Scheduling and QoS scheduling

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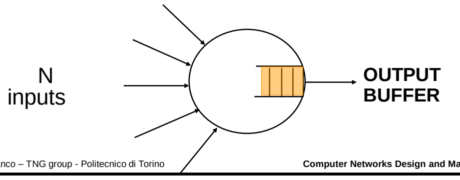
Scheduling algorithms

- Scheduling: choose a packet to transmit over a link among all packets stored in a given buffer (multiplexing point)
- Mainly look at QoS scheduling algorithms
  - Choose the packet according to QoS needs



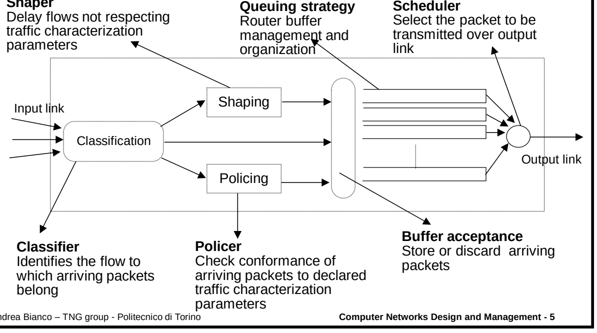
Output buffered architecture

- Advantage of OQ (Output Queued) architectures
  - All data immediately transferred to output buffers according to data destination
  - It is possible to run QoS scheduling algorithms independently for each output link
- In other architectures, like IQ or CIOQ switches, problems become more complex
  - Scheduling to satisfy QoS requirements and scheduling to maximize the transfer data from inputs to outputs have conflicting requirements

QoS scheduling algorithms

- Operate over multiplexing points
- Micro or nano second scale
- Easy enough to be implemented in hardware at high speed
- Regulate interactions among flows
  - Single traffic relation (1VP/1VC)
  - Group of traffic relations (more VC/1VP o more VC with similar QoS needs)
  - QoS classes
- Strictly related and dependent from buffer management techniques
- To simplify and make the problem independent, assume infinite capacity buffers
- Choice of the scheduler may have implications on CAC

QoS-capable router



QoS scheduling algorithms: properties

- Flow isolation
  - "mis-behaving" (non conformant) flows should not damage "well-behaved" (conformant) flows
  - PER-FLOW queuing, which implies resource partitioning
    - scheduler chooses from which queue to transmit the packet
  - Related to fairness
- End-to-end statistical or deterministic guarantees
  - Bit rate
    - Equal for all flows (useful for best effort traffic)
    - Specific for each flow
  - Delay
  - Losses

QoS scheduling algorithms classification

- Work-conserving scheduler
  - *Always* transmit a packet as long as there is at least a packet available in switch buffer
  - Optimal performance in terms of throughput
- Non-work-conserving scheduler
  - May delay packet transmission
    - No transmission even if there are packets stored in buffers
  - Reduced throughput
  - Better guarantees on delay jitter
    - Reduced buffer size
  - In theory appealing approach, not much used in practice

Scheduling discipline property

- Theorem
  - The sum of mean queuing delays received by a set of multiplexed connections, weighted by their share of the link load is independent of the scheduling algorithm
- A scheduling algorithm can reduce a connection mean delay only at the expense of increasing the delay of another connection
- A work-conserving scheduler can only reallocate delays among connections
- A non work-conserving scheduler can only provide a mean queuing delay larger than a work conserving discipline

Work conserving versus non-work conserving schedulers

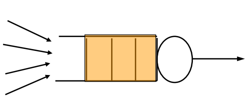
- Work-conserving schedulers disadvantage
  - Multiplexing point increase traffic burstiness
  - This increase packet jitter and buffering requirments to prevent losses
  - Patological scenarios demonstrate that this phenomena may become worse when the number of crossed nodes increases
- Non work-conserving schedulers have buffering requirements independent of the network depth

Scheduling algorithms goals

- Best-effort traffic scheduler
  - All active flows should obtain the same amount of service
  - Possibly max-min fair
  - No delay guarantees
  - FIFO, PS (Processor Sharing), RR (Round Robin), DRR (Deficit Round Robin)
- QoS scheduler, i.e. scheduler for traffic with QoS requirements
  - Specific bit rate guarantees for each flow
  - Specific delay guarantees for each flow
  - Strict priority, GPS (Generalized Processor Sharing), WRR (Weighted Round Robin), WFQ (Weighted Fair Queuing), EDD (Earliest Due Date)

FIFO

- FIFO (First In First Out) service discipline
  - Also known as FCFS (First Came First Served)
- Single queue
- Data queued according to arrival time and served in order



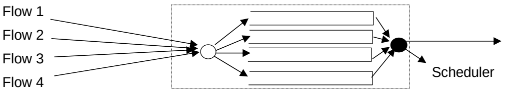
FIFO: properties

- Work-conserving
- Complete sharing of link bit rate and buffer space: no protection against non conformant flows
- All flows observe similar delay performance
  - Suited to best-effort traffic
- Neither bit rate (bandwidth) guarantees nor loss guarantees
  - Performance depend on the amount of ingress data traffic of each flow
- Aggressive flows obtain better performance
  - Unfair

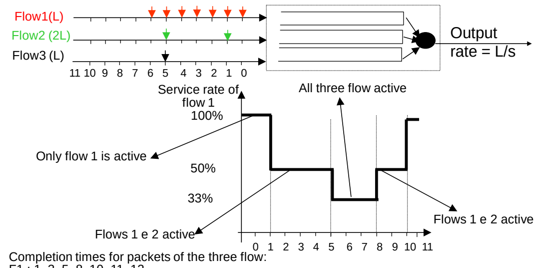
Processor Sharing

- Ideal work-conserving scheduler for best effort
- Each queue served according to a fluid model
- At time t, queue j is served at rate

$$rate[j] = \frac{rate_{link}}{\#activeflows}$$



Processor Sharing: example



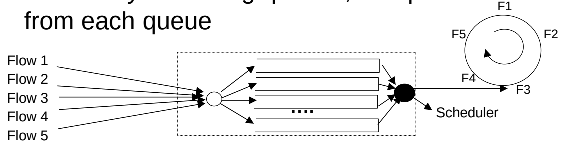
Completion times for packets of the three flow:
F1 : 1, 3, 5, 8, 10, 11, 12
F2 : 5, 10
F3 : 8

Processor Sharing

- Pros
  - If no data are discarded, a network of PS schedulers provides rates close to a max-min fair allocation
    - Rate of the max-min allocation only downstream from the bottleneck link
    - Fairness does not require congestion control mechanisms
    - If dropping packets, fair dropping must be ensured
- Cons
  - Ideal solution, non practical (packets are not fluids)
    - Devise approximations

Round Robin

- Processor sharing approximation
- Buffer organized in separate queues, one queue for each active flow
  - Each queue is a FIFO queue
- Service cycle among queues, one packet from each queue



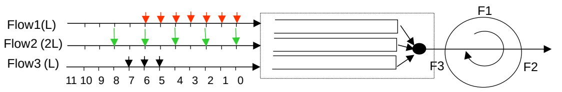
Round Robin

- May have some delay bias
- To improve delay fairness, at each serving cycle it is possible to modify queue service order
    - At time 0, queue service order: 1,2,3,..,K
    - At time 1, queue service order: 2,3,..,K,1

Round Robin: properties

- Relatively easy to implement in hardware
- Guarantees flow isolation
  - Through queue separation
- Service rate of each queue:
  - C/K, for fixed packet size and k flows
  - For variable packet size, some rate unfairness may arise (fair in #packets per flow)
  - Taking into account packet size makes implementation more complex

Round Robin: example



T	In F1	In F2	In F3	Q(F1)	Q(F2)	Q(F3)	Scheduled packets
0	P10[1]	P20[2]	-	P10	P20	-	F1:P10
1	P11[1]	-	-	P11	P20	-	F2:P20
2	P12[1]	P22[2]	-	P11,P12	P22	-	F2:P20 (cont)
3	P13[1]	-	-	P11,P12,P13	P22	-	F1:P11
4	P14[1]	P24[2]	-	P12,P13,P14	P22,P24	-	F2:P22
5	P15[1]	-	P35[1]	P12,P13,P14,P15	P24	P35	F2:P22 (cont)
6	P16[1]	P26[2]	P36[1]	P12,P13,P14,P15,P16	P24,P26	P35,P36	F3:P35
7	-	-	P37[1]	P12,P13,P14,P15,P16	P24,P26	P36,P37	F1:P12
8	-	P28[2]	-	P13,P14,P15,P16	P24,P26	P36,P37	F2:P24
9	-	-	-	P13,P14,P15,P16	P26,P28	P36,P37	F2:P24
10	-	P2A[2]	-	P13,P14,P15,P16	P26,P28	P36,P37	F3:P36

Deficit Round Robin

- Round robin work conserving scheduler working with variable packet size
- One queue[i] per flow i
- The scheduler visits each queue in a round robin fashion
  – Each queue[i] has a deficit counter D[i] associated with
  – F[i] is increased by a fixed quantum when queue[i] is visited
  – Send the packet if D[i] large enough wrt packet size

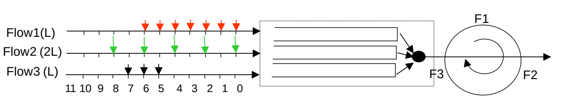
DRR: pseudo code

```
while true {
  for i=1..N {
    if queue[i] non empty {
      D[i]=D[i]+quantum;
      while(queue[i] non empty AND
           length_first_packet of queue[i] < D[i]) {
         packet transmitted on output link;
         D[i]=D[i]- packet_length;
         }
      }
    if (queue [i] empty) {
      D[i]=0;
    }
  }
}
```


Deficit Round Robin

– if (length_first_packet of queue[i] > d[i])
  { packet is kept in queue[i] }
– else
  {packet transmitted on output link;
  d[i]=d[i]- packet_length;
  if (queue [i] is empty) { d[i]=0; }
  }

Deficit Round Robin: example



T	Inc.	D[1]	D[2]	D[3]	Q(F1)	Q(F2)	Q(F3)	Scheduled
0	F1	0+1-1	0	0	P10	P20	-	F1:P10
1	F2,F1	0+1-1	0+1	0	P11	P20	-	F1:P11
2	F2	0	1+1-2	0	P12	P22	-	F2:P20
3	-	0	0	0	P12,P13	P22	-	F2:P20(cont)
4	F1	0+1-1	0	0	P13,P14	P22,P24	-	F1:P12
5	F2,F3	0	0+1	0+1-1	P13,P14,P15	P22,P24	P35	F3:P35
6	F1	0+1-1	1	0	P14,P15,P16	P22,P24,P26	P36	F1:P13
7	F2	0	1+1-2		P14,P15,P16	P22,P24,P26	P36,P37	F2:P22
8	-	0	0	0	P14,P15,P16	P24,P26	P36,P37	F2:P22(cont)
9	F3	0	0	0+1-1	P14,P15;P16	P24,P26	P36,P37	F3:P36
10	F1	0+1-1	0	0	P15,P16	P24,P26	P37	F1:P14
11	F2,F3	0	0+1	0+1-1	P15,P16	P24,P26	P37	F3:P37

...

Deficit Round Robin

- The idea is to keep track of queues that were not served in a round (compute deficit) and to compensate in the next round
- Keep an active list of indices of queues that contain at least a packet to avoid examining empty queues
- May be a problem to define the quantum
  – If too small, may need to visit too many times queues before serving a queue
  – If too large, some short term unfairness may arise
- Fair only over a time scale longer than a round time
  – Round time is a function of the number of flows and packet size
  – At a shorter time scale, some flows may get more service
  – Small packet size or high transmission speed reduce the round time

Strict priority

- First attempt to define a QoS capable scheduler
- Buffer partitioned in k queues, k being the number of priority classes
- Each queue is associated with a different priority
- Data unit are stored in a queue according to their priority level
- Higher priority queue is always served. Only if empty, the lower priority is considered
  - Non preemptive service: packet under service finish transmission
- Within each queue, data are served according to a FIFO service discipline

Strict priority algorithm

- Work-conserving
- Easy to implement
- Perfect isolation for high priority queue only, low priority queues may even suffer starvation (if CAC is not adopted on high priority queues)
  - Fair?
- No bit rate, loss and delay guarantees
- No isolation among flows stored in the same FIFO queue, i.e., within the same priority level

Generalized Processor Sharing

- Fluid system used as an ideal reference
- One queue for each flow
- Each queue is served as if it contains a fluid flow, i.e. by an infinitesimal fraction of time
- Each queue j is associated with a weight w[j], normally derived from bit rate requirements
- At time t, queue j is served at rate:

$$rate[j] = rate_{link} \frac{w[j]}{\sum_{i=activequeues} w[i]}$$

  - A queue is active if it contains some fluid
  - If the number of active flows decreases, excess bit rate is redistributed in proportion to queue weight
  - CAC algorithms must control the rate of served flows, otherwise bit rate guarantees cannot be obtained

GPS properties

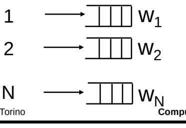
- Work conserving with flow isolation
- Per flow bit rate guarantees
  - When using a single GPS scheduler
  - When using a network of GPS schedulers
- End-to-end delay guarantees for token bucket (r,b) constrained flows
- Provides bounds on buffer size
- Simple jitter delay guarantees ([0,Dmax])
- Ideal scheduler, practical approximations needed

GPS approximation

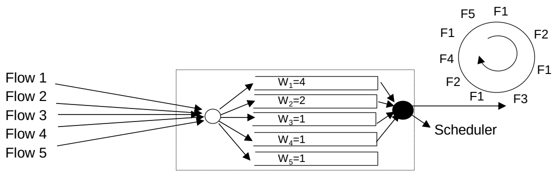
- Frame-based
  - Define a service cycle (frame)
  - Allocate frame portion to each flow
  - Example: WRR (Weighted-Round Robin), WDRR (Weighted Deficit Round Robin)
- Sorted priority
  - Compute a timestamp (tag) and associate it with each packet
  - Packets are ordered for increasing timestamp
  - Examples: Virtual Clock, WFQ (Weighted Fair Queuing), SCFQ

WRR: Weighted Round Robin

- GPS approximation
- Buffer partitioned in N queues
  - each queue served according to a FIFO discipline
- A weight $w_i \propto$ requested bit rate is associated with each queue
- A service cycle among queues is executed, each queue being served proportionally to its weight, i.e., w_i per cycle
- Cycle length is the summation of the weights (possibly normalized)



WRR: Weighted Round Robin



- If all flows are active
  - F1 obtains 4/9 of the link bit rate
  - F2 obtains 2/9
  - F3, F4 and F5 obtain 1/9

WRR: properties

- Work-conserving
- Flow isolation guaranteed
- For each queue i:
  - bit-rate = $w_i / (\Sigma_j w_j)$link_rate
    - if all packets are of the same size
- Easy to implement (for a small number of flows)
- Define a service cycle

WRR: problems

- Service cycle (and fairness) may become long when
  - Many flows are active
  - Flows have very different weights
  - On a 45Mbit/s link, 500 flows with weight 1 and 500 flows with weight 10
    - Service time of one cell (48 ytes) 9.422us
    - A cycle requires 500+500*10=5500 service time=51.82ms
- Service provided to flows may be bursty
  - Avoidable, but complex
- For each variation of the number of active flows (departure, arrival) service cycle must be redefined
  - How to deal with the remaining part of the cycle?
- To deal with variable packet size may use WDRR, Deficit Round-Robin extended to weight support
- Note. WRR may be exploited in best effort scenario
  - May use weights in WRR to compensate for variable packet size for best effort traffic (requires knowledge of flow average packet size)

Sorted priority approximation to GPS

- Per-flow queuing
- Data (cells) served on the basis of negotiated rate and cell arrival time
  - Each data has a tag (urgency) assigned
- Data are inserted in a Sorted Priority Queue on the basis of data tag
- Data are served according to tag ordering
- Several algorithms: virtual clock, WFQ o PGPS, SCFQ

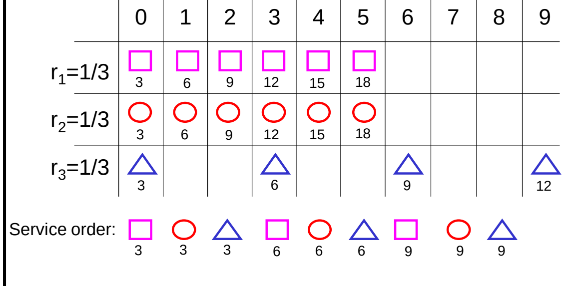
Virtual Clock

- Time Division Multiplexing emulation
- Each flow *j* has an assigned service rate r_j
- To each data *k* of length L_j^k belonging to flow *j*, a tag (label, urgency, auxiliary virtual clock) is assigned
  - Tag represents the data finishing service time (starting service time + service time) in a TDM system serving flow *j* at rate r_j:

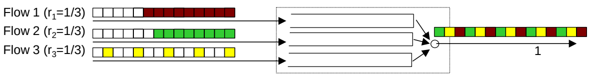
$$\text{Aux VC}_j^k = \text{Aux VC}_j^{k-1} + \frac{L_j^k}{r_j}$$

Virtual Clock scheduling

Example



Virtual Clock: example 1



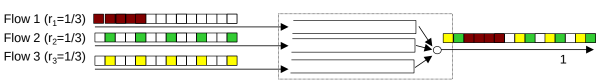
T	AV(F1)	Q(F1)	AV(F2)	Q(F2)	AV(F3)	Q(F3)	Scheduled flow
0	0+3	3	0+3	3	0+3	3	F1
1	3+3	6	3+3	3,6	3	3	F3
2	6+3	6,9	6+3	3,6,9	3	-	F2
3	9+3	6,9,12	9+3	6,9,12	3+3	6	F1
4	12+3	9,12,15	12+3	6,9,12,15	6	6	F3
5	15+3	9,12,15,18	15+3	6,9,12,15,18	6	-	F2
6	18+3	9,12,15,18,21	18+3	9,12,15,18,21	6+3	9	F1
7	21+3	12,15,18,...	21+3	9,12,15,18,21	9	9	F3
8	24+3	12,15,18,...	24+3	9,12,15,18,...	9	-	F2
9	....						

Virtual Clock scheduling

Problem:

	0	1	2	3	4	5	6	7	8	9	10	11	12	13
r_1=1/3	□ 3			□ 6			□ 9			□ 12			□ 15	
r_2=1/3	○ 3			○ 6			○ 9			○ 12			○ 15	
r_3=1/3										△ 3	△ 6	△ 9	△ 12	△ 15
	□ 3	○ 3		□ 6	○ 6		□ 9	○ 9		△ 3	△ 6	△ 9	□ 12	○ 12

Virtual Clock: problem



T	AV(F1)	Q(F1)	AV(F2)	Q(F2)	AV(F3)	Q(F3)	Scheduled flow
0	0	-	0+3	3	0+3	3	F2
1	0	-	3	-	3	3	F3
2	0	-	3	-	3	-	-
3	0	-	3+3	6	3+3	6	F2
4	0	-	6	-	6	6	F3
5	0	-	6	-	6	-	-
6	0	-	6+3	9	6+3	9	F2
7	0	-	9	-	9	9	F3
8	0	-	9	-	9	-	-
9	0+3	3	9+3	12	9+3	12	F1
10	3+3	6	12	12	12	12	F1
11	6+3	9	12	12	12	12	F1
12	9+3	12	12+3	12,15	12+3	12,15	F1
13	12+3	15	15	12,15	15	12,15	F2

Virtual Clock

- Long term fairness with some problems
  - Inactive flows “gain time” and get more service in the future, penalizing, and even starving, other active flows (even conformant flows)
  - Clock of different flows proceed independently
- Modify the tag computation, taking into account system real time:

$$\text{Aux } VC_j^k = \max(\text{Aux } VC_j^{k-1}, a_j^k) + \frac{L_j^k}{r_j}$$

  - where a_j^k is the arrival time of cell k of flow j

Virtual Clock scheduling

Problem solved

	0	1	2	3	4	5	6	7	8	9	10	11	12	13
r_1=1/3	□ 3			□ 6			□ 9			□ 12			□ 15	
r_2=1/3	○ 3			○ 6			○ 9			○ 12			○ 15	
r_3=1/3										△ 12	△ 15	△ 18	△ 21	△ 24
	□ 3	○ 3		□ 6	○ 6		□ 9	○ 9		□ 12	○ 12	△ 12	□ 15	○ 15

Modified Virtual Clock

Another problem

Time	0	1	2	3	4	5	6	7	8	9	10	11	12	13
r_1=1/3	□ 3	□ 6	□ 9	□ 12	□ 15	□ 18	□ 21	□ 24	□ 27	□ 30	□ 33	□ 36	□ 39	
r_2=1/3	○ 3	○ 6	○ 9	○ 12	○ 15	○ 18	○ 21	○ 24	○ 27	○ 30	○ 33	○ 36	○ 39	
r_3=1/3													△ 15	△ 18
	□ 3	○ 3	□ 6	○ 6	□ 9	○ 9	□ 12	○ 12	□ 15	○ 15	□ 18	○ 18	△ 15	△ 18

Virtual Clock

- Even the modified version of Virtual clock can lead to unfairness
- Clocks of flows are now synchronized by the system time
- However, tags may overcome the system time when flows get excess bandwidth
- Excess bandwidth must be redistributed among flows to ensure work conserving property but reallocation must not penalize flows in the future

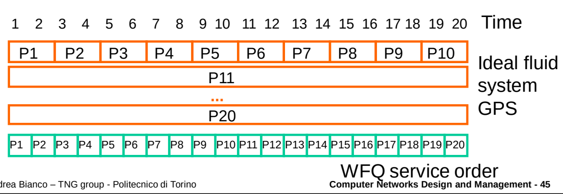
WFQ (Weighted Fair Queueing) or PGPS (Packetized GPS)

- Algorithms that try to approximate GPS behavior
  - The minimum amount of service that can be provided cannot be smaller than the service time of a cell, since no preemption is admitted
- At time τ, the transmitted packet is the packet whose service would finish first in the GPS system if no other packets arrive after τ
  - Need to emulate the GPS system

WFQ or PGPS

Example:

- 1 flow with negotiated rate 0.5
  - 10 fixed size packets arrive at rate 1 starting at time 1
- 10 flows with negotiated rate 0.05
  - 1 packet arrives at time 1



WFQ o PGPS

- Tag computation
  - Tag should represent the finishing service time of data in the GPS system
  - However, it is fundamental to compute the tag when data unit are received at buffer input
  - Future should be known, since the data finishing service time in the ideal system depends on flow activation in the future
  - The problem is trivial if all flows are always active, since service rate are fixed

WFQ or PGPS

- Tag computation:

$$\mathcal{F}_j^k = \max\{\mathcal{F}_j^{k-1}, V(a_j^k)\} + \frac{L_j^k}{\varphi_j}$$

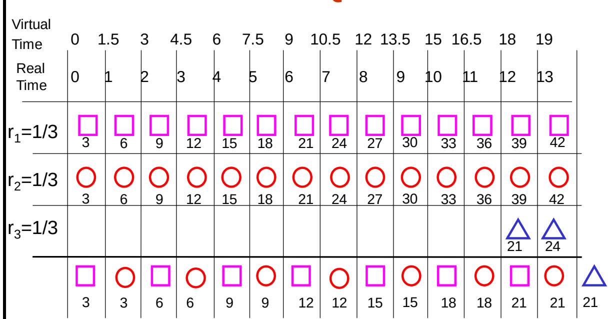
- V(t) is the system virtual time or system potential (k active flows):

$$V(0) = 0$$

$$\frac{\partial V}{\partial \tau} = \frac{1}{\Sigma_k \varphi_k}$$

- If flows are always active, the virtual time corresponds exactly to the real time

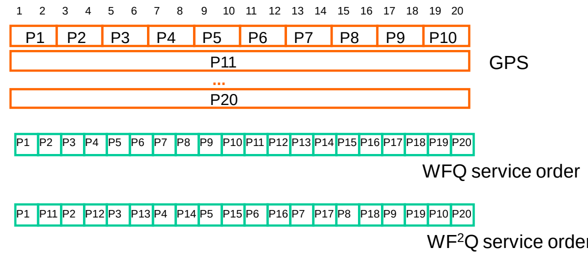
WFQ



WFQ o PGPS

- Very complex to implement
- Same properties of GPS
  - WFQ can emulate the ideal GPS system with a time difference bounded by the maximum size packet!
- Several variations were proposed
  - Indeed, in WFQ packets are never delayed too much, but could be transmitted too early
  - WF^2Q
    - improves the similarity of service order to GPS
    - among available packets, the packet with the smallest tag is chosen but only among packets whose service has already started in the ideal GPS system

WFQ vs WF^2Q

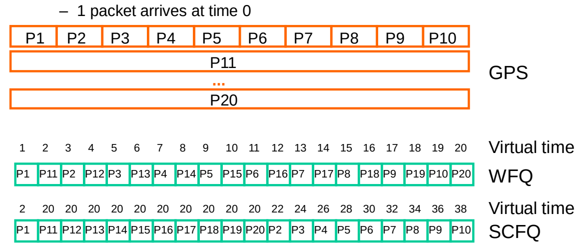


SCFQ (Self Clocked Fair Queueing)

- Variation of PGPS, simpler to implement
- Does not require emulation of GPS system
- Uses a simplified virtual time
  - Virtual time is set to the tag of the packet being serviced

SCFQ vs WFQ

- 1 flow with negotiated rate 0.5
  - 10 fixed size packets **arrive at rate 0.5** starting at time 0
- 10 flows with negotiated rate 0.05
  - 1 packet arrives at time 0



Delay bounds

- Can be computed for token bucket limited flows (R,B)
- Guarantees independent of other flow behavior
- Max delay through n scheduler (excluding fixed delays):
  - GPS $\quad \dfrac{B}{R}$
  - WFQ / PGPS $\quad \dfrac{B+n\cdot P_{\max}}{R}+\sum_{i=1}^{n}\dfrac{P_{\max}}{C_i}$
  - Virtual Clock $\quad \dfrac{B+n\cdot P_{\max}}{R}+\sum_{i=1}^{n}\dfrac{P_{\max}}{C_i}$
  - SCFQ $\quad \dfrac{B+n\cdot P_{\max}}{R}+\sum_{i=1}^{n}\dfrac{k_i\cdot P_{\max}}{C_i}$

  - C_i output rate of i-th switch
  - k_i number of flows
  - P_{max} maximum packet size
- Bandwidth delay coupling

EDD (Earliest Due Date)

- In classical EDD
  - Each packet is assigned a deadline
  - Packets served in deadline order
  - Deadline satisfied only if the scheduler is not overcommitted
- Traffic divided in classes
  - Each class i is characterized by a service deadline d_i
- Scheduler selects, at time t, the packet with the smallest residual time
  - Each packet is time stamped with time t_k on arrival
  - Residual time of a packet = $t_k + d_i - t$
    - the amount of time left before packet service deadline expires
- EDD tends to equalize the probability of violating the delay constraint

EDD (Earliest Due Date)

- Need to specify the process to assign deadlines
  - Delay EDD and Jitter EDD
- Delay EDD
  - packets belonging to sources obeying a peak rate constraint are assigned a worst case delay (in each node, deadline=expected arrival time+delay bound)
  - CAC must run a schedulability test to check if deadlines can be satisfied
  - Delay bound independent of bandwidth constraint (but need to reserve the peak)
- Jitter EDD
  - Delay jitter regulator in front of a EDD scheduler (non work conserving, see later)
- Issues
  - Interesting to manage delays, difficult to deal with bandwidth guarantees
  - Complex to implement (timers, dealing with real numbers)

Non work-conserving algorithms

- Packets can be scheduled only if eligible
- Eligibility through traffic regulators
  - Rate-jitter regulator
    - Bounds maximum rate
  - Delay jitter regulator
    - Compensates for variable delay at previous hop
- After the regulator use a scheduler (may be FIFO)
- Properties
  - Reduced throughput
  - Worse average delays but
    - Control on delay jitter
    - Reduced buffer size
- Examples
  - Stop and go
  - Hierarchical round robin

Regulators for non work-conserving algorithms

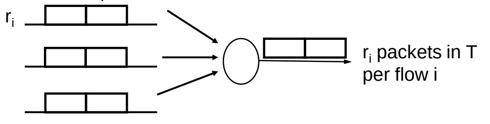
- Rate jitter regulators
  - E.g.: peak rate regulator
    - eligibility time of a packet is the eligibility time of the previous packet plus the inverse of the peak rate (time taken to serve the packet at the peak rate)
- Delay jitter regulators
  - The sum of the queuing delay in the previous switch and the regulator delay is constant
    - Eliminates the delay variability induced by the queuing delay at the previous hop
    - The output stream is a time shifted version of the traffic at input
    - Time shift equal to propagation delay plus delay bound (worst case) at previous switch
  - Burstiness cannot build up
  - Do not protect against misbehaving sources
  - Very complex to implement (it requires clock synchronization)
- Note: by properly selecting the regulator and the scheduler a wide range of work-conserving and non work-conserving schedulers may be emulated

An example of a non work-conserving scheduler: Stop & go

- Framing strategy
  - Time axis divided into frames of length T
- At each switch, the arriving frame of each incoming link is mapped to the departing frame of the output link by a constant delay smaller than T
- Transmission of packets arriving on any link during a frame are postponed to the beginning of the next frame

Stop & go

- Packets on the same frame at the source stay in the same frame throughout the network
- If the traffic is (r_i,T) smooth at source i, it will remain (r_i,T) smooth



Stop & go

- As long as each node can ensure local delay bound, end-to-end delay bound can be guaranteed
- Problem of coupling between delay bounds and bandwidth allocations granularity
  - Assume a fixed packet size P
  - Minimum bandwidth can be P/T
  - Delay bounded by two time frames T
  - Reducing T, reduced the delay but increases the minimum bandwidth
- Generalized stop&go with multiple frame sizes
  - Coupling still exist, but can have low delays for some flows and fine bandwidth granularity for other flows

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