



Scheduling and QoS scheduling

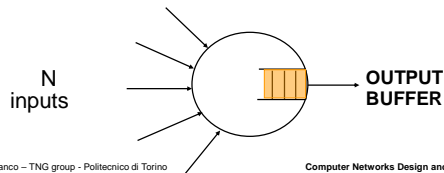
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Scheduling algorithms

- 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



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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

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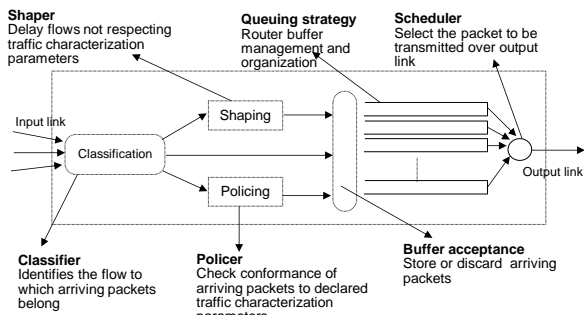
QoS scheduling algorithms

- 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 or 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

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QoS-capable router



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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

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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

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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

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Work conserving versus non-work conserving schedulers

- Work-conserving schedulers disadvantage
 - Multiplexing point increase traffic burstiness
 - This increase packet jitter and buffering requirements 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

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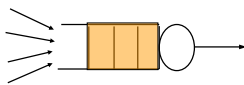
Scheduling algorithms goals

- 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)

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FIFO

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



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FIFO: properties

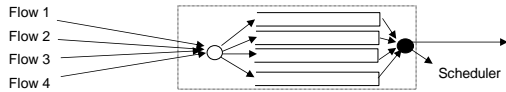
- Work-conserving
- Complete sharing of link bit rate and buffer space: no protection against non conformant flows
- All flows observe similar delay performance
 - Suited to best-effort traffic
- Neither bit rate (bandwidth) guarantees nor loss guarantees
 - Performance depend on the amount of ingress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

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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

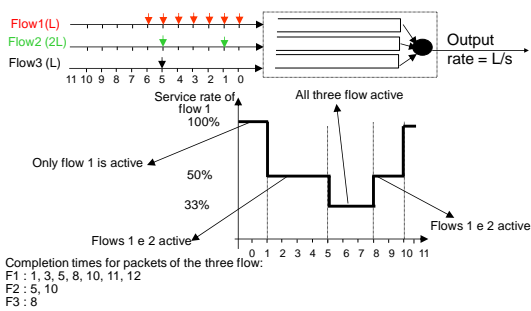
$$rate[j] = \frac{rate_{link}}{\#activeflows}$$



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Processor Sharing: example



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Processor Sharing

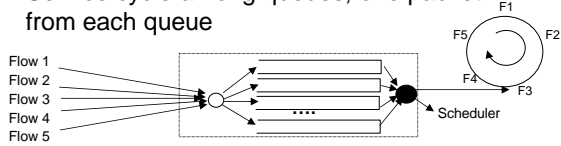
- Pros
 - If no data are discarded, a network of PS schedulers provides rates close to a max-min fair allocation
 - Rate of the max-min allocation only downstream from the bottleneck link
 - Fairness does not require congestion control mechanisms
 - If dropping packets, fair dropping must be ensured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

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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



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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

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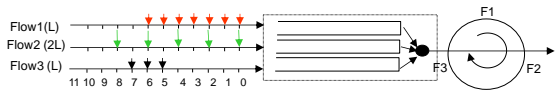
Round Robin: properties

- 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

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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

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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

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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;
    }
  }
}

```

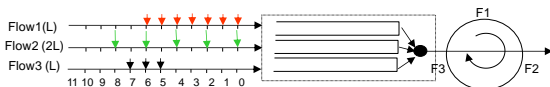
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Deficit Round Robin

- 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	0	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

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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

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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

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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 $([0,D_{max}])$
- Ideal scheduler, practical approximations needed

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GPS approximation

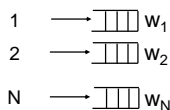
- Frame-based
 - Define a service cycle (frame)
 - Allocate frame portion to each flow
 - Example: WRR (Weighted-Round Robin), WDRR (Weighted Deficit Round Robin)
- Sorted priority
 - Compute a timestamp (tag) and associate it with each packet
 - Packets are ordered for increasing timestamp
 - Examples: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

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WRR: Weighted Round Robin

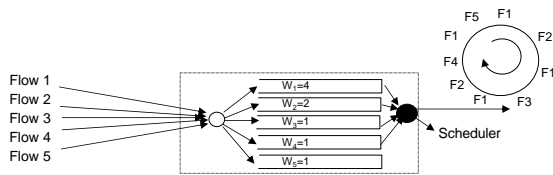
- GPS approximation
- Buffer partitioned in N queues
 - each queue served according to a FIFO discipline
- A weight $w_i \propto$ requested bit rate is associated with each queue
- A service cycle among queues is executed, each queue being served proportionally to its weight, i.e., w_i per cycle
- Cycle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



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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

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WRR: properties

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

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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 bytes) 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)

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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

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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 :

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

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Virtual Clock scheduling

Example

	0	1	2	3	4	5	6	7	8	9
$r_1=1/3$	□ 3	□ 6	□ 9	□ 12	□ 15	□ 18				
$r_2=1/3$	○ 3	○ 6	○ 9	○ 12	○ 15	○ 18				
$r_3=1/3$	△ 3			△ 6			△ 9			△ 12

Service order: □ 3 ○ 3 △ 3 □ 6 ○ 6 △ 6 □ 9 ○ 9 △ 9

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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

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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

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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

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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

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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

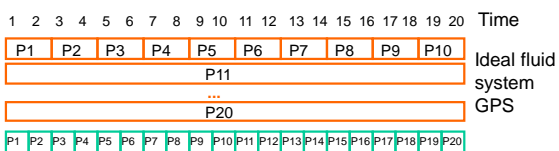
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WFQ or PGPS

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



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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

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WFQ or PGPS

- Tag computation:

$$F_j^k = \max \{ F_j^{k-1}, V(a_j^k) \} + \frac{L_j^k}{\phi_j}$$
- $V(t)$ is the system virtual time or system potential (k active flows):

$$V(0) = 0$$

$$\frac{\partial V}{\partial \tau} = \frac{1}{\sum_k \phi_k}$$

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

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WFQ

Virtual Time	0	1.5	3	4.5	6	7.5	9	10.5	12	13.5	15	16.5	18	19
Real 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	42
$r_2=1/3$	○	○	○	○	○	○	○	○	○	○	○	○	○	○
	3	6	9	12	15	18	21	24	27	30	33	36	39	42
$r_3=1/3$													△	△
													21	24
	□	○	□	○	□	○	□	○	□	○	□	○	□	○
	3	3	6	6	9	9	12	12	15	15	18	18	21	21
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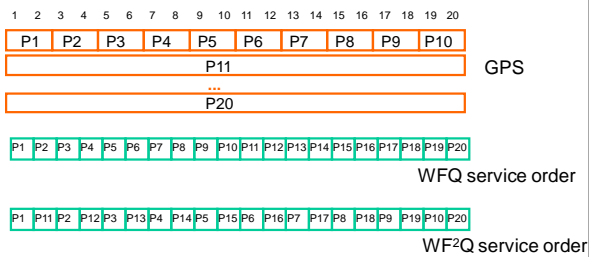
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WFQ o PGPS

- 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
 - WF²Q
 - 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 WF²Q



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

P1	P2	P3	P4	P5	P6	P7	P8	P9	P10
P11									
...									
P20									

GPS

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
P1	P11	P2	P12	P3	P13	P4	P14	P5	P15	P6	P16	P7	P17	P8	P18	P9	P19	P10	P20

WFQ

2	20	20	20	20	20	20	20	20	22	24	26	28	30	32	34	36	38		
P1	P11	P12	P13	P14	P15	P16	P17	P18	P19	P20	P2	P3	P4	P5	P6	P7	P8	P9	P10

SCFQ

Virtual time

Virtual time

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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 $\frac{B}{R}$
 - WFQ / PGPS $\frac{B + n \cdot P_{\max}}{R} + \sum_{i=1}^n \frac{P_{\max}}{C_i}$
 - Virtual Clock $\frac{B + n \cdot P_{\max}}{R} + \sum_{i=1}^n \frac{P_{\max}}{C_i}$
 - SCFQ $\frac{B + n \cdot P_{\max}}{R} + \sum_{i=1}^n \frac{k_i \cdot P_{\max}}{C_i}$
- Bandwidth delay coupling

C_i : output rate of i -th switch
 k_i : number of flows
 P_{\max} : maximum packet size

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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

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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, $\text{deadline} = \text{expected arrival time} + \text{delay bound}$)
 - 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)

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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

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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

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

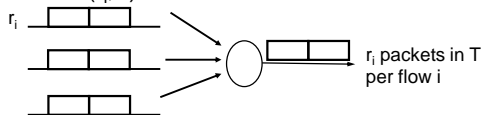
- Framing strategy
 - Time axis divided into frames of length T
- At each switch, the arriving frame of each incoming link is mapped to the departing frame of the output link by a constant delay smaller than T
- Transmission of packets arriving on any link during a frame are postponed to the beginning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

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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



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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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