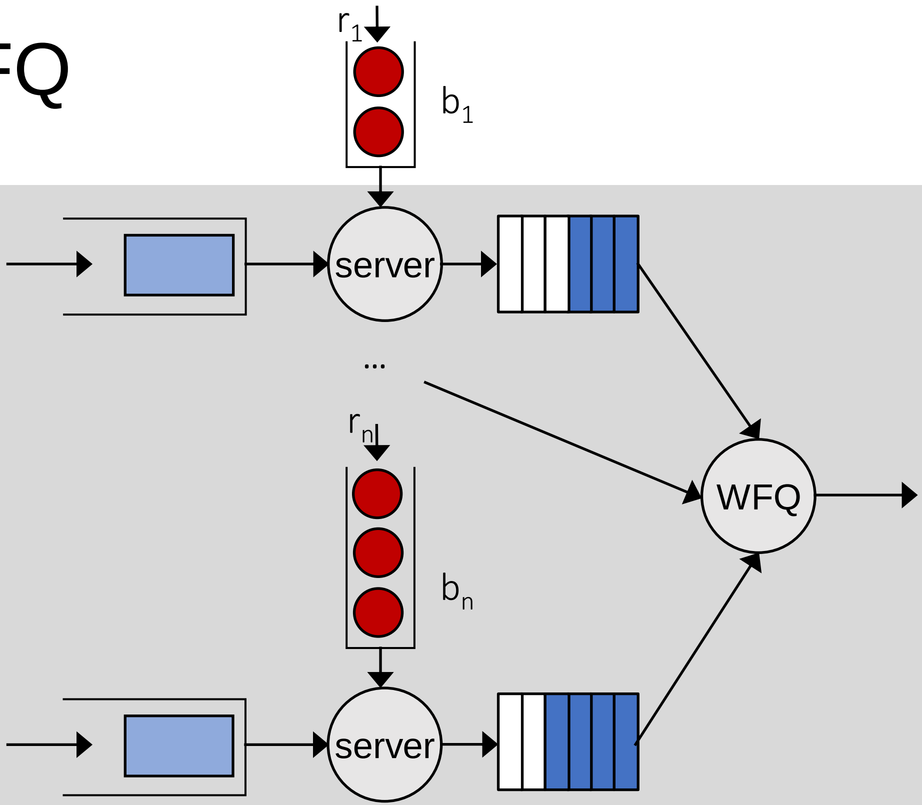
3. Scheduling Disciplines

4.2 Token Buckets and WFQ



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3. Scheduling Disciplines

4.3 WFQ: Delay Bound

Minimum throughput for flow i by WFQ = $R \cdot \phi(i) / \Sigma\, \phi(j)$

Maximum delay for flow i?

- Assumption: token bucket i is full.
- Then, burst of b_i packets arrives and consumes all tokens.
- b_i packets are served with rate of at least $R \cdot \phi(i) / \Sigma\, \phi(j)$.
- Last packet will experience maximum delay = $b_i / (R \cdot \phi(i) / \Sigma\, \phi(j))$.

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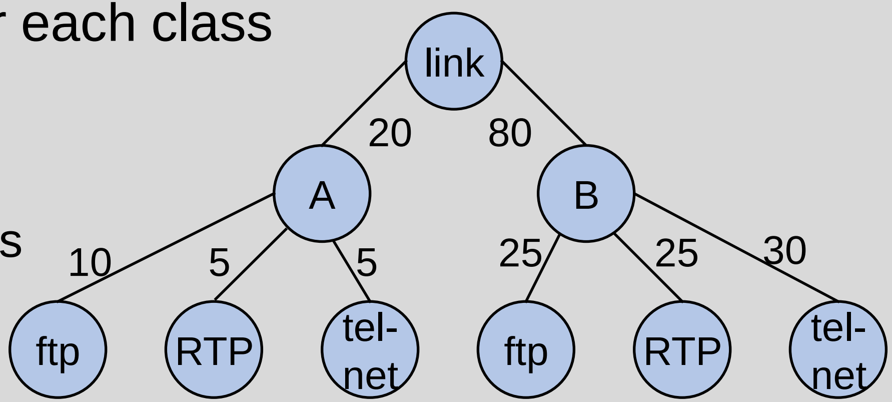
3. Scheduling Disciplines

5. Class-Based Queuing

- Hierarchical Link Sharing
- Implementation by WFQ, DRR
- Definition of bandwidth available for each class
- Class =
  - Protocol / application
  - Traffic from / to certain sub-networks



3. Scheduling Disciplines

6. Earliest Due Date

- Assignment of a deadline (= arrival time + period of traffic stream) to each packet
- Scheduler selects packets in the order of their deadlines.
- Packets missing their deadline are discarded.

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3. Scheduling Disciplines

6.1 Delay-EDD

- Negotiation of a service contract (in addition to EDD): If a source obeys a peak rate, the delay is less than some delay bound.
- Deadline =
  arrival time + delay bound

- Delay-EDD requires
  - admission control and
  - bandwidth reservation at peak rate.
- Example
  - One packet arrives every 0.2 s with a delay bound of 1 s
  - Deadline of k^{th} packet = (0.2k+1) s

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3. Scheduling Disciplines

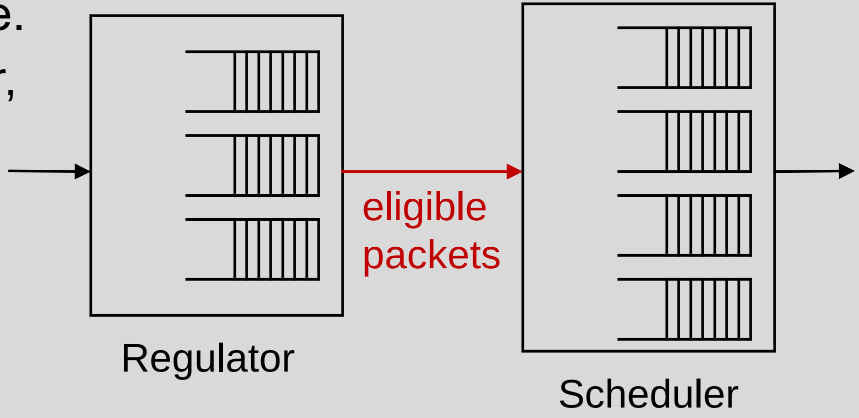
6.2 Jitter-EDD

- Extension of Delay-EDD: Delay-jitter-regulator precedes EDD scheduler.
- Packets get timestamp = deadline - finishing time.
- Next server delays packet by timestamp value.
- All packets receive the same delay at every hop (except at the last hop).

3. Scheduling Disciplines

7. Rate-Controlled Scheduling

- can provide bandwidth and delay bounds to connections
- Regulator
  - determines the packet‘s eligibility time.
  - forwards eligible packets to scheduler, e.g., FIFO, WFQ, EDD.

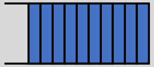


4. Packet Dropping

1. Issues

Limited queue length requires packet dropping by scheduler in overload conditions.

- Degree of aggregation
  - Protection versus state information
- Marking of several drop priorities
  - Packets with high drop priorities are dropped first.
  - Either applications or routers must be able to mark packets.
  - Low dropping priority for packets that traveled very long



- Late / early dropping
  - Early drop: Packets are dropped even in case of non-full queues. Cooperative sources experience low packet loss.
- Drop position
  - Tail: easy to implement, may be unfair
  - Head: more complex, sources notice dropping earlier
  - Random: very complex, fair

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4. Packet Dropping

2. Late and Early Dropping

Late Dropping

- Arriving packets are discarded, if queue is full.
- Certain flows can monopolize the queue.
- Higher delays
- Queues can not absorb bursts.
- Reaction onto congestion, but no congestion avoidance
- Global synchronisation
  - When queue is full, all packets from all flows are dropped.
  - All flows back-off simultaneously.
  - Periods of congestion followed by periods of low network utilisation

Early Dropping

- Flows (e.g., TCP connection) reduce rate before queue becomes overloaded.
- Examples
  - Early Random Drop:
    Arriving packet is dropped with fixed probability, if queue level exceeds a certain limit.
  - Random Early Detection

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4. Packet Dropping

3.1 Random Early Detection

```
avg := exponential average of queue length;
if (avg < TH_min)
   store packet in queue
else if (TH_min ≤ avg < TH_max){
   P := calculate dropping probability;
   discard packet with probability P;
   store packet with probability 1-P}
else if (avg ≥ TH_max)
   discard packet;
```

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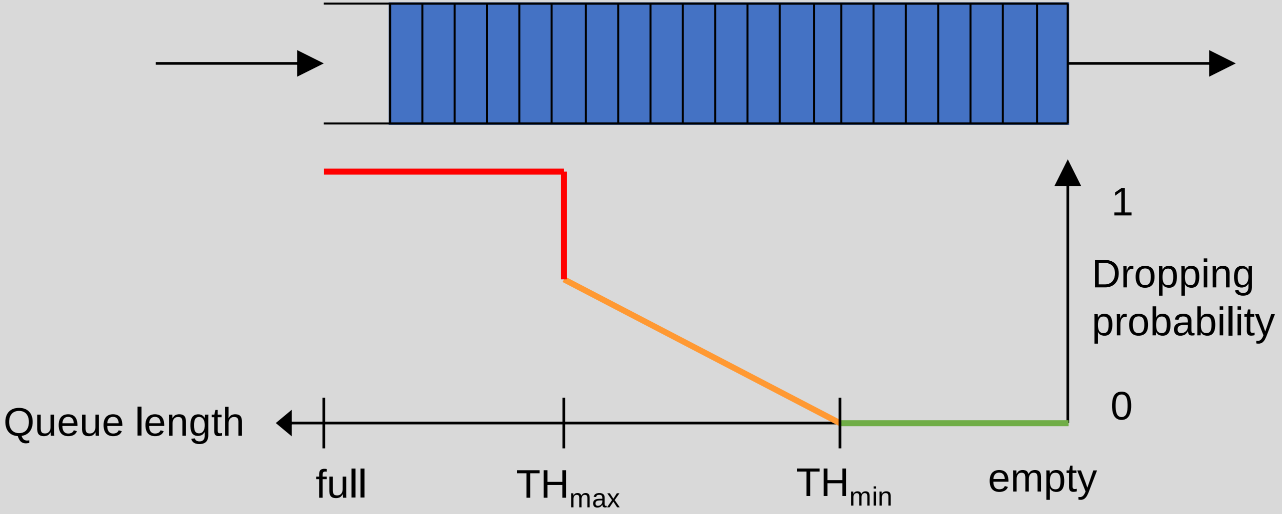
4. Packet Dropping

3.2 Random Early Detection

Dropping probability increases with the exponential average queue length.



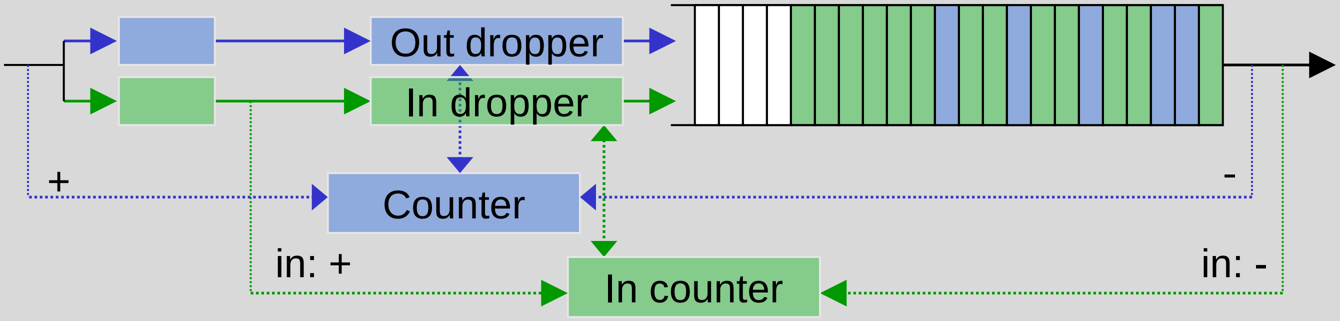
4. Packet Dropping

4.1 RED with In and Out (RIO)

Different droppers for high / low priority (in-service / out-of-service) packets

– Out dropper drops earlier and more aggressively.

– In dropper considers high-priority packets only.



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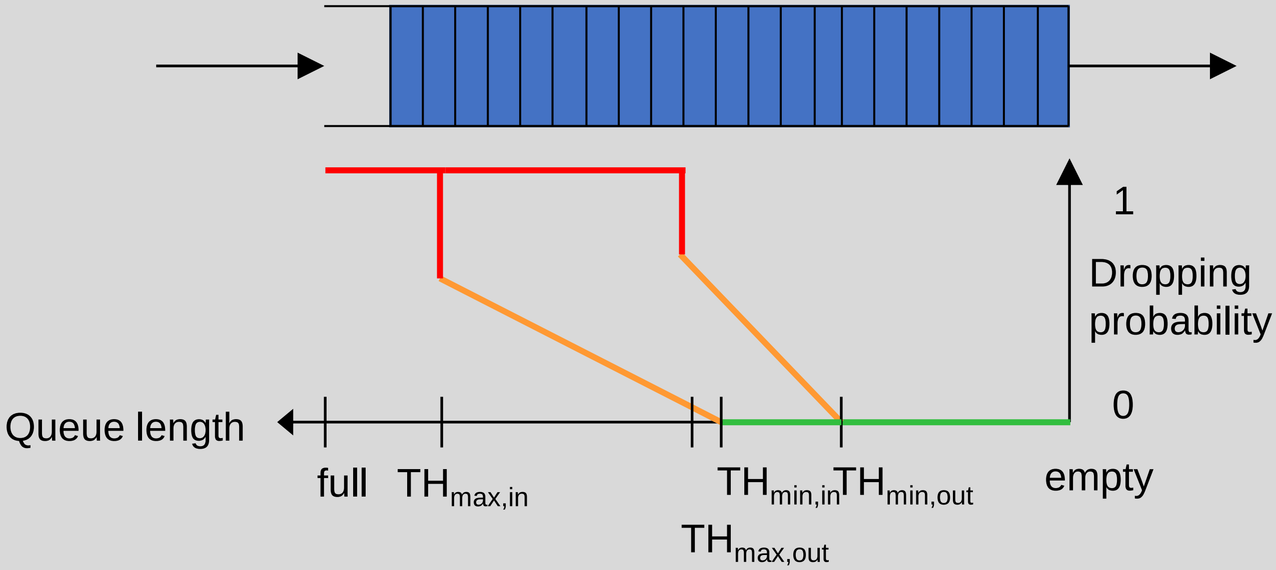
4. Packet Dropping

4.2 RIO



Thanks

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