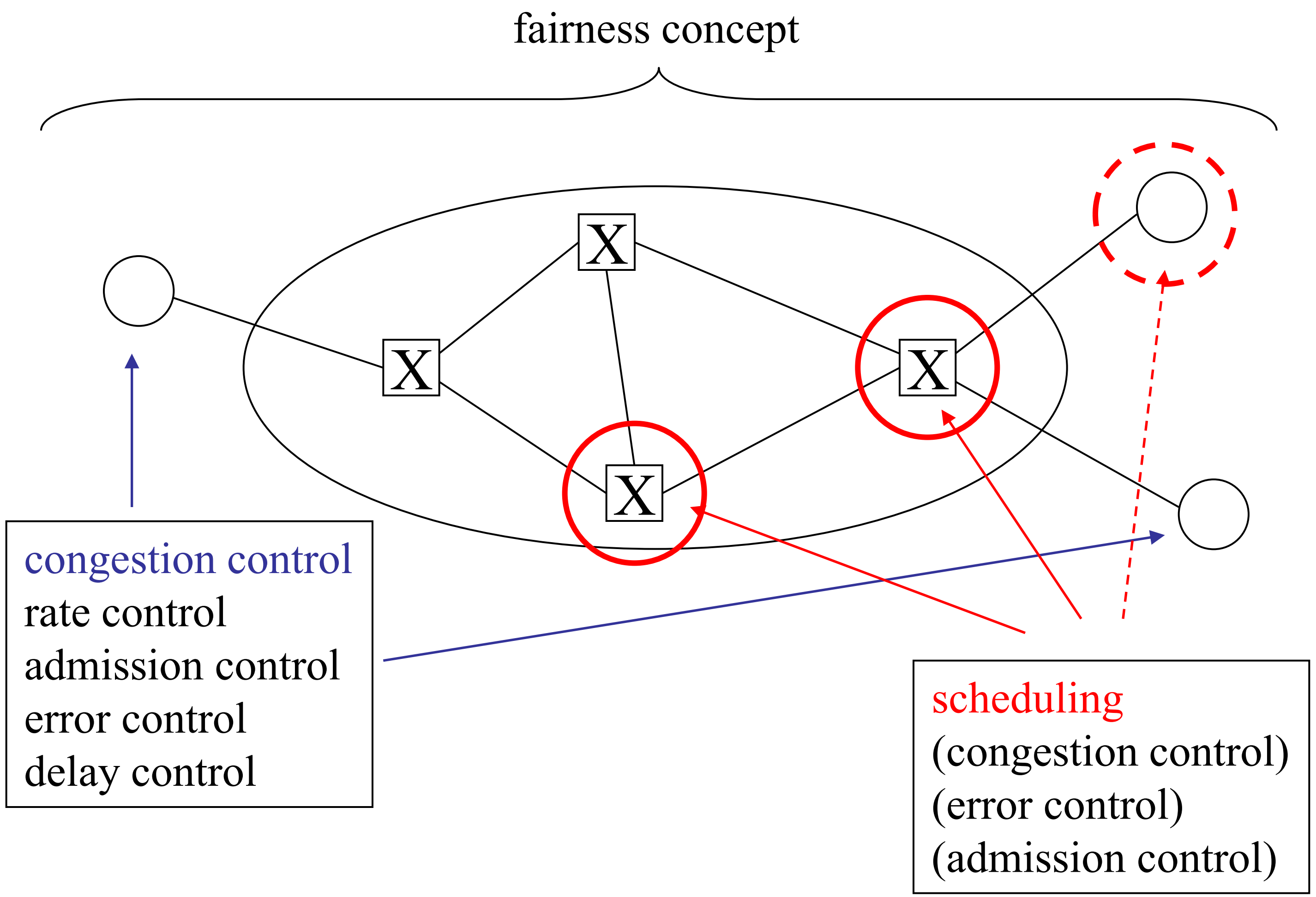
EP2210
Scheduling

- Lecture material:
  - Bertsekas, Gallager, 6.1.2.
  - MIT OpenCourseWare, 6.829
  - A. Parekh, R. Gallager, “A generalized Processor Sharing Approach to Flow Control - The Single Node Case,” IEEE Infocom 1992

Scheduling



fairness concept
X
X
X
X
congestion control
rate control
admission control
error control
delay control
scheduling
(congestion control)
(error control)
(admission control)

Scheduling - Problem definition

- Scheduling happens at the routers (switches) – or at user nodes if there are many simultaneous connections
  - many flows transmitted simultaneously at an output link
  - packets waiting for transmission are buffered
- Question: which packet to send, and when?

- Simplest case: FIFO
  - packets of all flows stored in the same buffer in arrival order
  - first packet in the buffer transmitted when the previous transmission is complete
  - packet transmission in the order of packet arrival
  - packet arriving when buffer is full dropped

- Complex cases: separate queues for flows (or set of flows)
  - one of the first packets in the queues transmitted
  - according to some policy
  - needs separate queues and policy specific variable for each flow
    - PER FLOW STATE

Scheduling - Requirements

- Fair bandwidth allocation
  - for elastic (or best effort) traffic
  - all competing flows receive the some “fair” amount of resources
- Provide performance guarantees for flows or aggregates
  - service provisioning in the Internet (guaranteed service per flow)
  - guaranteed bandwidth for SLA, MPLS, VPN (guaranteed service for aggregates)
  - integrated services in mobile networks (UMTS, 4G)
- Performance guarantees
  - throughput, delay, delay variation, packet loss probability
  - performance guarantees should be de-coupled
    (coupled e.g., high throughput -> low delay variation)
- Easy implementation
  - has to operate on a per packet basis at high speed routers

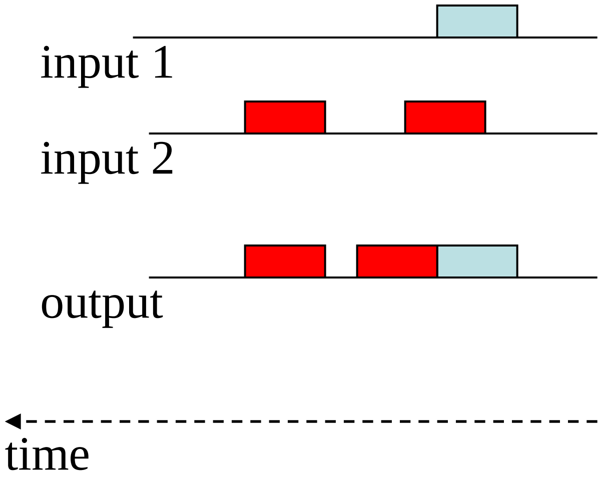
Scheduling – Implementation issues

- Scheduling discipline has to make a decision before each packet transmission – every few microseconds
- Decision complexity should increase slower then linearly with the number of flows scheduled
  - e.g., complexity of FIFO is 1
  - scheduling where all flows have to be compared scales linearly
- Information to be stored and managed should scale with the number of flows
  - e.g., with per flow state requirement it scales linearly (e.g., queue length or packet arrival time)

- Scheduling disciplines make different trade-off among the requirements on fairness, performance provisioning and complexity
  - e.g., FIFO has low complexity, but can not provide fair bandwidth share for flows

Scheduling classes

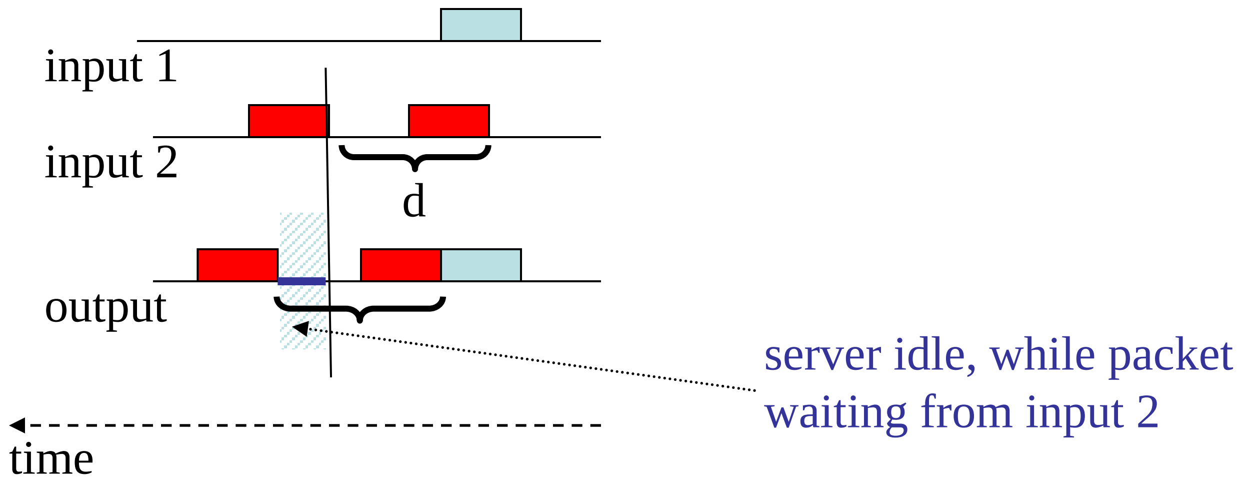
- Work-conserving
  - server (output link) is never idle when there is packet waiting



  - utilizes output bandwidth efficiently
  - burstiness of flows may increase → loss probability at the network nodes on the transmission path increases
  - latency variations at each switch → may disturb delay sensitive traffic

Scheduling classes

- Nonwork-conserving
  - add rate control for each flow
  - each packet assigned an eligibility time when it can be transmitted
    - e.g, based on minimum *d* gap between packets
  - server can be idle if no packet is eligible



  - burstiness and delay variations are controlled
  - some bandwidth is lost
  - can be useful for transmission with service guarantees.

Scheduling for fairness

- The goal is to share the bandwidth among the flows in a “fair” way
  - fairness can be defined a number of ways (see lectures later)
  - here fairness is considered for one single link, not for the whole transmission path

- Max-min fairness
  - *Maximize* the *minimum* bandwidth provided to any flow not receiving all bandwidth it requests
  - E.g.: no maximum requirement, single node – the flows should receive the same bandwidth
  - Specific cases: weighted flows and maximum requirements

Max-min fairness

- *Maximize* the *minimum* bandwidth provided to any flow not receiving all bandwidth it requests

C: link capacity

B(t): set of flows with data to transmit at time t
(backlogged (saturated) flows)

n(t): number of backlogged flows at time t

$C_i(t)$: bandwidth received by flow i at time t

Case: without weights or max. requirements

$$C_i(t) = \frac{C}{n(t)}$$

Case: weights

w_i: relative weight of flow i

$$C_i(t) = \frac{w_i}{\sum_{j \in B(t)} w_j} C$$

Case: max. requirements

r_i: max. bandwidth requirement for flow i

$\alpha(t)$: fair share at time t

$$C_i(t) = \min(r_{i,} \alpha(t))$$

$$\alpha(t): \quad \sum_{j \in B(t)} \min(r_j, \alpha(t)) = C$$

Max-min fairness

C: link capacity

B(t): set of backlogged flows at time t

C_i(t): bandwidth received by flow i at time t

Case: weights

w_i: relative weight of flow I

$$C_i(t) = \frac{w_i}{\sum_{j \in B(t)} w_j} C$$

Case: max. requirements

r_i: max. bandwidth requirement for flow I

α(t): fair share at time t

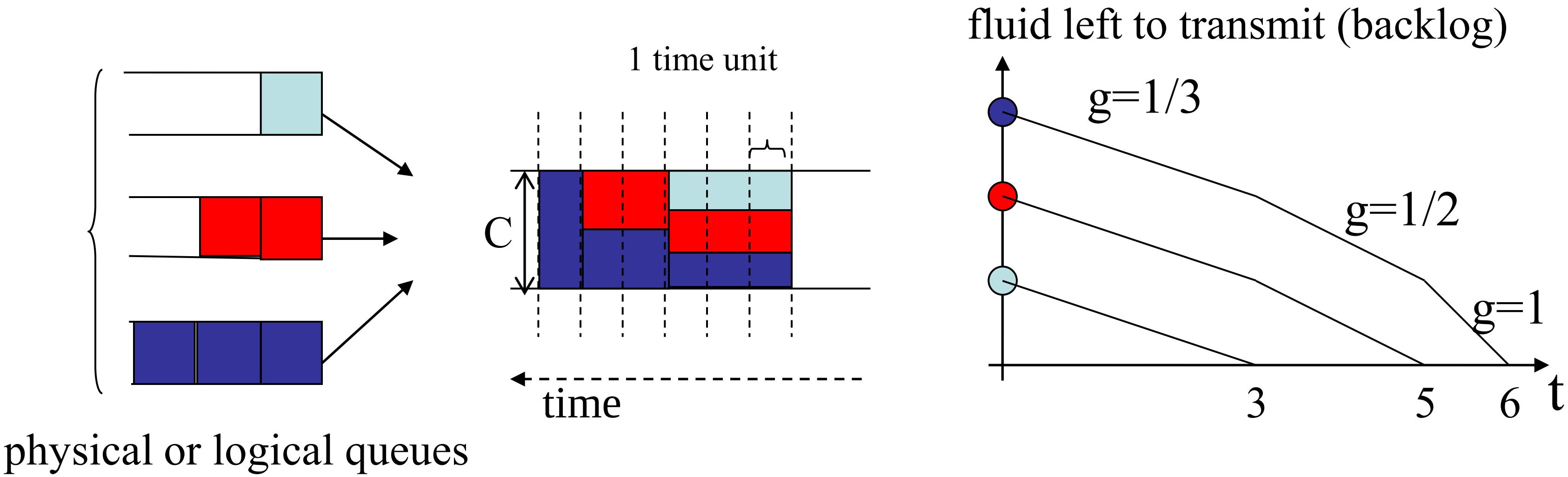
$$C_i(t) = \min(r_{i,} \alpha(t))$$

$$\alpha(t): \quad \sum_{j \in B(t)} \min(r_j, \alpha(t)) = C$$

- Calculate fair shares:
  - 3 backlogged (saturated) flows, equal weights, link capacity 10.
  - 3 backlogged flows, weights 1,2,2 link capacity 10
  - 4 backlogged flows, max requirements: 2, 3, 4, 5, link capacity 11.
  - 3 backlogged flows, rate requirements: 2,4,5, the link capacity is 11. What are the fair shares now?

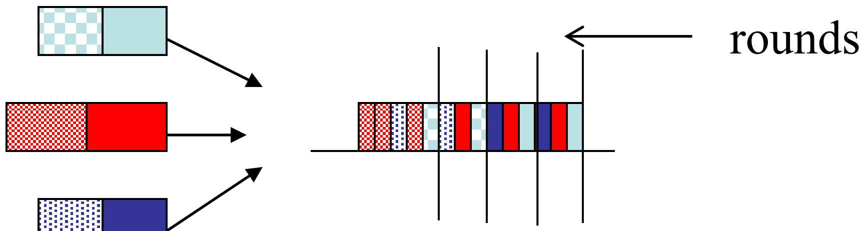
Fair queuing-for max-min fairness

- Fluid approximation
  - fluid fair queuing (FFQ) or generalized processor sharing (GPS)
  - idealized policy to split bandwidth
  - assumption: dedicated buffer per flow
  - assumption: flows from backlogged queues served simultaneously (like fluid)
  - not implementable, used to evaluate real approaches
  - used for performance analysis if per packet performance is not interesting

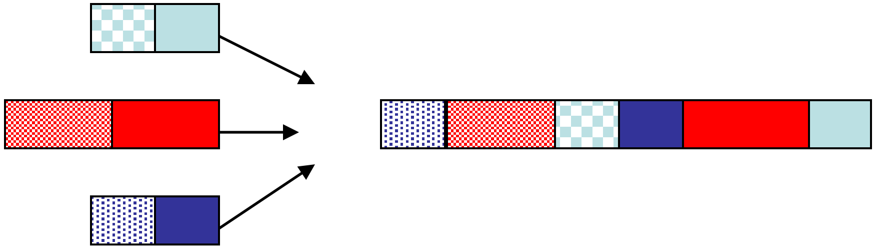


Packet-level Fair queuing

- How to realize GPS/FFQ?
- Bit-by-bit fair queuing
  - one bit from each backlogged queue in rounds (round robin) – still not possible to implement



- Packet-level fair queuing
  - one packet from each backlogged queue in rounds ???

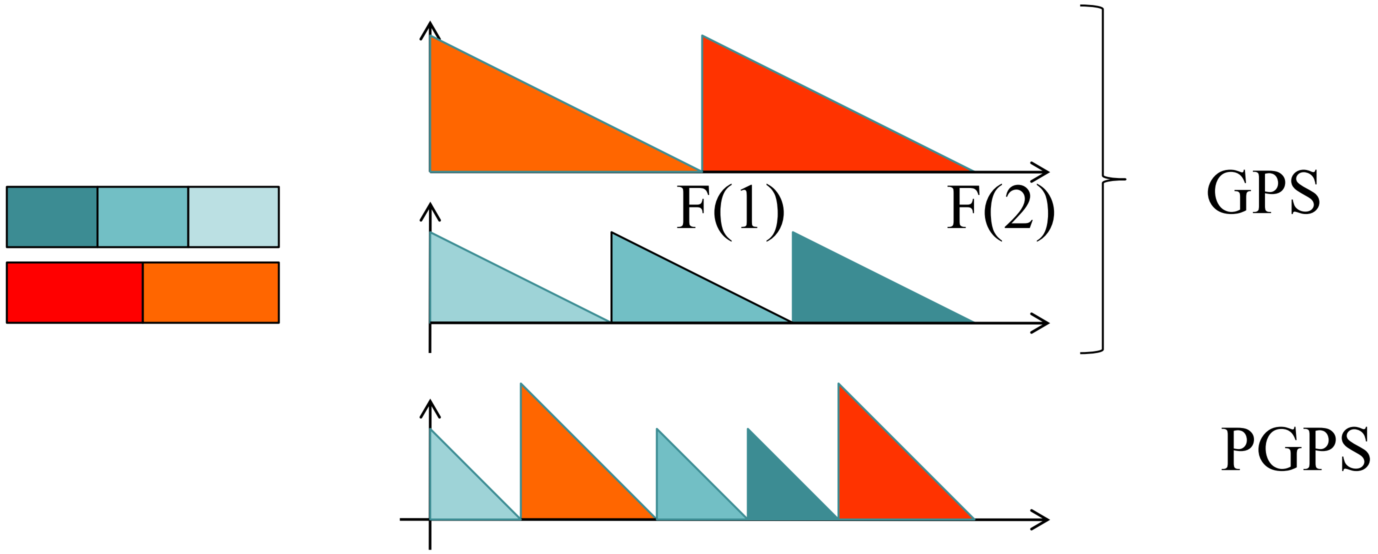


Flows with large packets get more bandwidth!

More sophisticated schemes required!

Packetized GPS (PGPS)

- How to realize GPS/FFQ?
- Try to mimic GPS
- Transmit packets that would arrive earliest with GPS
  - Finishing time (F(p))
- Quantify the difference between GPS and PGPS



Fair queuing – group work

- Packet-by-packet GPS (PGPS)
- Compare GPS (fluid) and PGPS (packetized) in the following scenarios – draw diagrams "backlogged traffic per flow vs. time".
- Consider one packet in each queue. C=1 unit/sec

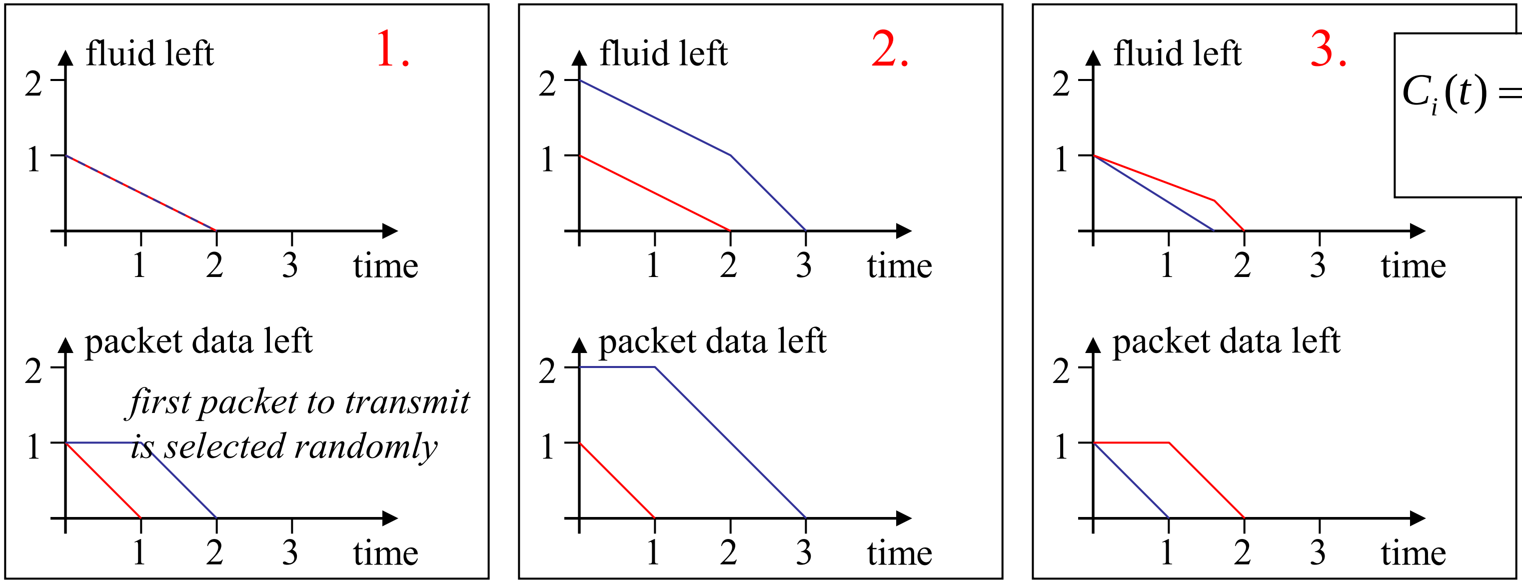
1. Two flows, equal size packets, same weight, L1=L2=1 unit
2. Two flows, different size packets, same weight L1=1, L2=2 units
3. Two flows, same packet size, different weight, L1=L2=1 unit, w1=1, w2=2

$$C_i(t) = \frac{w_i}{\sum_{j \in B(t)} w_j} C$$

Fair queuing – group work

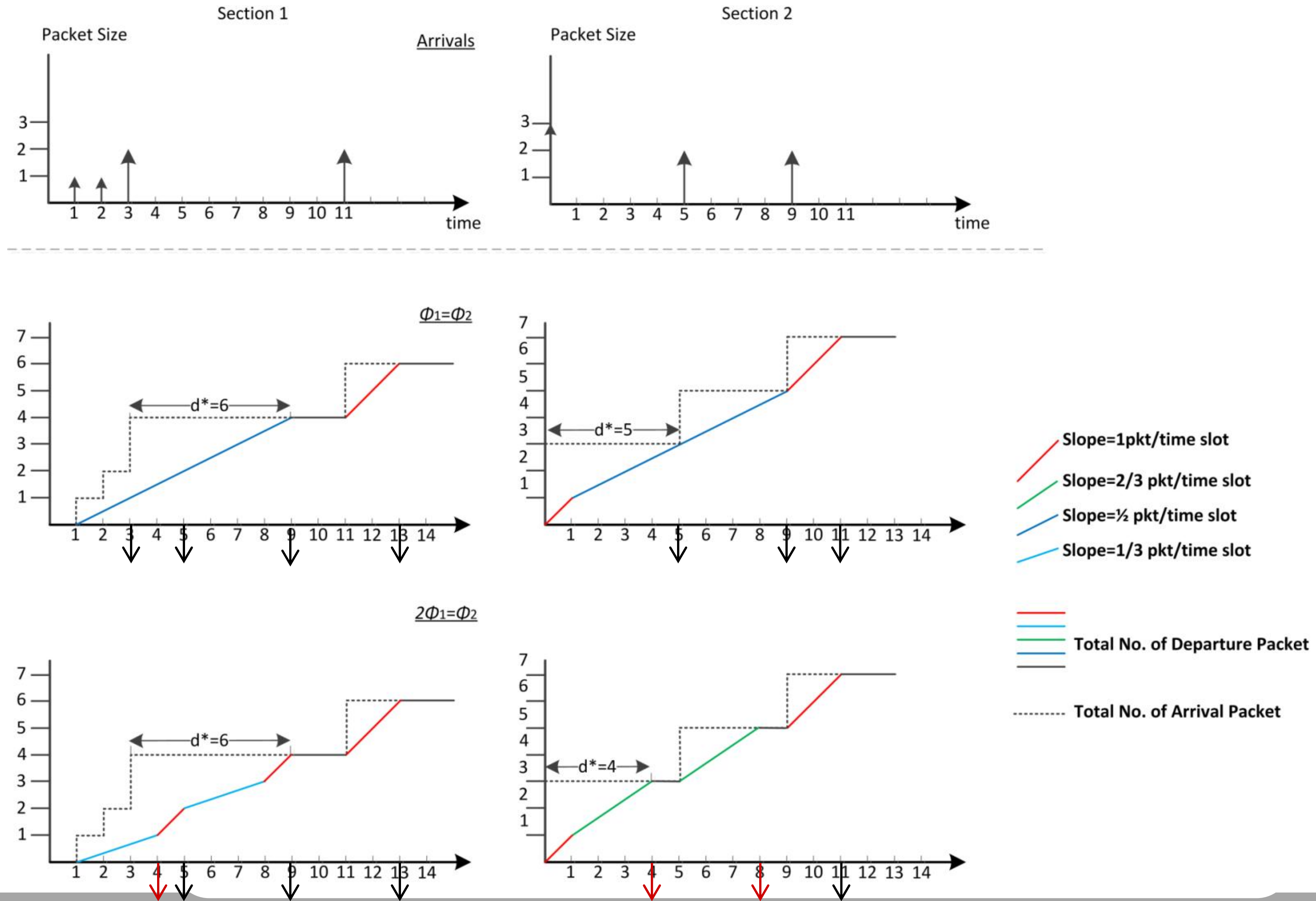
- Compare GPS (fluid) and PGPS (packetized) in the following scenarios – draw diagrams "backlogged traffic per flow vs. time".
- Consider one packet in each queue. C=1 unit/sec

1. Two flows, equal size packets, same weight, L1=L2=1 unit
2. Two flows, different size packets, same weight L1=1, L2=2 units
3. Two flows, same packet size, different weight, L1=L2=1 unit, w1=1, w2=2

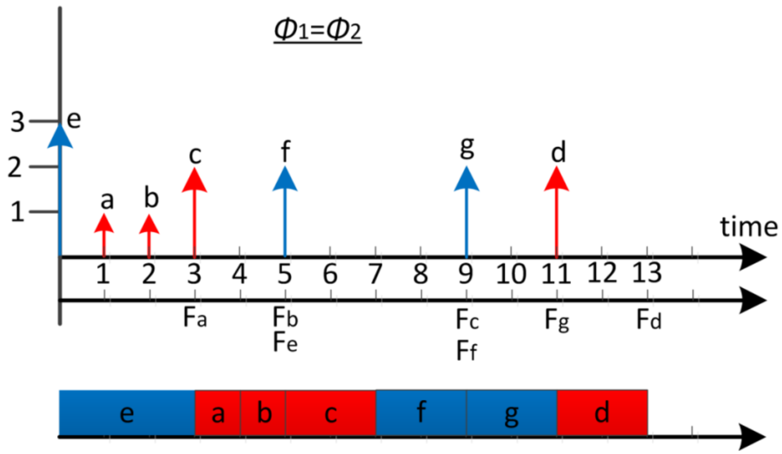


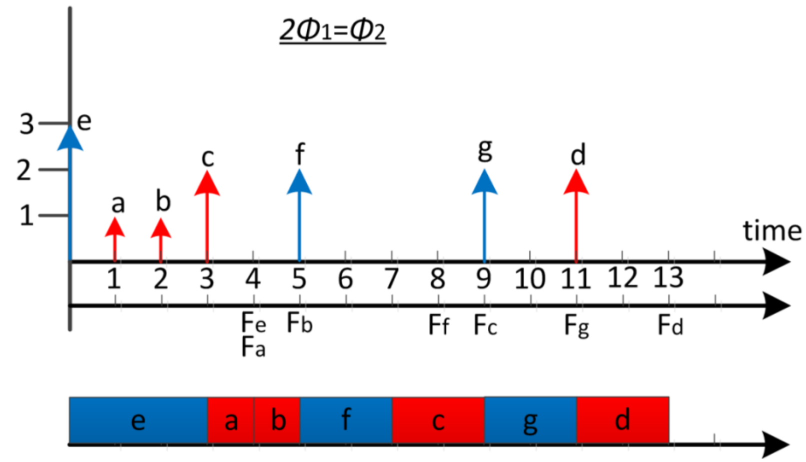
$$C_i(t) = \frac{w_i}{\sum_{j \in B(t)} w_j} C$$

GPS vs. PGPS dynamic packet arrival



GPS vs. PGPS main results





		Section 1				Section 2		
Pkt. Info	Arrival	1	2	3	11	0	5	9
	Size	1	1	2	2	3	2	2
	Label	a	b	c	d	e	f	g
$\phi_1 = \phi_2$	GPS	3	5	9	13	5	9	11
	PGPS	4	5	7	13	3	9	11
$2\phi_1 = \phi_2$	GPS	4	5	9	13	4	8	11
	PGPS	4	5	9	13	3	7	11

GPS vs. PGPS main results

- Only packets that arrive “too late” to be scheduled in the GPS order are delayed more in PGPS than is GPS.
- Theorem 1: $F^*(p)-F(p) \le L(max)/r$
  - $F^*(p)$, $F(p)$: finishing time under PGPS and GPS
- Theorem 2: $S(0,t)-S^*(0,t) \le L(max)$
  - $S(0,t)$, $S^*(0,t)$: amount of traffic transmitted under GPS and PGPS
- Theorem 3: $Q^*(t)-Q(t) \le L(max)$
  - $Q(t)$, $Q^*(t)$: amount of traffic still in the queue in GPS and PGPS

GPS vs. PGPS main results

- Packet-by-packet GPS (PGPS)
  - transmit packet from buffers with earliest GPS finishing time.

- Question 1: how much later can a packet be “finished” in PGPS compared to GPS (reason, not in buffer at time of decision).

- Lemma 1: consider p and p´ in buffer at time t, p completing service before p´ - then the same happens under all future arrival pattern (since future arrivals delay the service of p and p´ the same way.
- Theorem 1: F*(p)-F(p)<=L(max)/r
  - F*(p), F(p): finishing time under PGPS and GPS

GPS vs. PGPS main results

- Theorem 1: F*(p)-F(p)<=L(max)/r
  - F*(p), F(p): finishing time under PGPS and GPS
- Proof

$$t_k \le u_k + \frac{L_{\max}}{r}$$

finishing GPS

finishing PGPS

  - consider a busy period
  - consider the last packet *m* that arrives before but leaves after packet *k* under GPS $u_m > u_k \ge u_i \quad \text{for} \quad m < i < k.$
    (packet *k* is scheduled after packet *m* in PGPS)
  - start service time for *m* in PGPS is before arrivals *m+1…k*

$$\min\{a_{m+1}, ..., a_k\} > t_m - \frac{L_m}{r}.$$

start service in PGPS

  - finish time of *k* in GPS is larger then the time of fluid service of *m+1…k* plus the earliest arrival time of *m+1*

$$u_k \ge \underbrace{\frac{1}{r}(L_k + L_{k-1} + L_{k-2} + \ldots + L_{m+1}) + t_m}_{t_k \text{ in PGPS}} - \frac{L_m}{r}$$

Scheduling summary

- Scheduling:
  - At the network nodes and at the edge
  - To provide quality guarantees or fairness
  - Work-conserving and non-work-conserving
- Max-min fairness in a single link, with weights and max. rate requirement
- GPS for max-min fairness in a fluid model
- PGPS (or WFQ) in the packetized version
  - Schedule according to finish time in GPS
  - Guaranteed performance compared to GPS
- Next lecture: work-conserving and non-work-conserving scheduling

Reading assignment

- For the test and home assignment: A. Parekh, R. Gallager, “A Generalized Processor Sharing Approach to Flow Control - The Single Node Case,” IEEE Transaction on Networking, 1993, Vol.1, No.3.
  - Read I-III-before part A
- For next lecture: H. Zhang, “Service Disciplines for Guaranteed Performance Service in Packet-Switching Networks,” Proceedings of the IEEE, Oct, 1995, pp. 1374-1396
  - Read sections I and II,
  - Group 1: III.A,B,G (parts related to A,B)
  - Group 2: IV.A,B,D,G (parts related to A,B)
- Next lecture: group work in Groups 1 and 2, short presentation.
- Next lecture: project introduction

Reading assignment

- Groups:

1:

- Davood Babazdeh
- Mariana Montenegro
- Cyrille Laroche
- Majid Gerami

2:

- Wu Yiming
- Ali Zaidi
- Lukas Jornitz
- Boris Tamezanang Tekeusso
- Romain Lacam