On the Fairness-Efficiency Tradeoff for Packet Processing with Multiple Resources

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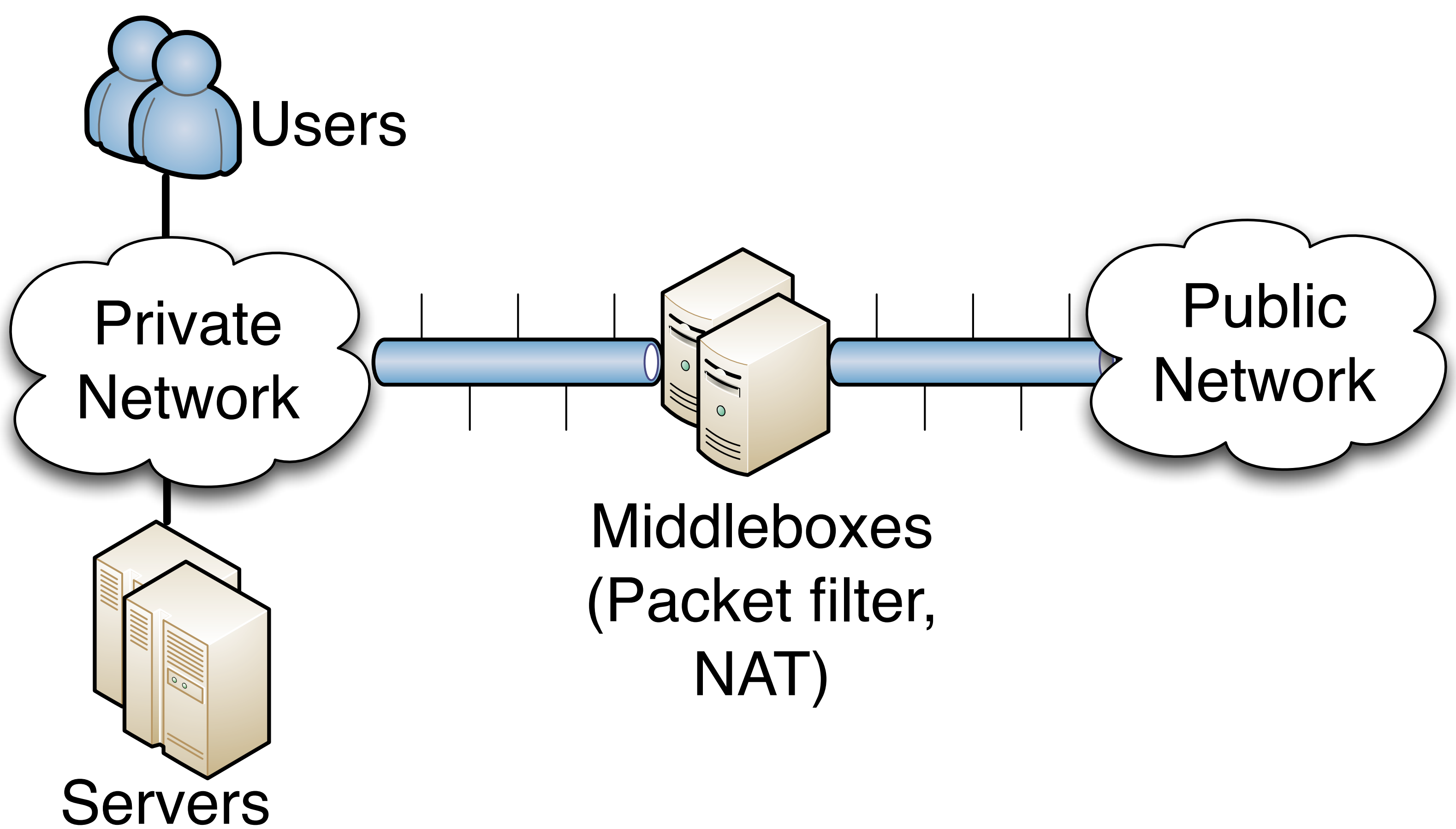
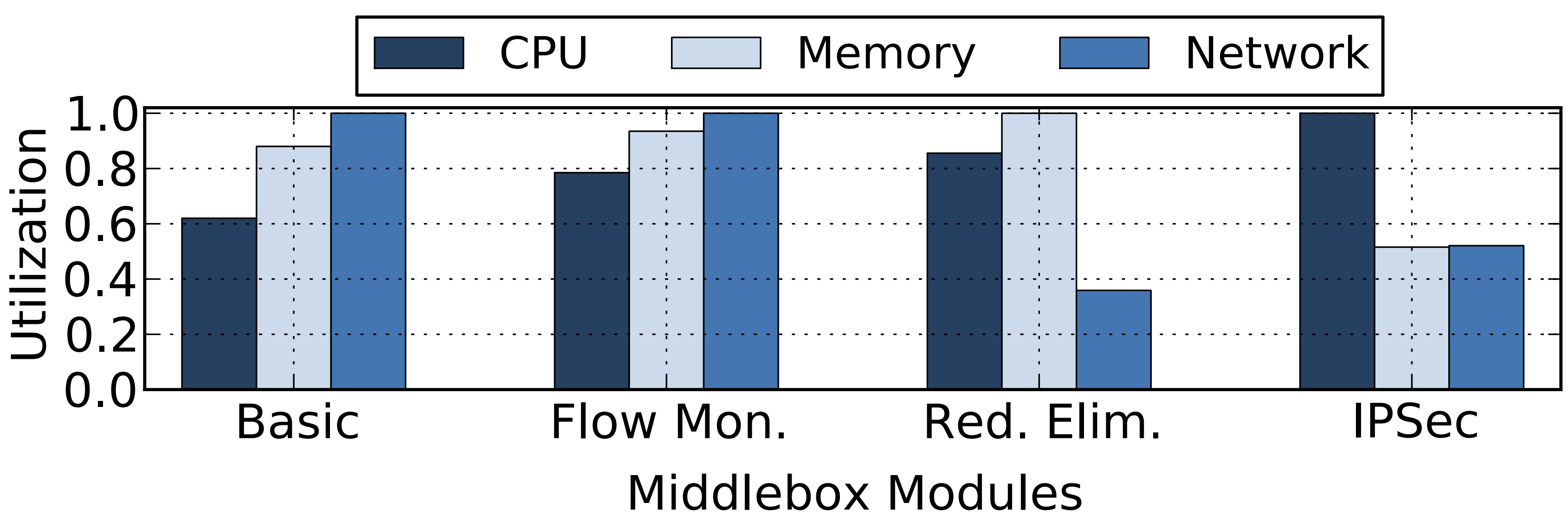
Middleboxes and Deep Packet Inspection

- Process packets based on payload
  - IPsec, Monitoring, Firewalls, WAN optimization, etc



Consumption of Multiple Resources

- Packet processing requires multiple types of resources (e.g., CPU, memory b/w, link b/w)
- Different middlebox (MB) modules consume different amounts of resources



Ghodsi et al. SIGCOMM'12

Resources should be shared **fairly** and **efficiently** among flows

Fairness

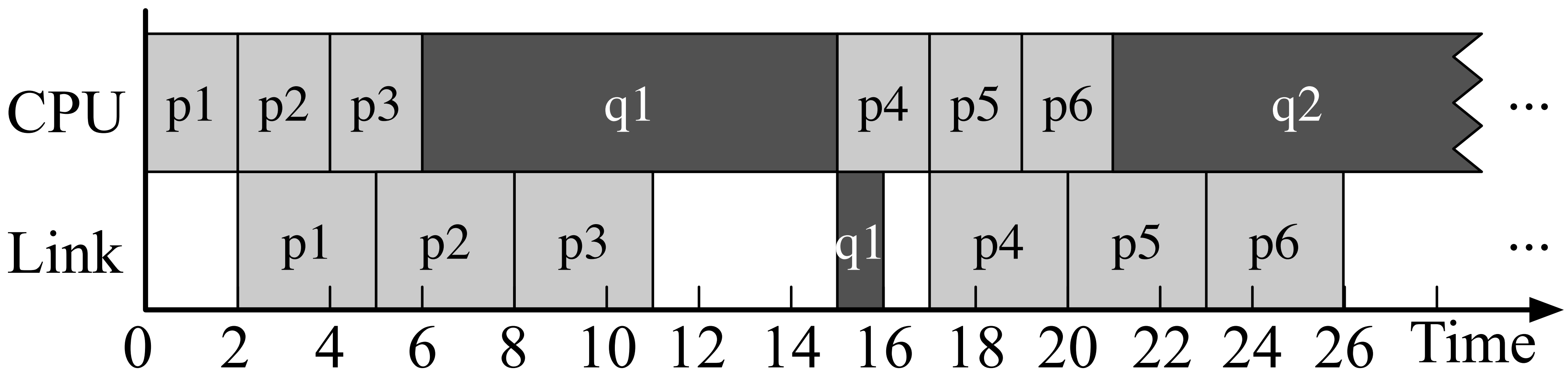
- Predictable service isolation
  - The service a flow receives in an *n*-flow system is at least 1/*n* of that it achieves when the flow monopolizes all resources
- Dominant Resource Fairness (DRF)
  - Flows receive *approximately the same* processing time on the *dominant resources* of their packets

Efficiency

- High resource utilization given a non-empty system, with high traffic throughput
  - Important in today's enterprise networks, as a surging volume of traffic now passes through MBs

However, fairness and efficiency are **conflicting** objectives in the presence of multiple resources

Fair but Inefficient

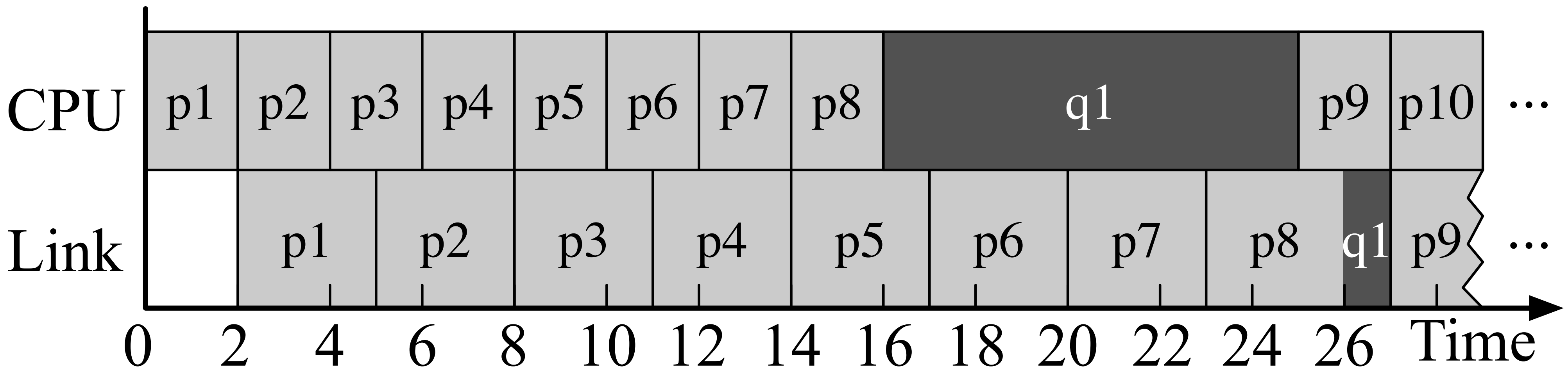


(a) A packet schedule that is fair but inefficient.

- Fair: both flows receive 9 time units to process on their dominant resources in each round

- Inefficient: link is idle at 1/3 of time

Efficient but Unfair



(b) A packet schedule that is efficient but unfair.

- Unfair: Flow 1 receives 96% of the link bandwidth; Flow 2 receives 36% of the CPU time
- Efficient: 100% CPU and link utilization given a non-empty system

Ideally…

- Allow the network operator to flexibly specify the tradeoff preference
    - Many applications may have loose fairness requirements
- Implement the specified tradeoff via a queueing algorithm

However…

- Existing multi-resource queueing algorithms focus only on fairness, without efficiency consideration
  - The tradeoff problem has never been mentioned before, and is **unique** to multi-resource scheduling
- Even the efficiency measure is unclear!

The Efficiency Measure

Schedule Makespan

- Time elapsed from the arrival of the first packet to the time when all packets finish processing on all resources
  - The completion time of the last flow

Max efficiency = Min makespan

Quantifying the Efficiency Loss

- Theoretical results
  - *m*: # of resource types concerned
  - the makespan of fair queueing could be up to *m* times the optimal makespan
- Experiment confirms 20% throughput loss of existing multi-resource fair queueing

Makespan minimization is notoriously hard, especially when there are more than two types of resources concerned (NP-hard)

We limit our discussion to the two most concerned types of resources for packet processing—CPU and link bandwidth

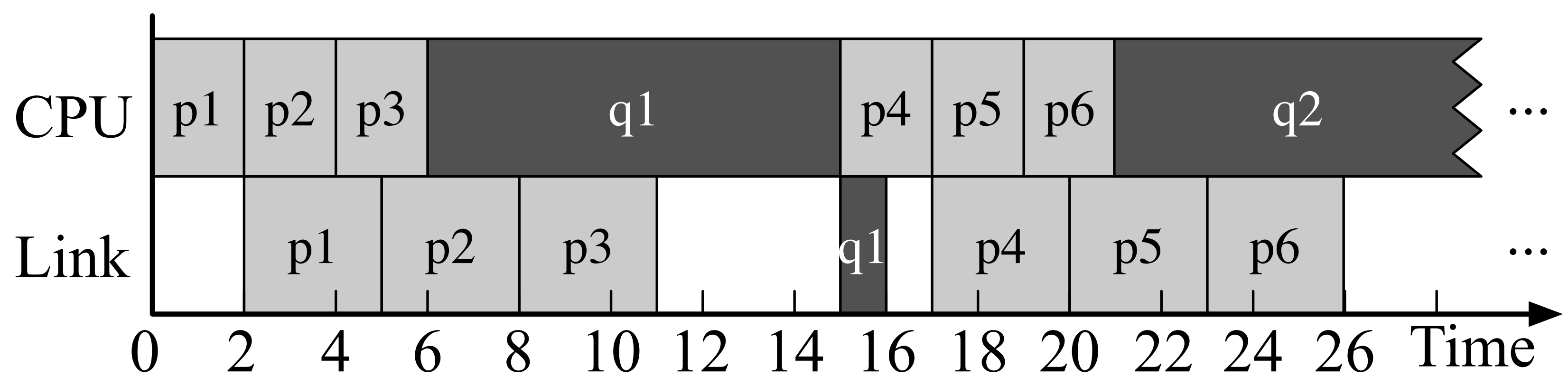
Our Approach

- Relax the scheduling problem to an idealized *fluid model*
- Discuss the tradeoff between fairness and efficiency in the fluid model
- Implement the fluid model in the real world via a packet-by-packet tracking algorithm

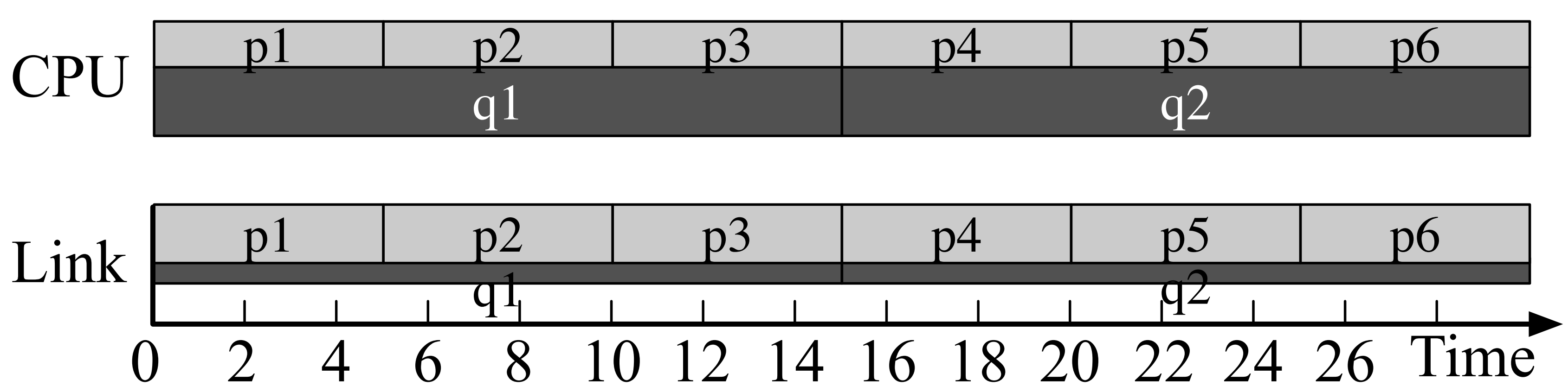
The Fluid Relaxation: packets are assumed to receive services in arbitrarily small increments on all resources

Fluid Relaxation

- Discrete schedule



- Fluid relaxation



Fluid w/ the Perfect Fairness

- Implement the strict DRF allocation at all times

Max-min flow's dominant share

$$\max_{d_i} \quad \min_{i \in \mathcal{B}} d_i$$
$$\text{s.t.} \quad \sum_{i \in \mathcal{B}} \bar{\tau}_{i,r} d_i \leq 1, \quad r = 1, 2 \ .$$

Resource constraints

- All flows receive the same *fair dominant share*

$$\bar{d} = 1 / \max \left\{ \sum_i \bar{\tau}_{i,1}, \sum_i \bar{\tau}_{i,2} \right\}$$

Fluid w/ the Optimal Efficiency

- Greedily maximizes the *system dominant share* at all times

Maximize system dominant share

$$\max_{d_i \geq 0} \quad \sum_{i \in \mathcal{B}_t} d_i$$

$$\text{s.t.} \quad \sum_{i \in \mathcal{B}_t} \bar{\tau}_{i,r} d_i \leq 1, \quad r = 1, 2.$$

Resource constraints

Fairness-Efficiency Tradeoff

Specifying Fairness Requirement

- Let $\bar{d}$ be the *fair dominant share* under DRF
- Let $\alpha \in [0, 1]$ be a *fairness knob* specified by the operator
- **Fairness constraint**: flows receive at least α-portion of fair dominant share

Fair share under DRF

$$d_i \geq \alpha \bar{d}, \quad \forall i \in \mathcal{B},$$

Dominant share of flow *i*

Fairness-Efficiency Tradeoffs

- Maximize the *system dominant share* under a specified tradeoff level (quantified by fairness knob $\alpha \in [0, 1]$)

$$\begin{aligned} \max_{d_i} \quad & \sum_{i \in \mathcal{B}_t} d_i \\ \text{s.t.} \quad & \sum_{i \in \mathcal{B}_t} \bar{\tau}_{i,r} d_i \leq 1, \quad r = 1, 2, \\ & d_i \geq \alpha \bar{d}, \quad \forall i \in \mathcal{B}_t \ . \end{aligned}$$

Resource constraint

Fairness constraint

Implement the fluid model via packet-by-packet tracking

Start-Time Tracking

- Maintain the Tradeoff Fluid as a reference system in the background
- In the real world, whenever there is a packet scheduling opportunity, the one that starts the **earliest** in the Tradeoff Fluid is scheduled first
- An O(log n) implementation based on a *special structure* of the Tradeoff Fluid
- **Asymptotically close** to the fluid model in terms of both makespan and fairness guarantee

Evaluation

Experiment Setup

- Prototype implementation in Click modular router
- 60 UDP flows each sending 2,000 800-byte pkts/s
- Three middlebox processing modules
  - Packet checking (bandwidth-bound): Flows 1~20
  - Statistical monitoring (bandwidth-bound): Flow 21~40
  - IPsec (CPU-bound): Flows 41~60

Scenario 1: No packet drop

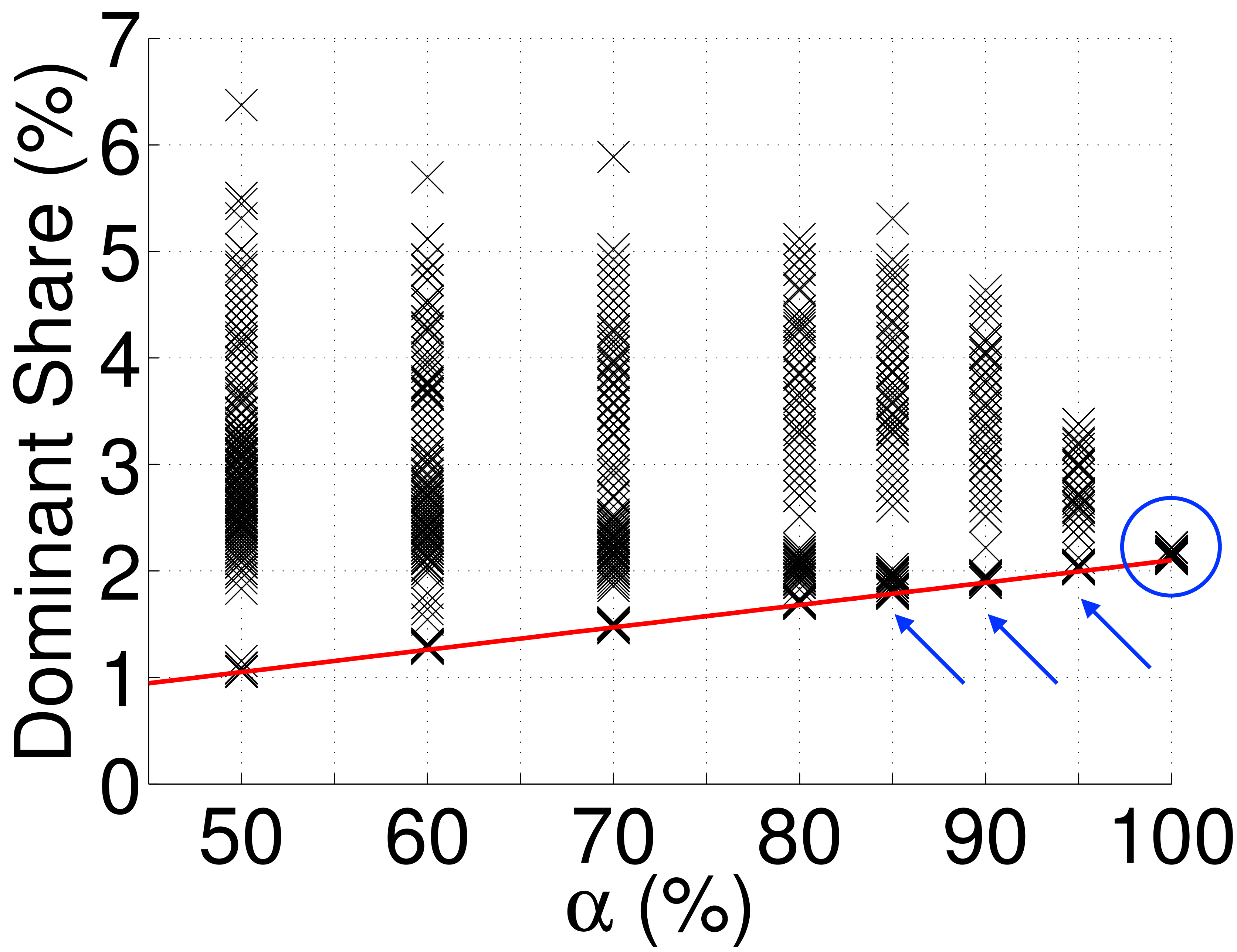
Makespan

- Each flow sends 10s traffic

α	**Makespan (s)**	**Normalized Makespan (%)**
1.00	55.68	100.00
0.95	52.50	94.28
0.90	48.97	87.95
0.85	47.17	84.72
0.70	47.13	84.64
0.60	47.07	84.54
0.50	47.07	84.54

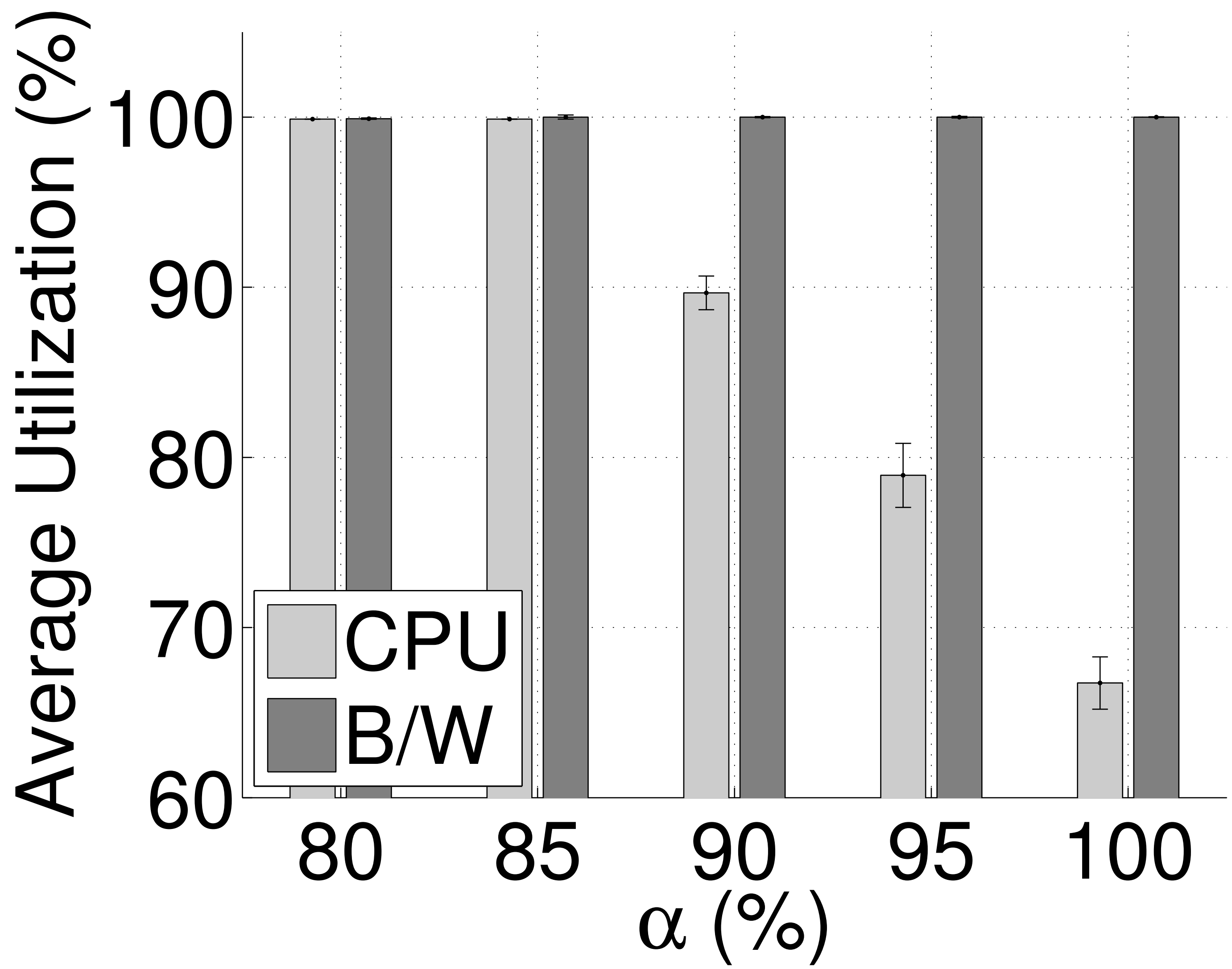
- Trading off 15% of fairness is sufficient to achieve the shortest makespan (20% throughput improvement)

Fairness

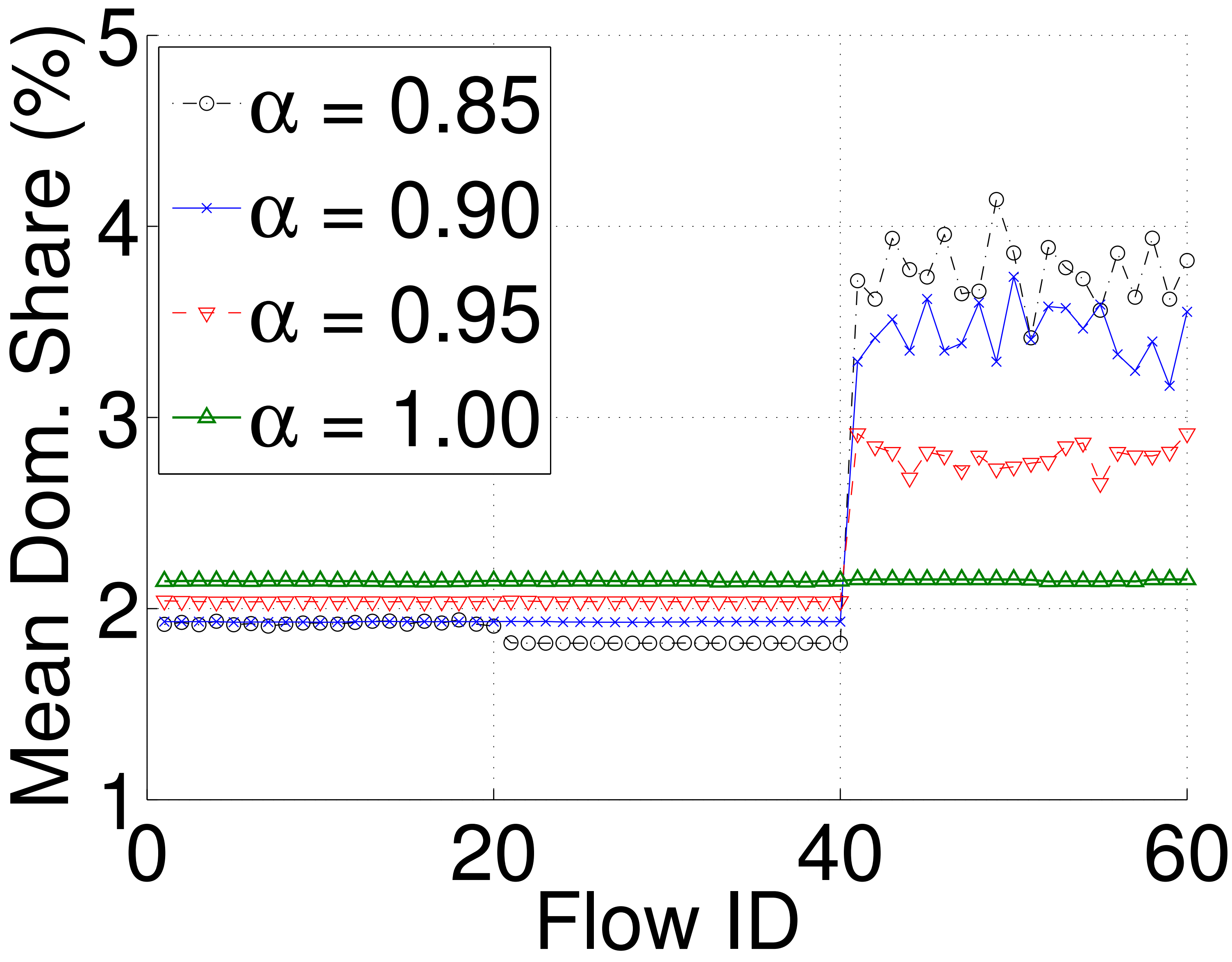


Scenario 2: buffer size=200

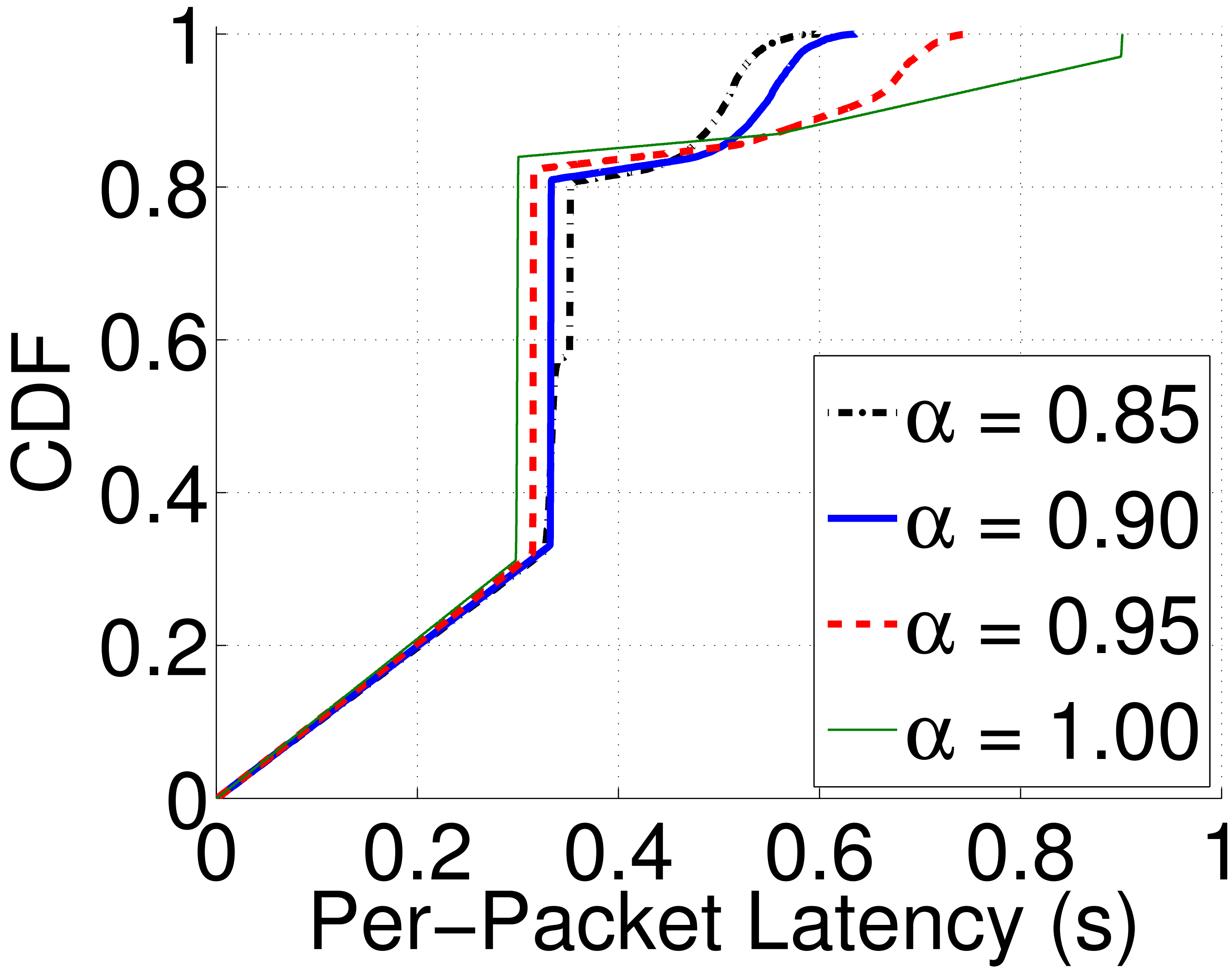
Resource Utilization



Dominant Share



Per-Packet Latency



Conclusions

- We have identified the problem of fairness-efficiency tradeoffs for multi-resource packet scheduling
- We have designed a scheduling algorithm to achieve a flexible tradeoff between fairness and efficiency for packet processing that requires both CPU and link bandwidth
- We have prototyped the tradeoff algorithm in Click. Experimental results show that slight fairness tradeoff is sufficient to achieve the highest efficiency

Thank you!

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