DRFQ: Multi-Resource Fair Queueing for Packet Processing

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Increasing Network Complexity

- Packet processing becoming evermore *sophisticated*
  - Software Defined Networking (SDN)
  - Middleboxes
  - Software Routers (e.g. RouteBricks)
  - Hardware Acceleration (e.g. SSLShader)

- Data plane no longer merely forwarding
  - WAN optimization
  - Caching
  - IDS
  - VPN

Motivation

- Flows increasingly have *heterogeneous resource consumption*
  - Intrusion detection bottlenecking on CPU
  - Small packets bottleneck memory-bandwidth
  - Unprocessed large packets bottleneck on link bw

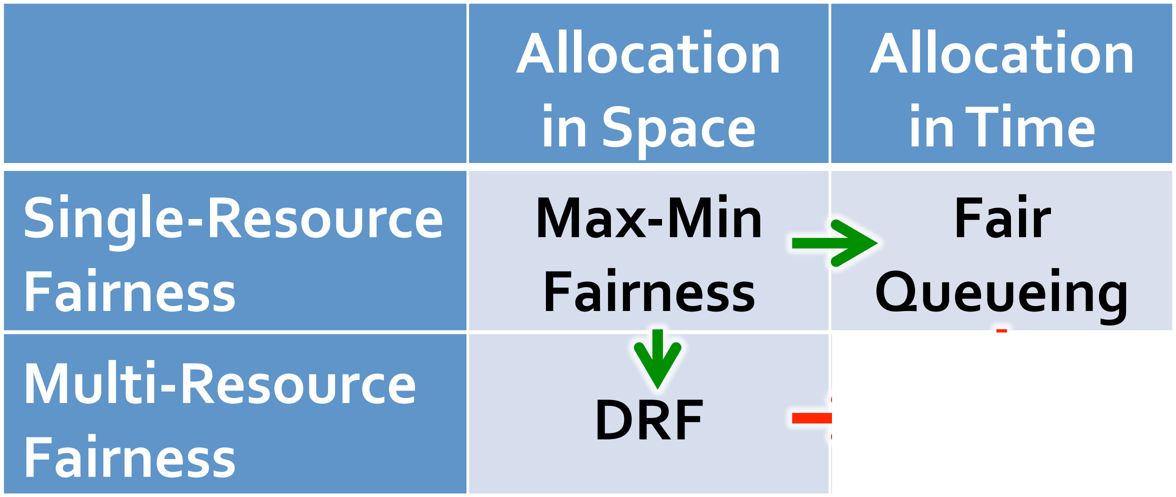
Scheduling based on a single resource insufficient

Problem

How to schedule packets from different flows, when packets consume *multiple resources*?

How to generalize fair queueing to multiple resources?

Contribution



	Allocation in Space	Allocation in Time
Single-Resource Fairness	Max-Min Fairness	Fair Queueing
Multi-Resource Fairness	DRF	

Generalize Virtual Time to Multiple Resources

Outline

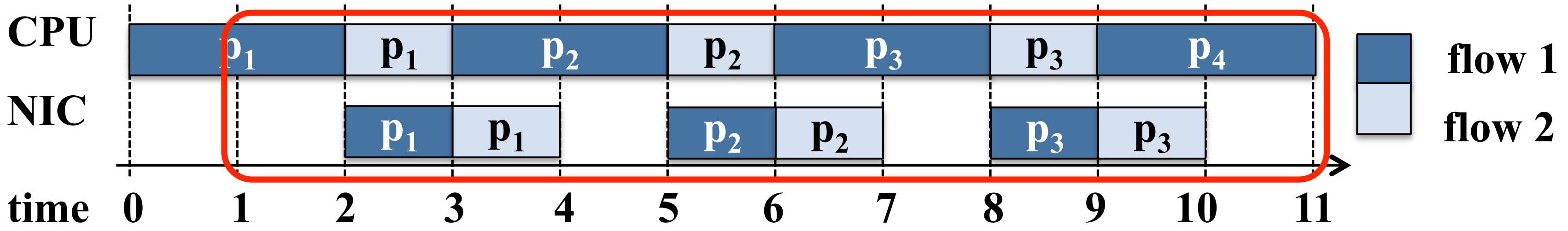
- Analysis of Natural Policies
- DRF allocations in Space
- DRFQ: DRF allocations in Time
- Implementation/Evaluation

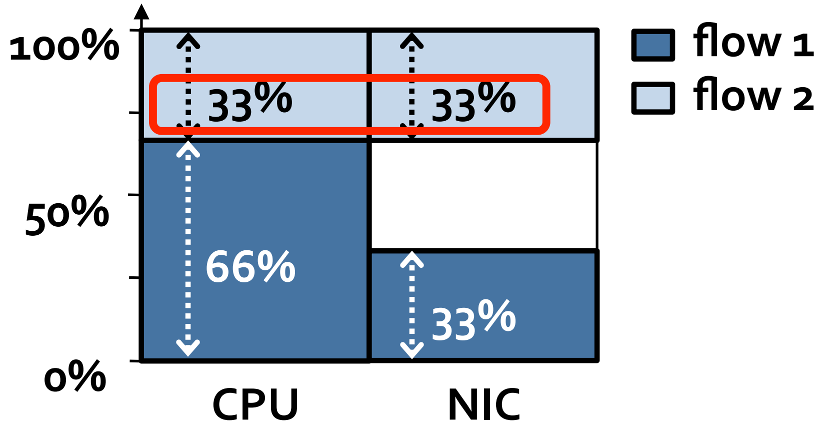
Desirable Multi-Resource Properties

- **Share guarantee:**
  - Each flow can get 1/n of at least one resource
- **Strategy-proofness:**
  - A flow shouldn't be able to finish faster by increasing the resources required to process it.

Violation of Share Guarantee

- Example of FQ applied to a
  - Two resources CPU and NIC, *used serially*
  - Two flows with profiles <2 μs,1 μs> and <1 μs,1 μs>
  - FQ based on NIC alternates one packet from each flow



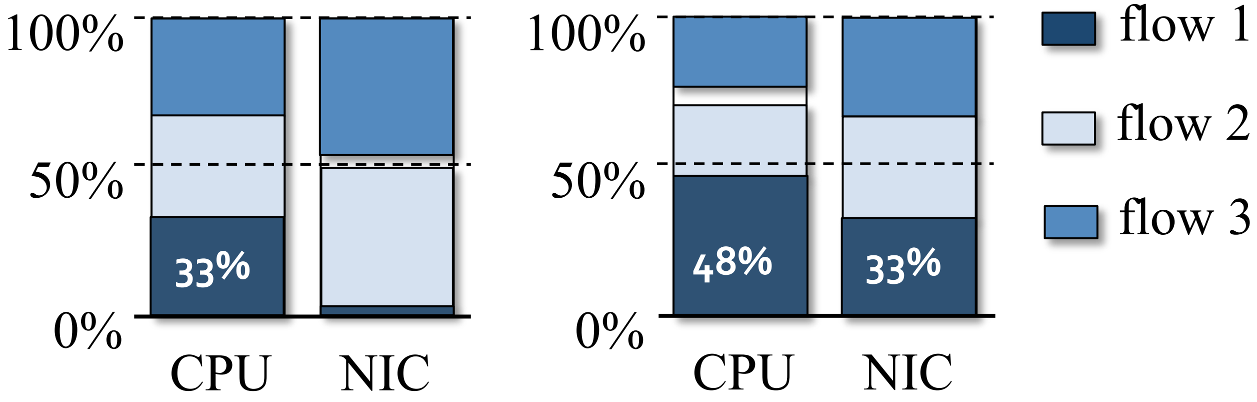


Share Guarantee Violated by Single Resource FQ

Violation of Strategy-Proofness

- **Bottleneck fairness**
  - Determine which resource is bottlenecked
  - Apply FQ to that resource

- Example with Bottleneck Fairness
  - 2 resources (CPU, NIC), 3 flows <10,1>, <10,14>, <10,14>
  - *CPU bottlenecked* and split equally

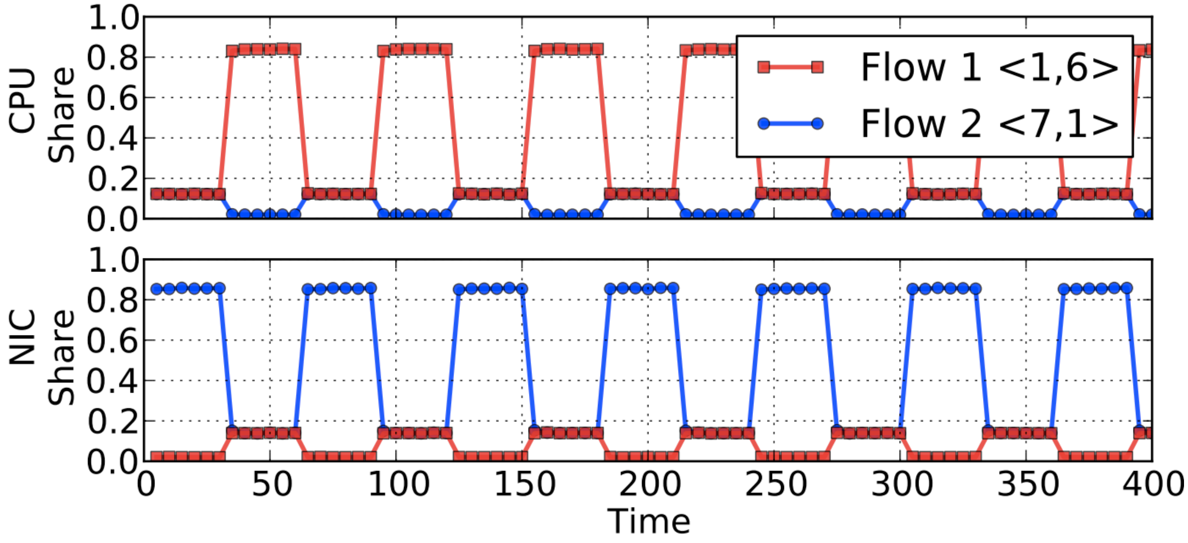


  - Flow 1 changes to <10,7>. *NIC bottlenecked* and split equally

Bottleneck Fairness Violates Strategy-Proofness

Bottleneck Fairness and Multiple Bottleneck

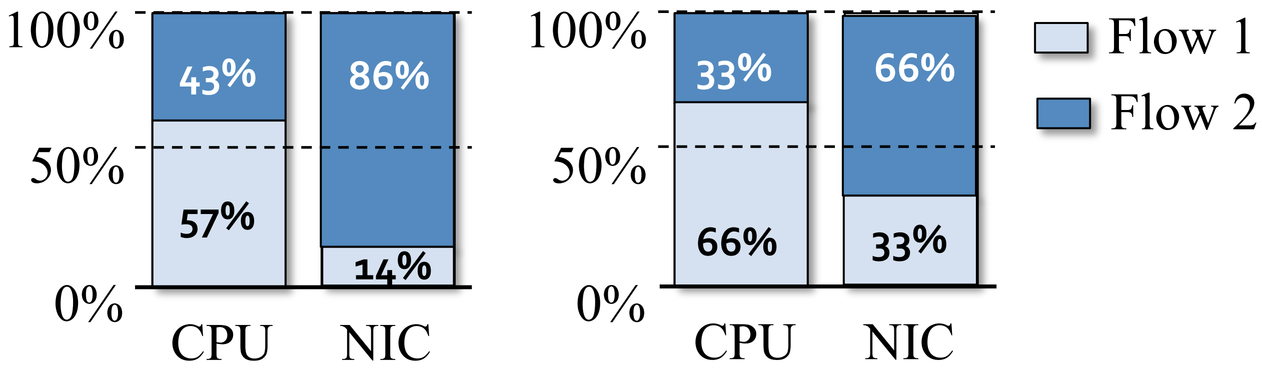
- Example with 2 flows and 2 res. <CPU, NIC>
  - Demands <1,6> and <7,1> → *bottleneck unclear*
  - CPU bottleneck: 7×<1,6> + <7,1> = <14,$\underline{43}$>
  - *Oscillates* to the other resource
  - NIC bottleneck: <1,6> + 6×<7,1> = <$\underline{43}$, 12>



Natural Policy

- *Per-Resource Fairness (PRF)*
  - Have a buffer between each resource
  - Apply fair queueing to each resource

- Per-Resource Fairness not strategy-proof
  - 2 resources, 2 flows <4,1>, <1,2>



  - Flow 1 changes demand to <4,2>

Problems with Per-Resource Fairness

- PRF *violates* strategy-proofness
  - Can be manipulated by wasting resources
- PRF requires *per-resource queues*
  - Problematic for parallel resource consumption e.g. CPU and memory consumption in a module

Why care about strategy-proofness?

- Lack of strategy-proofness encourages *wastage*
  - Decreasing goodput of the system
- Networking applications especially savvy
  - Peer-to-peer apps manipulate to get more resources
- Trivially *guaranteed* for single resource fairness
  - But not for multi-resource fairness

Summary of Policies

Policy	Share Guarantee	Strategy-Proofness
Fair Queueing a Single Resource		
Bottleneck Fairness		
Per-Resource Fairness	X	
Dominant Resource Fairness	X	X

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Dominant Resource Fairness

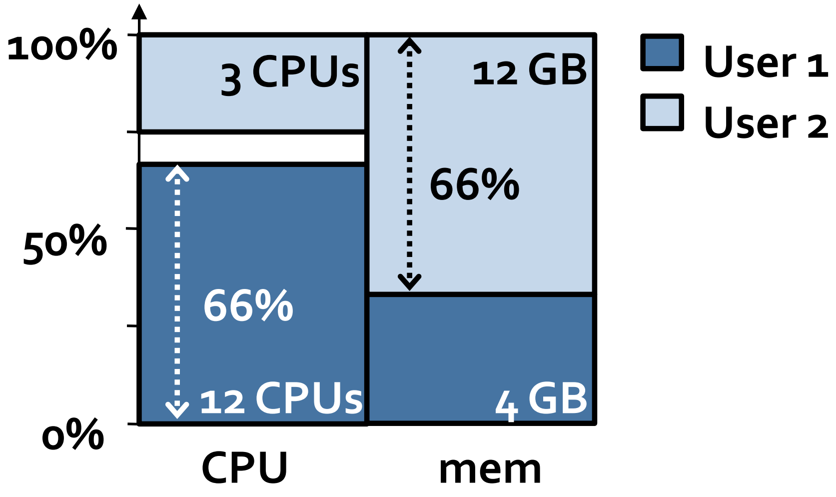
- DRF originally in the cloud computing context
  - – Satisfies *share guarantee*
  - – Satisfies *strategy-proofness*

DRF Allocations

- *Dominant resource* of a user is the resource she is allocated most of
  - *Dominant share* is the user's share of her dominant resource

- *DRF*: apply max-min fairness to dominant shares
  - "Equalize" the dominant share of all users

Total resources: **<16 CPUs, 16 GB mem>**
User 1 demand: **<3 CPU, 1 GB mem>** dom res: **CPU**
User 2 demand: **<1 CPU, 4 GB mem>** dom res: **mem**



Allocations in Space vs Time

- DRF provides allocations *in space*
  - Given 1000 CPUs and 1 TB mem, how much to allocate to each user
- DRFQ provides DRF allocations *in time*
  - Multiplex packets to achieve DRF allocations over time

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Determining Packet Resource Consumption

- A-priori packet link usage known in FQ
  - Packet size divided by throughput of link
- Packet processing time a-priori unknown for multi-resources
  - Depends on the modules that process it
- Leverage Start-time Fair Queueing (SFQ)
  - Schedules based on virtual start time of packets
  - Start time of packet p independent of resource consumption of packet p

Memoryless Requirement

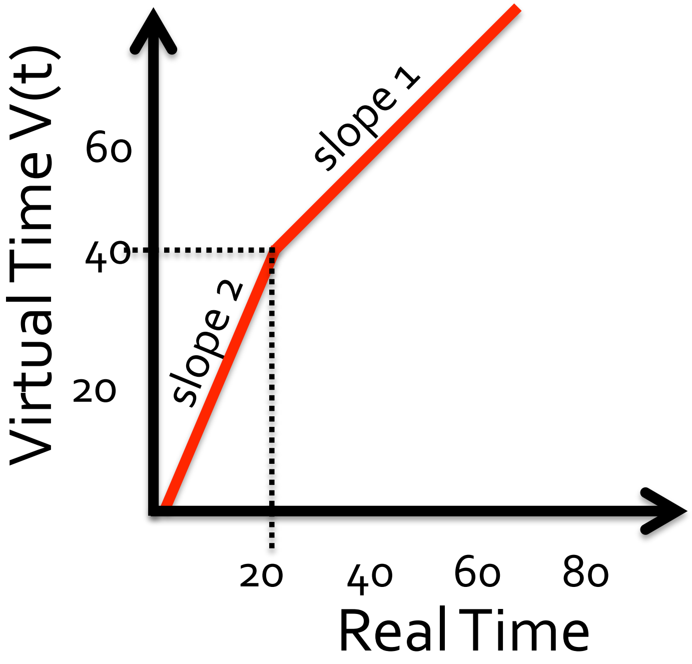
- Virtual Clock simulates flows with dedicated 1/n link
  - Attach *start* and *finish tags* according to dedicated link
  - Serve packet with smallest finish tag (work conserving)

- *Problem*
  - During light load a flow might get more than 1/n
  - That flow experiences long delays when new flows start

- Requirement: *memoryless scheduling*
  - A flow’s share of resources should be independent of its share in the past

Memoryless through Virtual Time

- *Virtual time* to track amount service received
  - A unit of virtual time always corresponds to same amount of service
- Example with 2 flows
  - Time 0: one backlogged flow
  - Time 20: two backlogged flows



- Schedule the packets according to V(t)
  - Assign virtual start/finish time when packet arrives

Dove-tailing Requirement

- FQ: flow size should determine service, not packet size
  - Flow with 10 1kb packets gets same service as 5 2kb packets

- Want flow processing time, not packet processing time
  - Example: give same service to these flows:
    Flow 1: p_1 <1,2>, p_2 <2,1>, p_3 <1,2>, p_4 <2,1>, …
    Flow 2: p_1 <3,3>, p_2 <3,3>, p_3<3,3>, p_4 <3,3>, …

- Requirement: *dove-tailing*
  - Packet processing times should be independent of how resource consumption is distributed in a flow

Tradeoff

- Dovetailing and memoryless property *at odds*
  - Dovetailing needs to remember past consumption

- DRFQ developed in three steps
  - *Memoryless DRFQ*: uses a single virtual time
  - *Dovetailing DRFQ* : use virtual time per resource
  - *DRFQ*: generalizes both, tradeoff between memoryless and dovetailing

Memoryless DRFQ

- Attach a *virtual start* and *finish time* to every packet
  - S(p) and F(p) of packet p

- Computing virtual finish time F(P)
  1. $F(p) = S(p) + \max_i\{\ p\_time(p, i)\ \}$

     $p\_time(p, i) = \{$ processing time of p on resource i $\}$

- Computing virtual start time, S(p)
  2. $S(p) = \max(\ F(p^{-1}), C(t)\ )$

     $C(t) = \{$ max start time of currently serviced packet $\}$

- Service the packet with *minimum* virtual start time

Memoryless DRFQ

- Attach a *virtual start* and *finish time* to every packet

- Computing virtual finish time
  1. finish time = start time + packet-max-processing-time

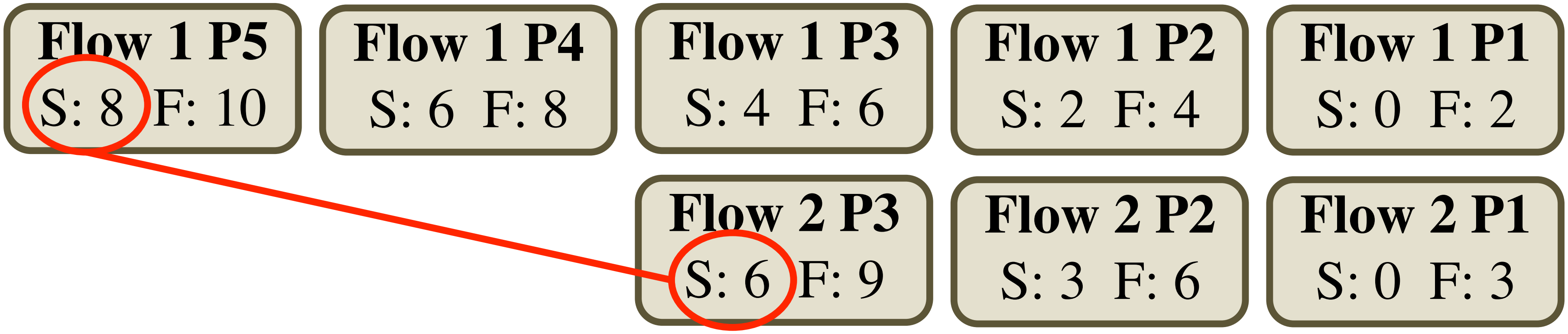
- Computing virtual start time
  2. Start time of the first packet in a burst equals the start time of the packet currently serviced (zero if none)
  3. For a backlogged flow, the start time of a packet is equal to finish time of previous packet

- Service the packet with *minimum* virtual start time

Memoryless DRFQ example

- Two flows become backlogged at time 0
  - Flow 1 alternates <1,2> and <2,1> packet processing
  - Flow 2 uses <3,3> packet processing time

1. $F(p) = S(p) + \max_i\{\ p\_time(p, i)\ \}$
2. $S(p) = \max(\ F(p^{-1}), C(t)\ )$



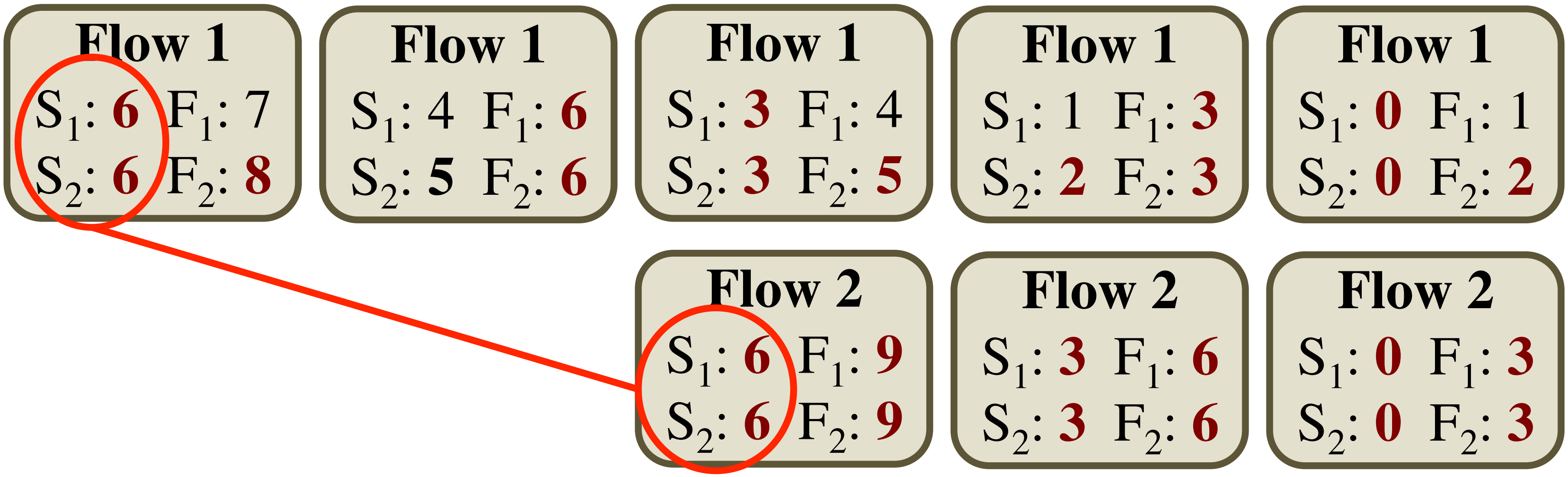
Flow 1 gets worse service than Flow 2

Dovetailing DRFQ

- Keep track of start and finish time *per resource*
  - Use max start time per resource for scheduling
  - Dovetail by keeping track of all resource usage

Dovetailing DRFQ example

- Two flows become backlogged at time 0
  - Flow 1 alternates <1,2> and <2,1> packet processing
  - Flow 2 uses <3,3> per packet



Flow 1
S_1: 6 F_1: 7
S_2: 6 F_2: 8

Flow 1
S_1: 4 F_1: 6
S_2: 5 F_2: 6

Flow 1
S_1: 3 F_1: 4
S_2: 3 F_2: 5

Flow 1
S_1: 1 F_1: 3
S_2: 2 F_2: 3

Flow 1
S_1: 0 F_1: 1
S_2: 0 F_2: 2

Flow 2
S_1: 6 F_1: 9
S_2: 6 F_2: 9

Flow 2
S_1: 3 F_1: 6
S_2: 3 F_2: 6

Flow 2
S_1: 0 F_1: 3
S_2: 0 F_2: 3

Dovetailing ensures both flows get same service

DRFQ algorithm

- DRFQ *bounds* dovetailing to Δ processing time
  - Dovetail up to Δ processing time units
  - Memoryless beyond Δ

- DRFQ is a *generalization*
  - When Δ=0 then DRFQ=memoryless DRFQ
  - When Δ=∞ then DRFQ=dovetailing DRFQ

- Set Δ to a few packets worth of processing

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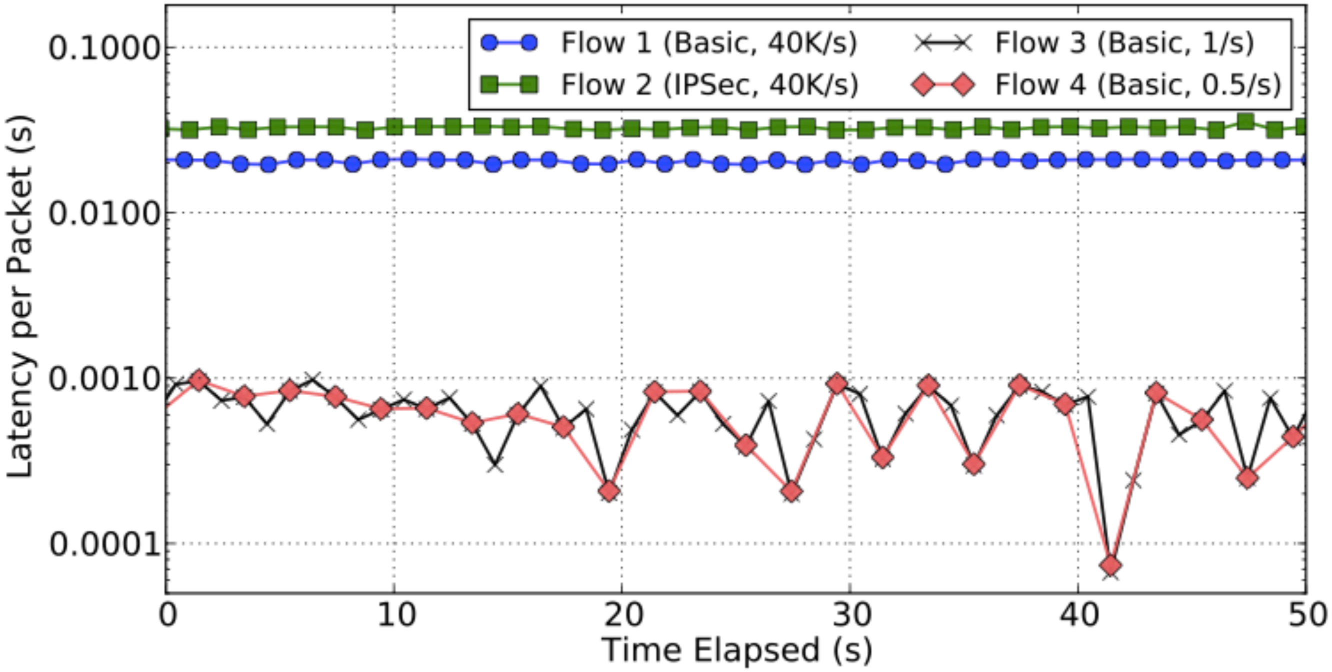
Isolation Experiment

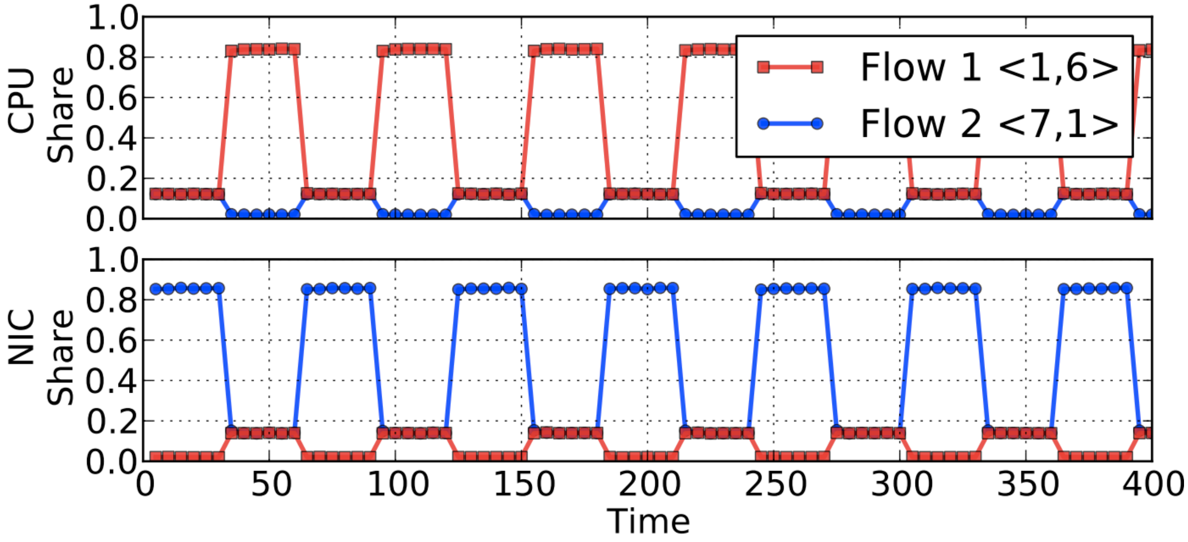
- DRFQ Implementation in Click
  - 2 elephants: 40K/sec basic, 40K/sec IPSec
  - 2 mice: 1/sec basic, 0.5/sec basic



Non-backlogged flows isolated from backlogged flows

Simulating Bottleneck Fairness

- 2 flows and 2 res. <CPU, NIC>
  - Demands <1,6> and <7,1> → *bottleneck unclear*



- Especially bad for TCP and video/audio traffic

Summary

- Packet processing becoming evermore sophisticated
  - Consume multiple resources

- Natural policies not suitable
  - Per-Resource Fairness (PRF) not strategy-proof
  - Bottleneck Fairness doesn't provide isolation

- Proposed *Dominant Resource Fair Queueing (DRFQ)*
  - *Generalization* of FQ to multiple resources
  - Generalizes virtual time to multiple resources
  - Provides tradeoff between memoryless and dovetailing
  - Provides share-guarantee (isolation) and strategy-proofness

Overhead

- 350 MB trace run through our Click implementation

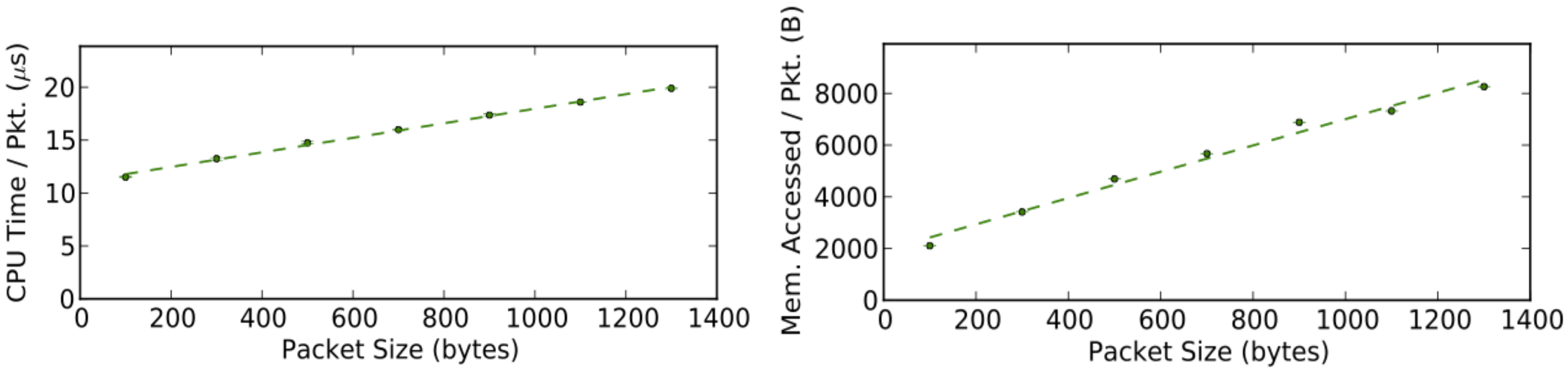
- Evaluate overhead of two modules
  - Intrusion Detection, 2% overhead
  - Flow monitoring, 4% overhead

Determining Resource Consumption

- Resource consumption obvious in routers
  - Packet size divided by link rate
- Generalize consumption to *processing time*
  - *Normalized* time a resource takes to process packet
- Normalized processing time
  - e.g. 1 core takes 20µs to service a packet,
    on a quad-core the packet processing time is 5µs
  - Packet processing time ≠ packet service time

Module Consumption Estimation

- Linear estimation of processing time
  - – For module m and resource r as function of packet size



- $R^2 > 0.90$ for most modules

Simulating Bottleneck Fairness

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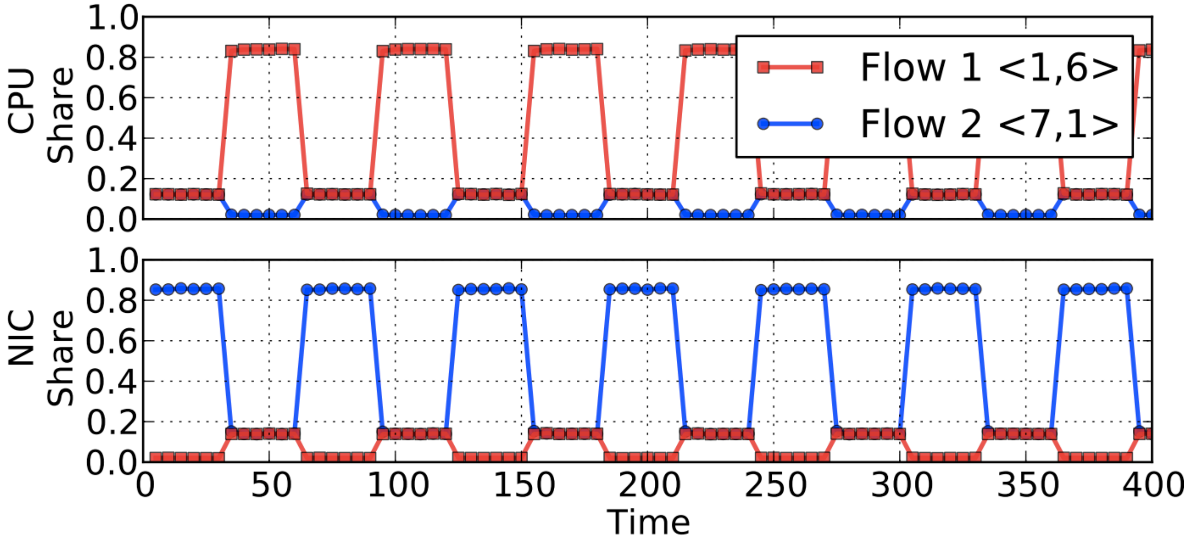
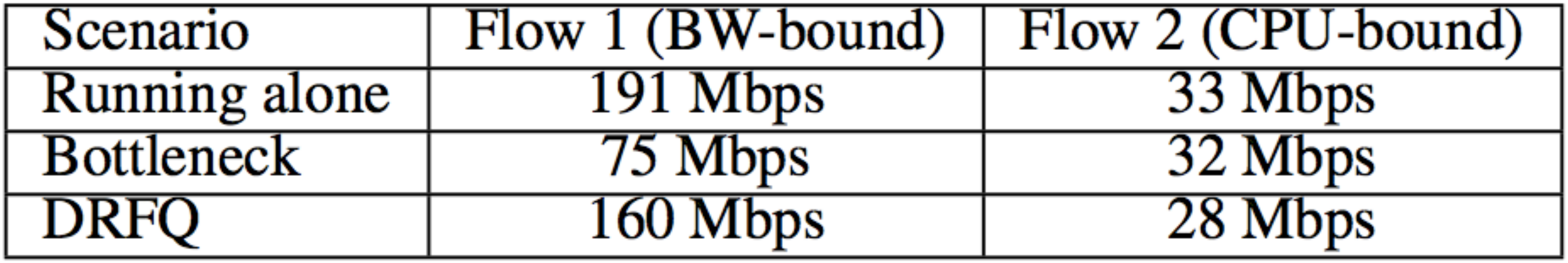


  - CPU bottleneck: 7×<1,6> + <7,1> = <14,43>
  - NIC bottleneck: <1,6> + 6×<7,1> = <43, 12>
  - *Periodically oscillates* the bottleneck

TCP and oscillations

- Implemented Bottleneck Fairness in Click
  - 20 ms artificial link delay added to simulate WAN
  - Bottleneck determined every 300 ms
  - 1 BW-bound flow and 1 CPU-bound flow



Scenario	Flow 1 (BW-bound)	Flow 2 (CPU-bound)
Running alone	191 Mbps	33 Mbps
Bottleneck	75 Mbps	32 Mbps
DRFQ	160 Mbps	28 Mbps

Oscillations in Bottleneck degrade performance of TCP

Multi-Resource Consumption Contexts

- Different modules within a middlebox
  - E.g. Bro modules for HTTP, FTP, telnet
- Different apps on a consolidated middlebox
  - Different applications consume different resources
- Other contexts
  - VM scheduling in hypervisors
  - Requests to a shared service (e.g. HDFS)