Multi-Resource Generalized Processor Sharing for Packet Processing

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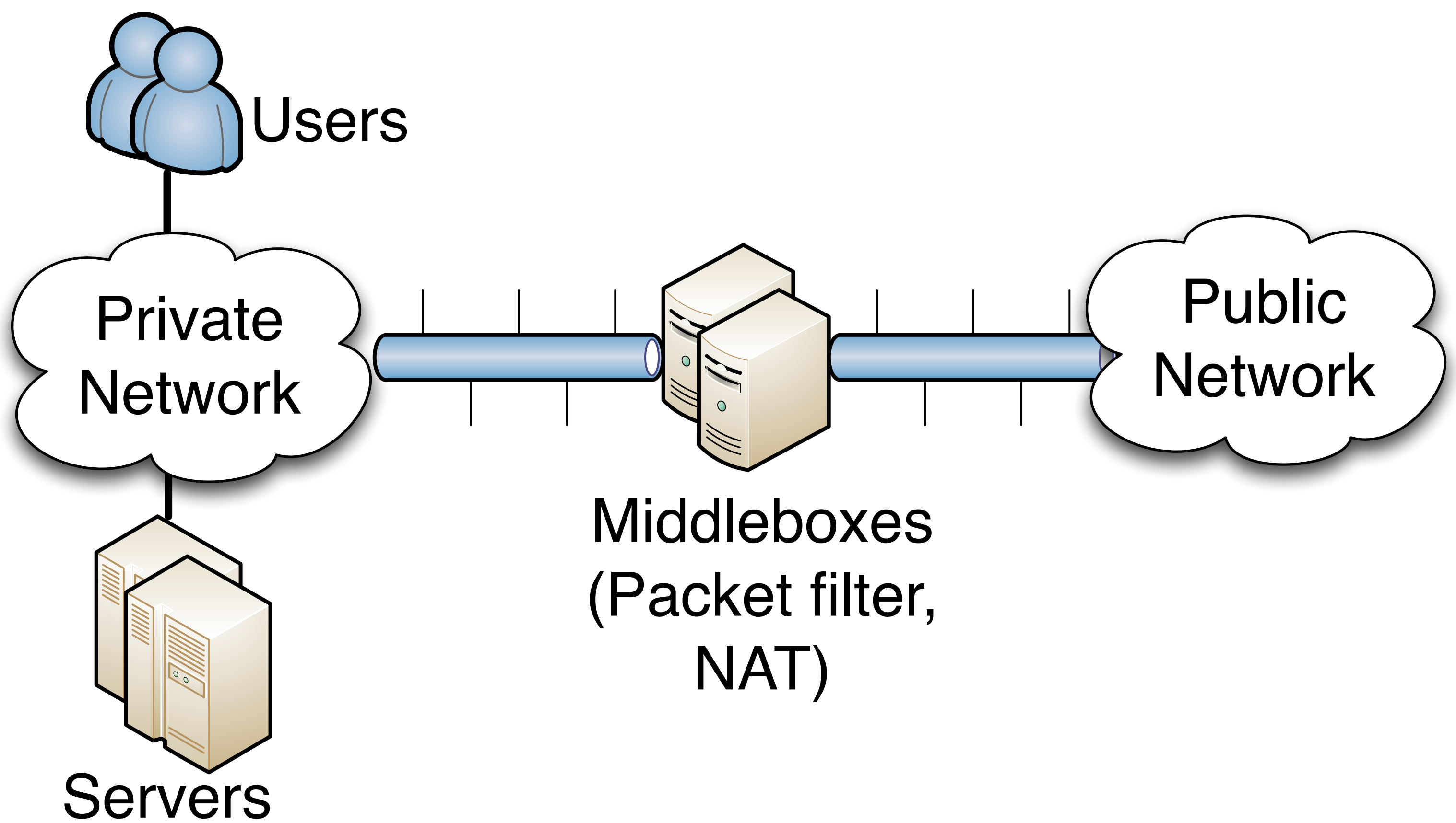
Background

Middleboxes (MBs) are ubiquitous in today's networks

The sheer number is on par with the L2/L3 infrastructures

Perform a wide range of critical network functionalities

WAN optimization, intrusion detection and prevention, etc.

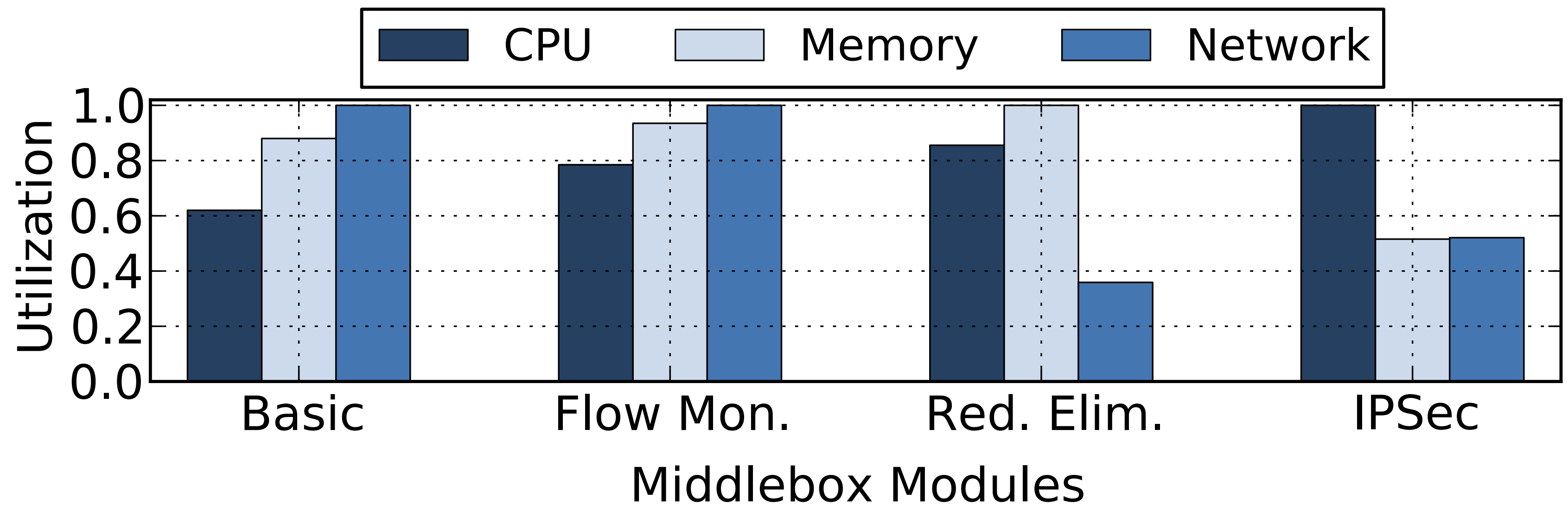


Multi-Resource Packet Processing in MBs

Performing different network functionalities requires different amounts of MB resources

Basic Forwarding: Bandwidth intensive

IP Security Encryption: CPU intensive



Ghodsi et al SIGCOMM12

How to let flows *fairly* share *multiple resources* for packet processing?

What do we mean by fairness?

Fair queueing can be defined via a set of highly desired scheduling properties

Predictable service isolation

For each backlogged flow, the received service is *at least* at the level when *every resource* is *equally* allocated (or in proportion to the flow's weight)

What do we mean by fairness? (Cont'd)

Service isolation cannot be compromised by some strategic behaviours

- A flow may cheat by asking for the amount of resources that are not needed
- E.g., asking for more bandwidth by adding dummy payload to inflate the packet size

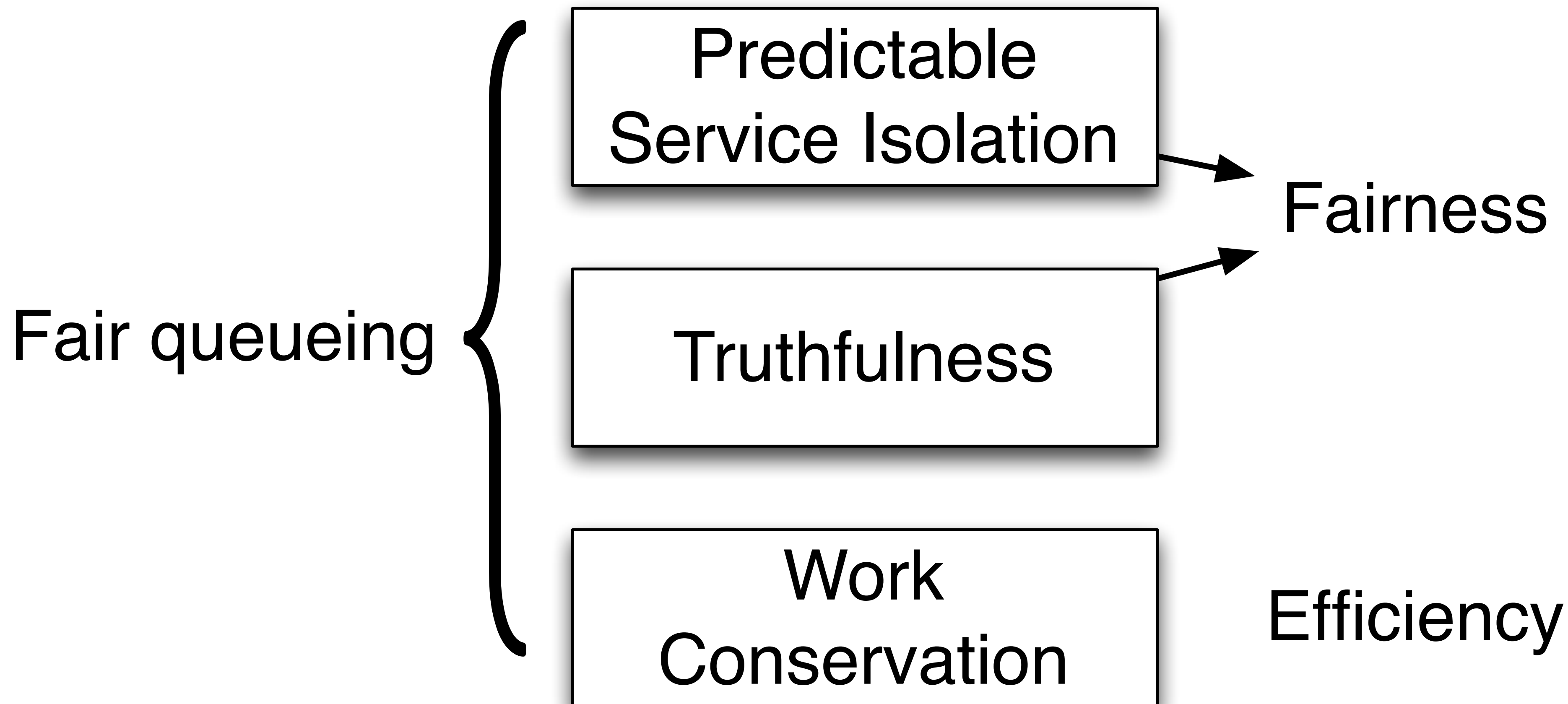
Truthfulness (Strategy-proofness)

- No flow can receive better service (*i.e.*, finish faster) by misreporting the amount of resources it requires

What do we mean by fairness? (Cont'd)

Work conservation

No resource that could be used to serve a busy flow is wasted in idle



Multi-Resource Fair Queueing

Simple fairness notion leads to unfairness in the multi-resource setting [Ghodsi12]

- Per-resource fairness
- Bottleneck fairness

A promising insight is suggested in [Ghodsi12]

- Dominant Resource Fairness (DRF)
- Flows should receive roughly the same service on their most congested resources (DRFQ)

Open Questions

Is there a general guideline to design multi-resource fair queueing?

What's the benchmark for multi-resource fair queueing?

- Any GPS-like fair queueing benchmark?

Can the techniques developed for the single-resource fair queueing be leveraged in the multi-resource setting?

Our Contribution

Dominant Resource GPS (DRGPS)

An *idealized fluid fair queueing benchmark* that achieves all desired scheduling properties

Clarify the design objective for practical queueing algorithms

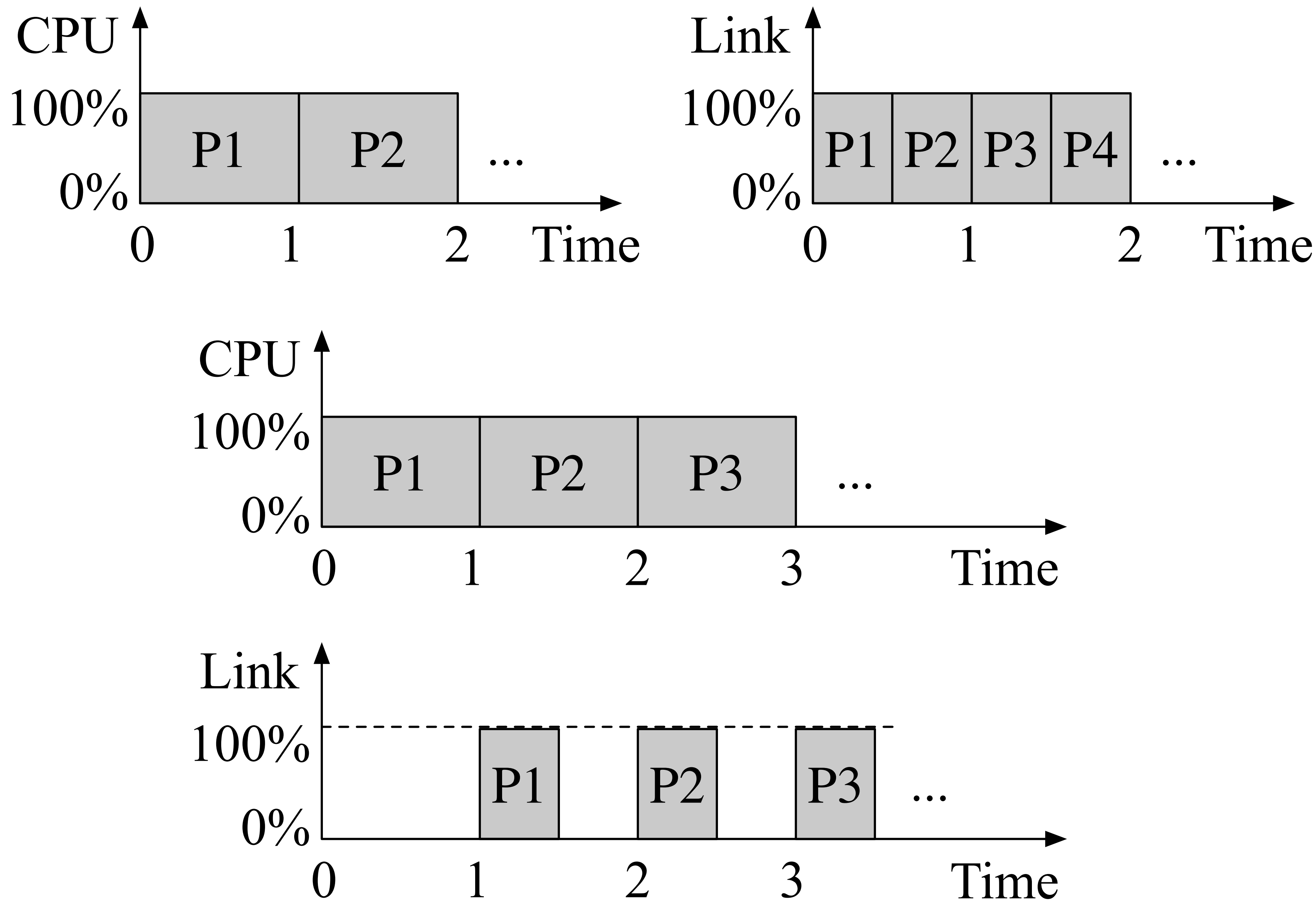
Techniques developed for single-resource fair queueing algorithms can be leveraged in the multi-resource setting

DRGPS

Resource Model

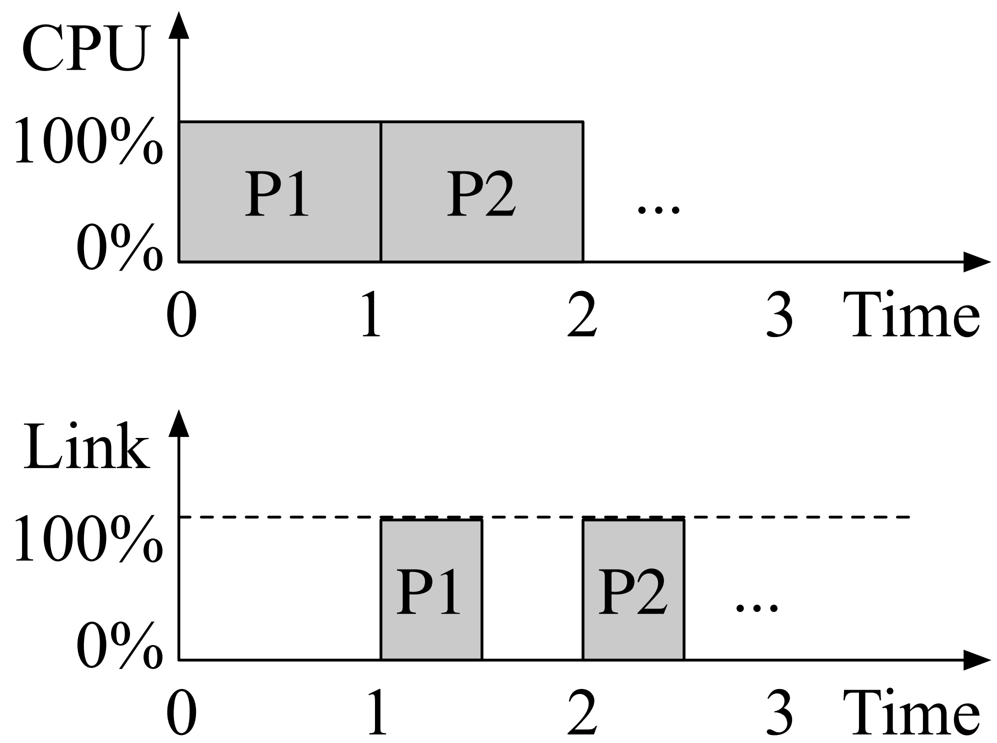
Resources are scheduled in serial for packet processing

E.g., CPU first, followed by the link bandwidth

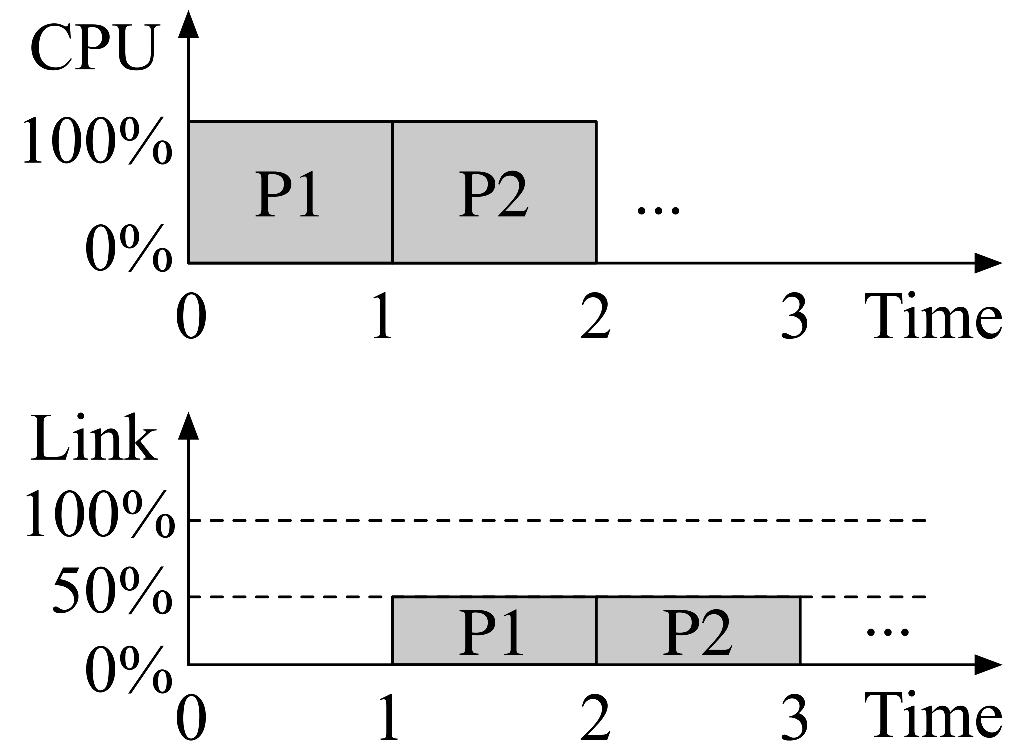


Multi-Resource Fluid Flow Model

Assume packets can be served in arbitrarily small increments on *every* resource



(a) ⟨100% CPU, 100% Link⟩.



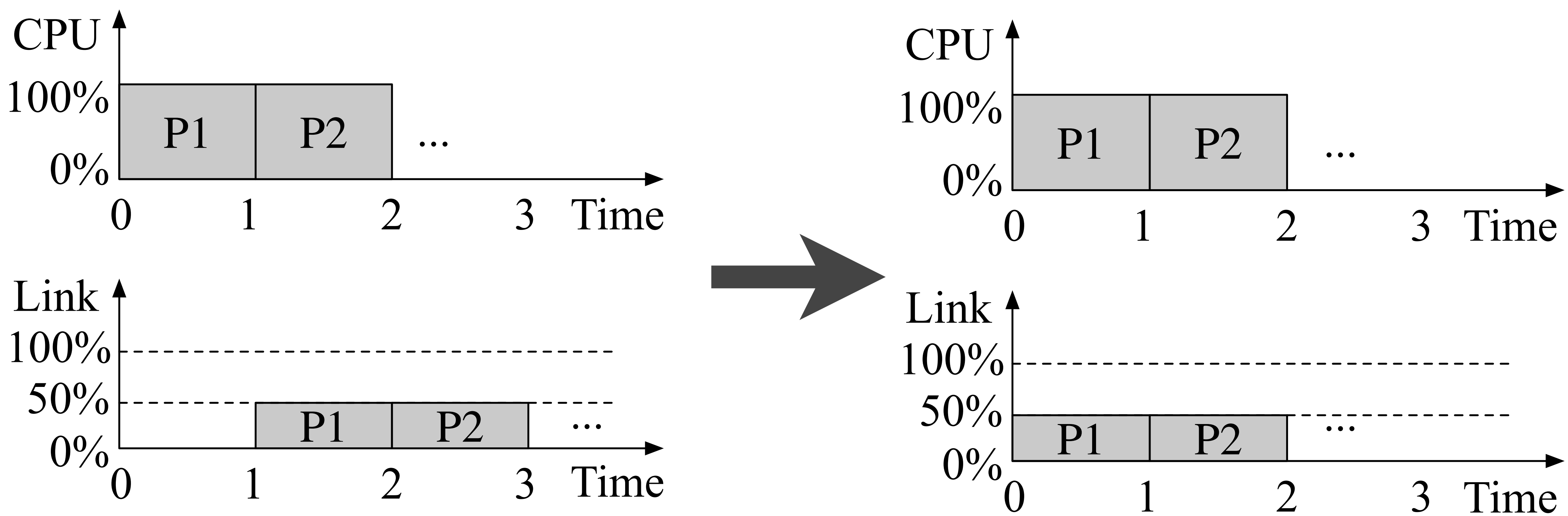
(b) ⟨100% CPU, 50% Link⟩.

50% link allocation is wasted

No resource allocation is wasted

Non-wasteful allocation

Under non-wasteful allocation, we can view that all resources are consumed simultaneously, at the same rate



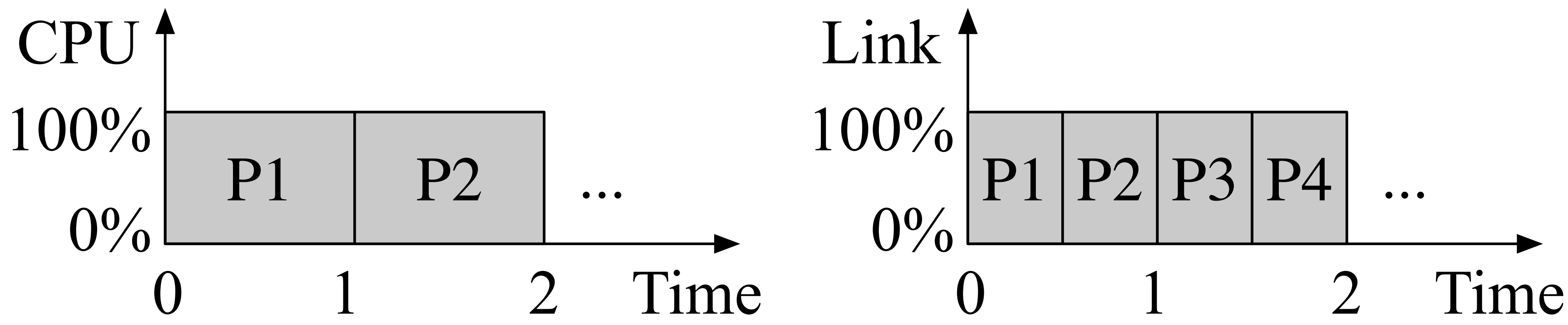
<100% CPU, 50% Link>

Dominant Resource & Dominant Share

For a packet, its *dominant resource* is the one that requires the most packet processing time

E.g., Packet P1 has <CPU time, Transmission Time> = <1, 0.5>

CPU is the dominant resource of P1



The *dominant share* is the fraction of dominant resource allocated to process the packet

E.g., <70% CPU, 60% Link> is allocated to process P1

The dominant share of P1 is 70%

DRGPS

Dominant Resource Fairness (DRF)

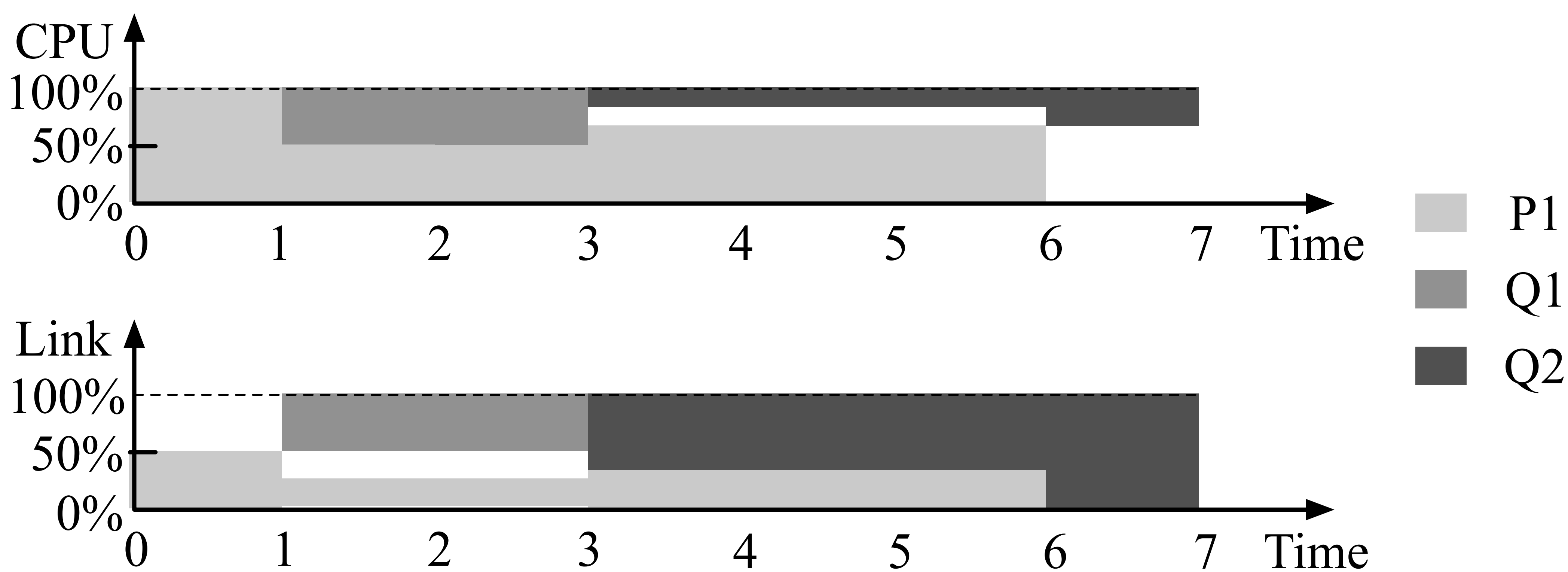
- At any given time, every backlogged flow is allocated the same dominant share
- Max-min fair on the dominant resource

DRGPS achieves the DRF allocation at all times!

DRGPS: An Example

TABLE I
RESOURCE PROFILES OF PACKETS IN TWO FLOWS.

Packet	**Flow**	**Arrival Time**	**$\langle$CPU, Link$\rangle$**
P1	Flow 1	0	$\langle 4, 2\rangle$
Q1	Flow 2	1	$\langle 1, 1\rangle$
Q2	Flow 2	2	$\langle 1, 3\rangle$



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Properties of DRGPS

DRGPS achieves all desired scheduling properties

- Predictable service isolation
- Truthfulness
- Work conservation

DRGPS therefore serves as an *idealized* fluid fair queueing benchmark in the multi-resource setting

- *Cannot* be implemented because packets are assumed to be infinitely divisible

Packet-Based Multi-Resource Fair Queueing

DRGPS offers a design guideline

Leverage the design techniques developed for the traditional single-resource fair queueing

- Schedule packets by emulating DRGPS
  - WFQ, WF^2Q, FQS can have direct extensions to multiple resources
- Approximate DRGPS without strict emulation
  - Estimate the work progress (virtual time) of DRGPS, e.g., SCFQ, SFQ, etc.
  - DRFQ [Ghodsi12] is a multi-resource SFQ extension
- Serve flows in a simple round-robin fashion
  - Deficit Round Robin (DRR), Smoothed Round Robin (SRR), Stratified Round Robin (StRR)

Schedule packets by emulating DRGPS

Emulating DRGPS in Real-Time

DRGPS can be accurately emulated by stamping two service tags upon packet arrival

Virtual time *v*(*t*)

- Tracks the work progress of DRGPS

Virtual starting time

- The virtual time when the packet arrives the system

Virtual finishing time

- The virtual time when packet finishes service under the DRGPS system

Emulating DRGPS in Real-Time (Cont'd)

Proposition 4: Under DRGPS, for every flow i, its virtual starting and finishing times satisfy the following relationship:

$$\begin{aligned} S_i^k &= \max\{F_i^{k-1}, v(a_i^k)\} , \\ F_i^k &= \tau_{i,r_i^{k*}}^k / w_i + S_i^k , \end{aligned} \tag{14}$$

where $F_i^0 = 0$ for all flow i.

Emulating DRGPS in Real-Time (Cont'd)

Upon a packet arrival, both the starting time and the finishing time are stamped to the packet

With the service tags, the scheduling results of DRGPS can be fully recovered

- Just like how GPS is emulated in the single-resource setting

Schedule Packets by Emulating DRGPS

A referencing DRGPS system is maintained in background

Many scheduling choices are available

- Packet that *finishes service the earliest* in the reference DRGPS system is scheduled first, e.g., WFQ, PGPS
- Packets that *starts service the earliest* in the reference DRGPS system is scheduled first, e.g., FQS
- Imposing some admission control policy, e.g., WF^2Q

A Case Study:
Dominant Resource WF^{2}Q

Dominant Resource WF²Q (DRWF²Q)

A referencing DRGPS system is maintained in background

Whenever there is a scheduling opportunity

- Packets that already started their service under the referencing DRGPS system are *eligible* for scheduling
- Among them, the one that finishes the earliest will be scheduled

A Running Example

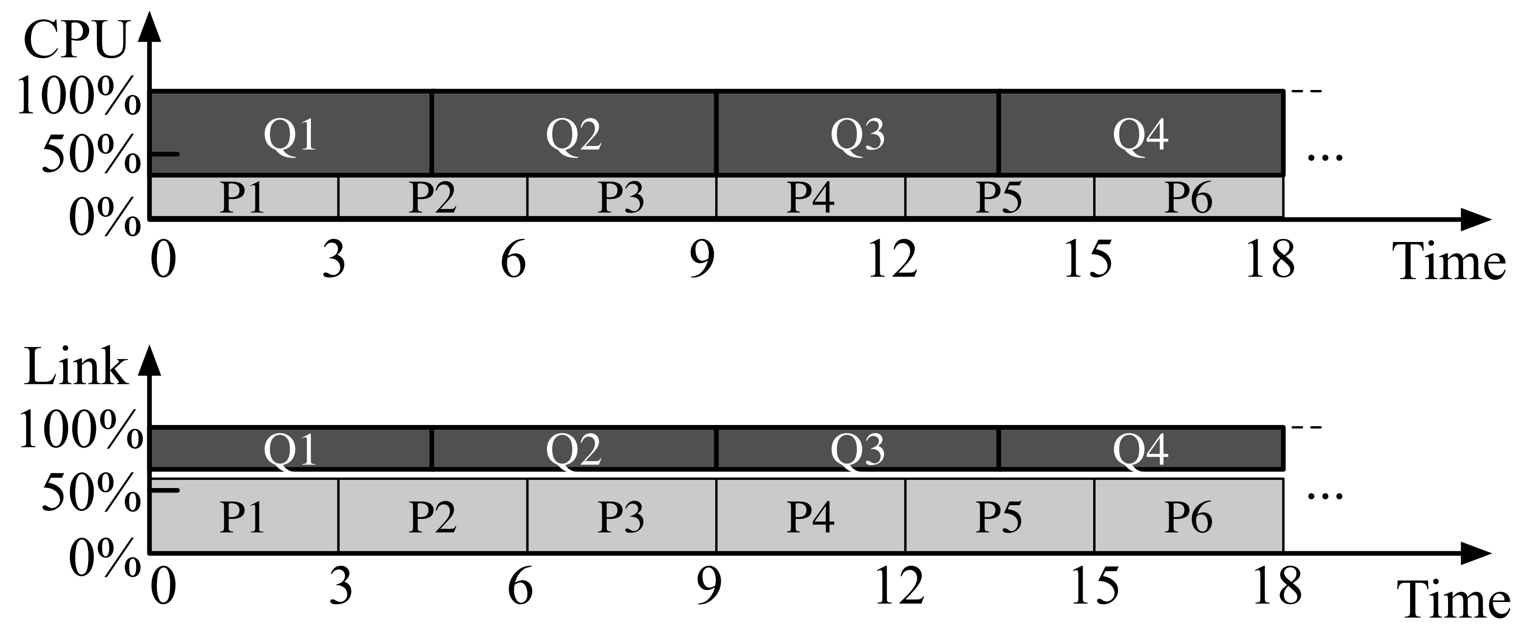
Flow 1 sends P1, P2, ...

Each packet requires <1 CPU time, 2 Transmission Time>

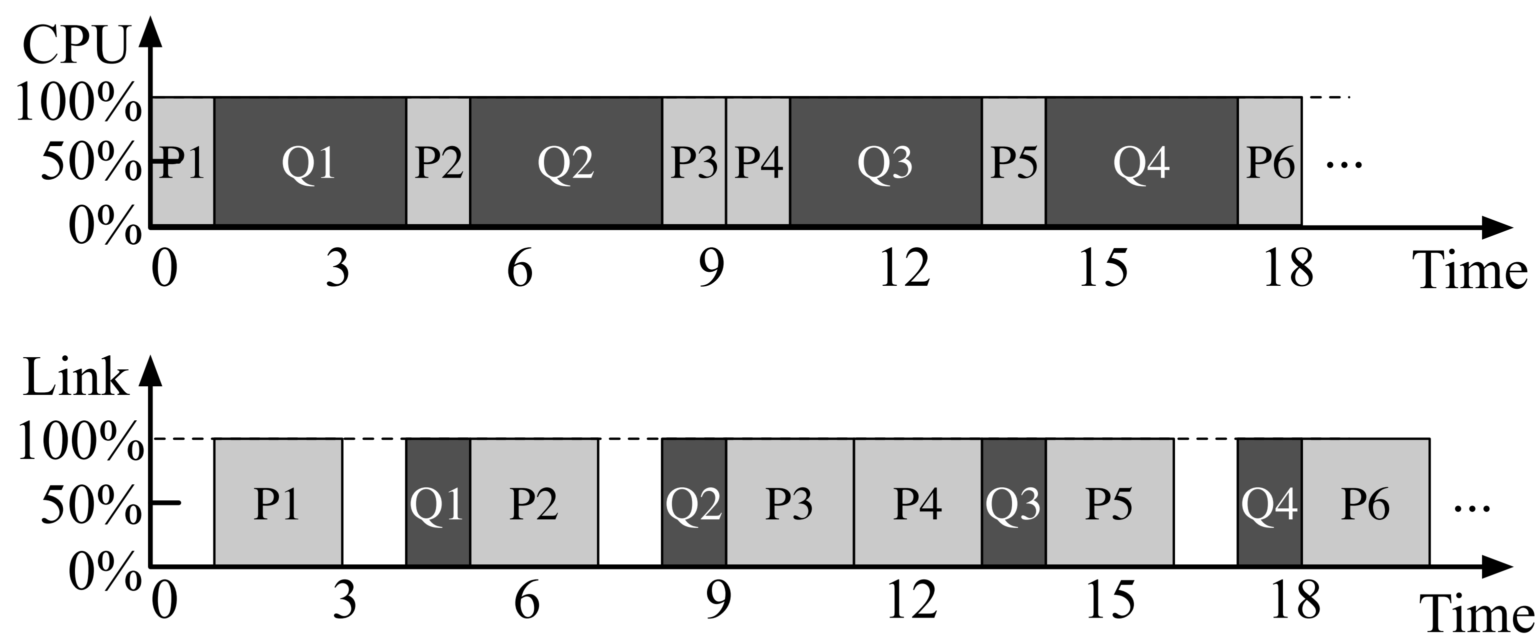
Flow 2 sends Q1, Q2, ...

Each packet requires <3 CPU time, 1 Transmission Time>

A Running Example



(a) Scheduling outcome under DRGPS.



(b) Scheduling outcome under DRWF^{2}Q.

Fairness Measure

Relative fairness bound (RFB)

$$R = \sup_{t_1, t_2; i, j \in \mathcal{B}(t_1, t_2)} \left| \frac{T_i(t_1, t_2)}{w_i} - \frac{T_j(t_1, t_2)}{w_j} \right| .$$

DRGPS has RFB = 0

Fairness of Dominant Resource WF^{2}Q (DRWF^{2}Q)

Proposition 6: Under DRWF^{2}Q, for any two flows i and j that are backlogged in (t_1, t_2), we have

$$\left| \frac{T_i(t_1,t_2)}{w_i} - \frac{T_j(t_1,t_2)}{w_j} \right| \leq 4 \max \left\{ \frac{\tau_i^{\max}}{w_i}, \frac{\tau_j^{\max}}{w_j} \right\}. \qquad (23)$$

Corollary 1 (RFB): The RFB of DRWF^{2}Q is

$$R = 4 \max_i \left\{ \frac{\tau_i^{\max}}{w_i} \right\} .$$

Conclusion

DRGPS generalizes GPS to the multi-resource setting in MBs

- Offers perfect service isolation that is immune to any strategic behaviours and is work conserving as well
- Serves as a perfect multi-resource fair queueing benchmark to which all practical alternatives should approximate

With DRGPS, techniques developed for traditional fair queueing can be leveraged to the multi-resource setting

We design DRWF^{2}Q as a case study and analyze its fairness performance

Thanks!

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