Titan: Fair Packet Scheduling for Commodity Multiqueue NICs

Brent Stephens, Arjun Singhvi, Aditya Akella, and Mike Swift

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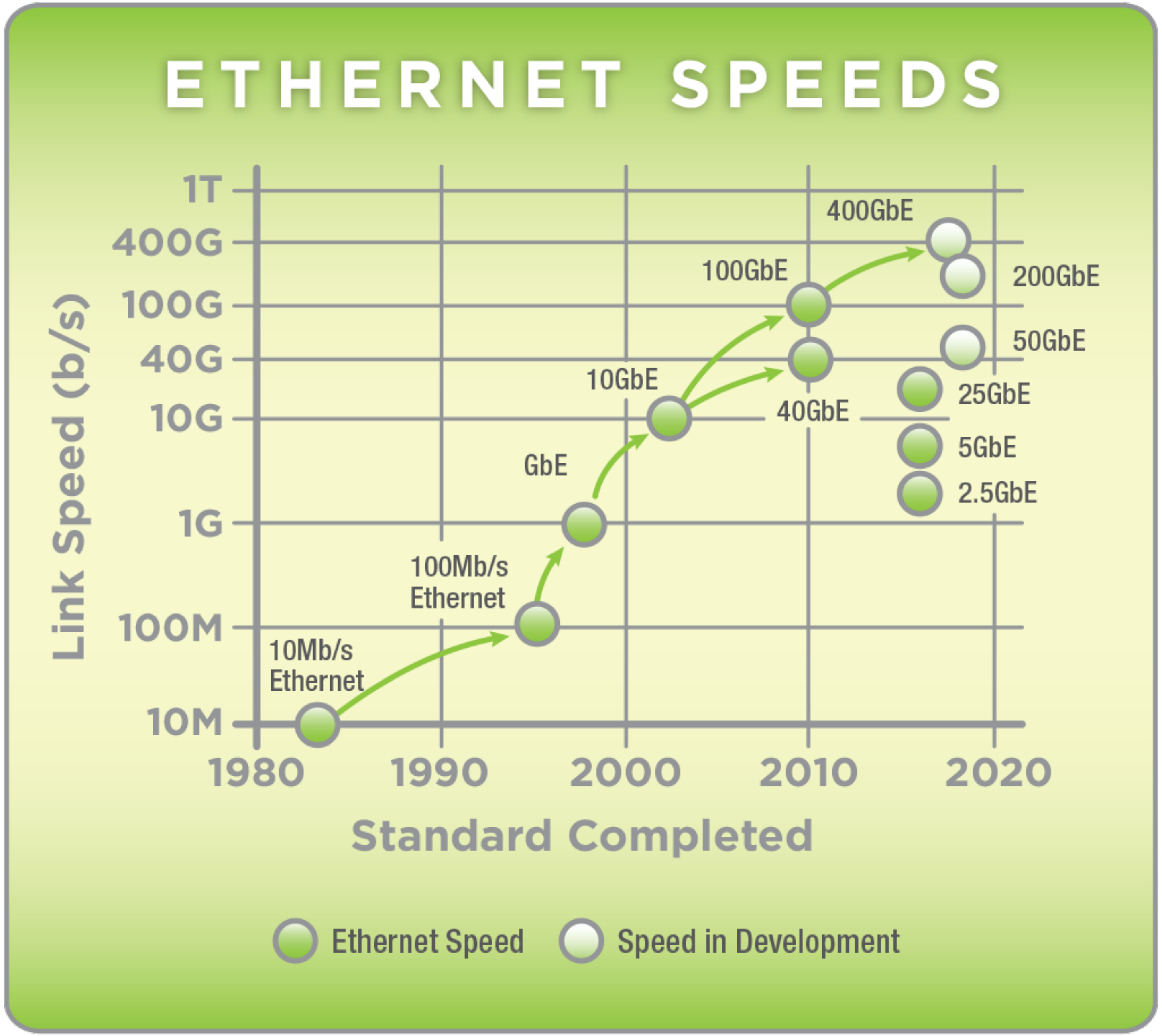
THE UNIVERSITY of WISCONSIN MADISON

Ethernet line-rates are increasing!



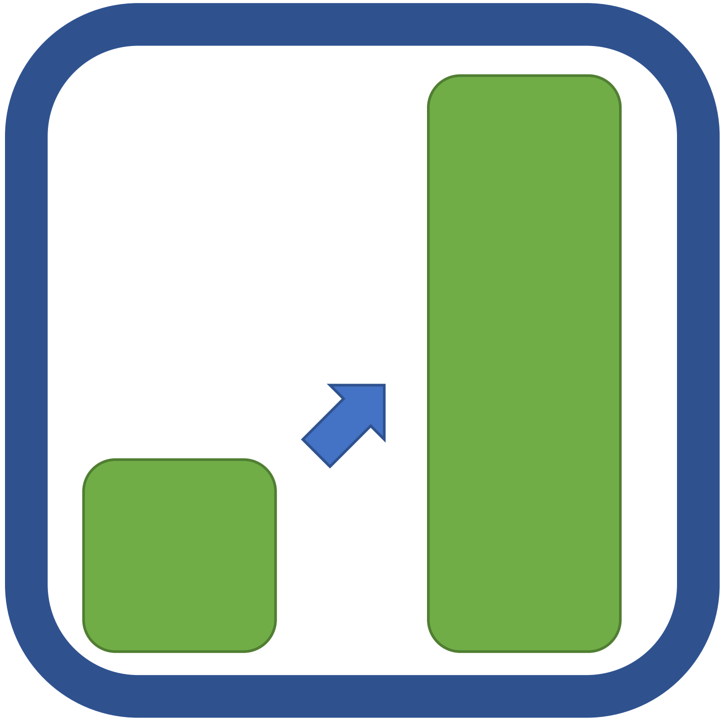
ethernet alliance

Servers need:

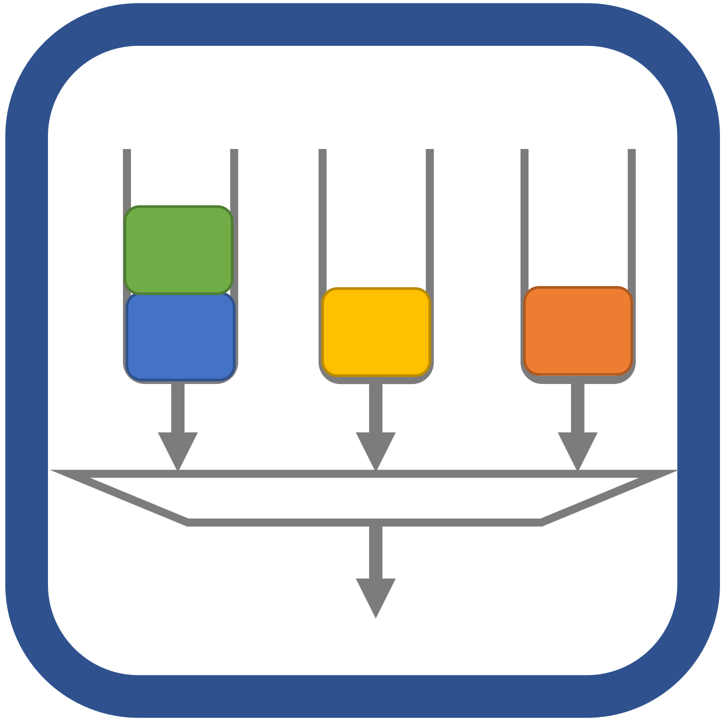
To drive increasing line-rates

Low CPU utilization networking

Underlying mechanisms:



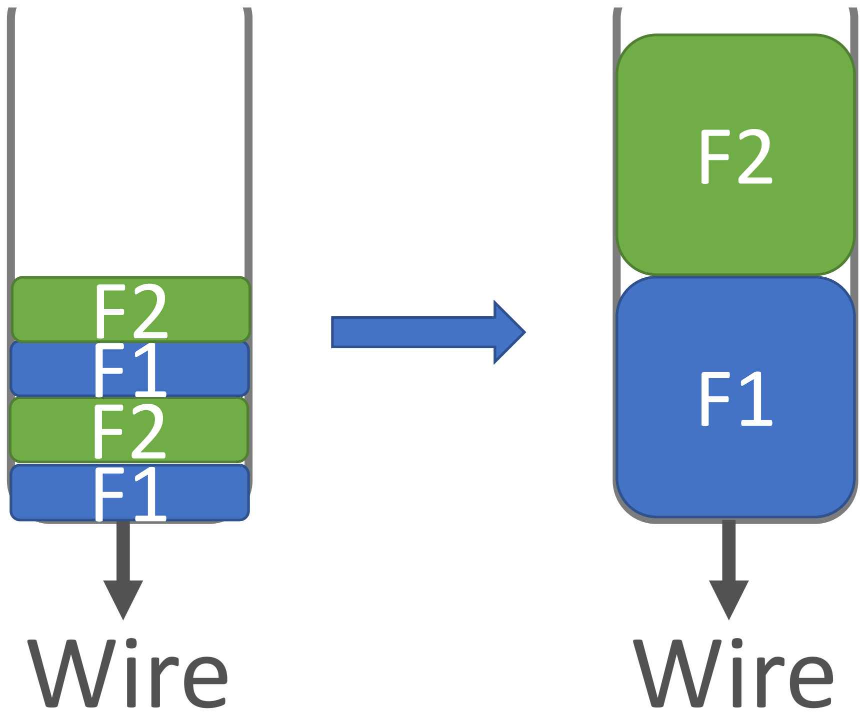
Segmentation Offload



Multiqueue NICs

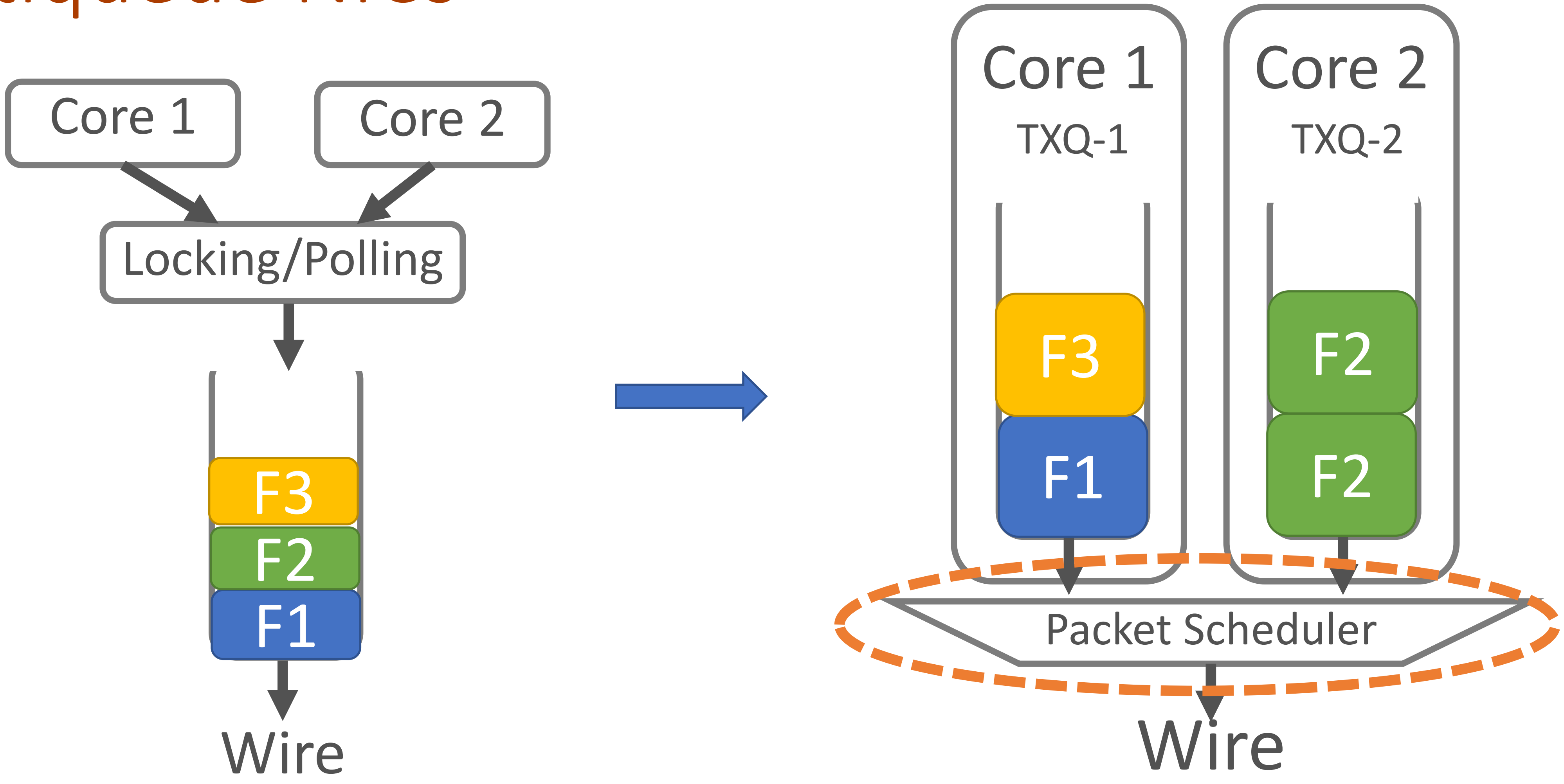
TCP Segmentation Offload (TSO)

- Many operations performed by the OS are per-packet, not per-byte
- TSO allows the OS to send large segments to the NIC
- TSO NIC hardware generates packets from segments



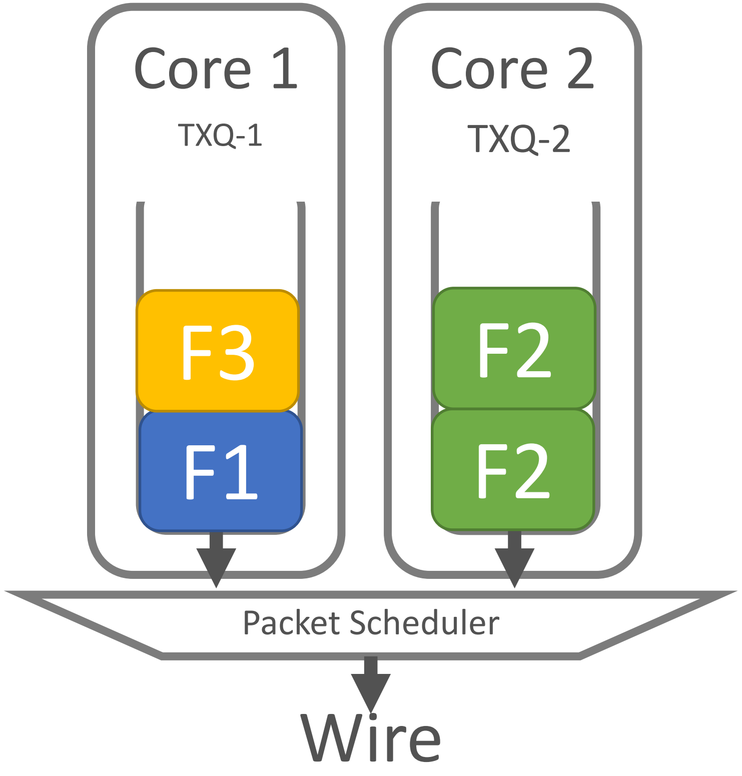
Using large segments (64KB) instead of packets can reduce CPU load

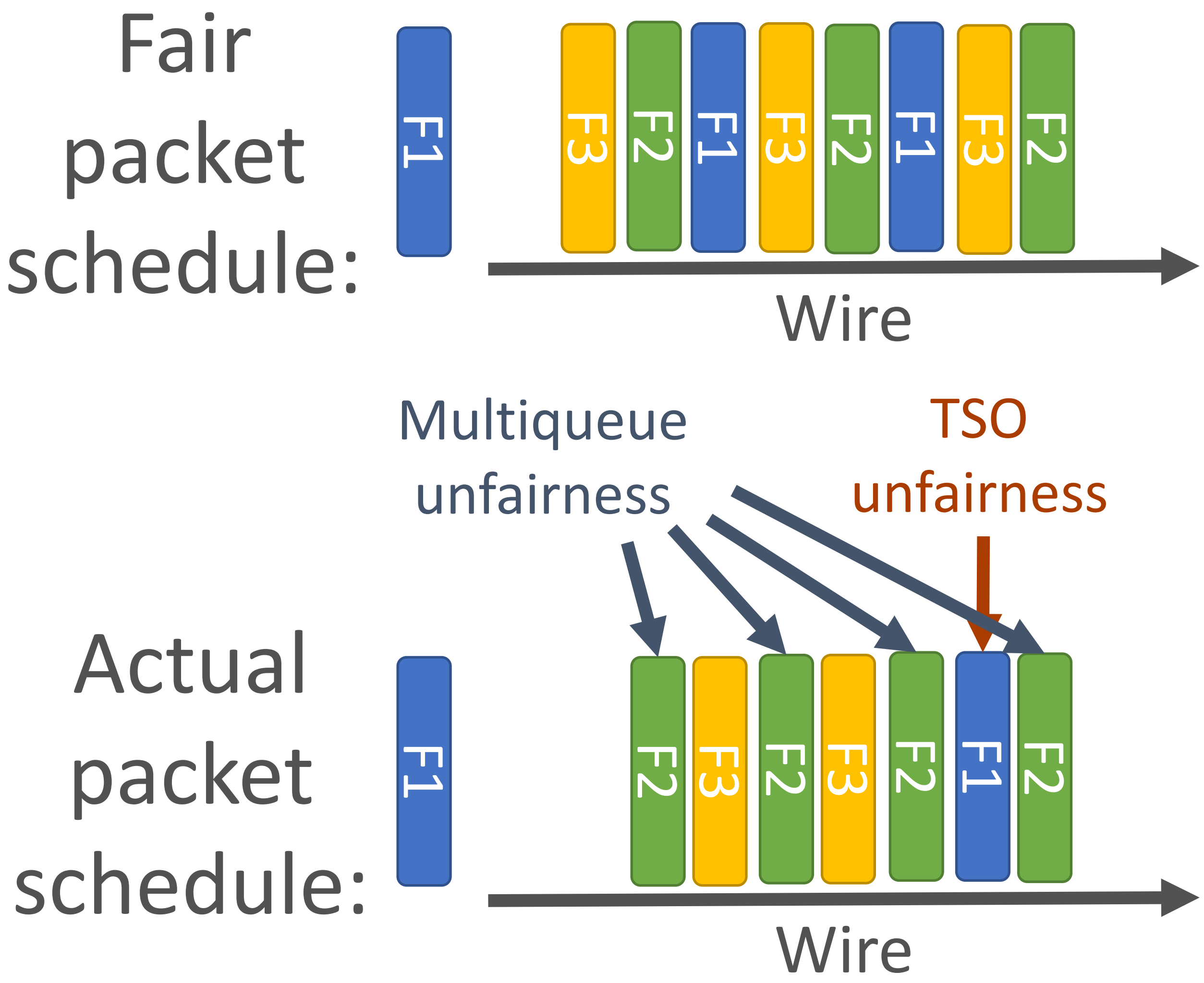
Multiqueue NICs



Multiqueue NICs enable parallelism

Fairness Problems





TSO and multiqueue cause pervasive unfairness

Fairness is important

- Fairness is needed so competing applications can **share the network**
- Fairness is needed for **predictability**
  - Unfairness leads to unpredictable completion times across runs
  - Perfect fairness → perfect predictability
- Fairness can **improve application performance**
  - Ex: Weighted Coflow Scheduling
    - [Chowdhury SIGCOMM11, Chowdhury SIGCOMM14]

Titan Goals:

Drive increasing line-rates ✓

Low CPU utilization ✓

Per-flow fairness ✗

Work on commodity NICs ✓

Multiqueue Fairness in Linux:

- Flow arrivals to each transmit queue are **dynamic**
- The OS **statically** uses a per-flow hash to assign flows to queues
- The NIC scheduler **statically** uses deficit round-robin (DRR) to provide per-queue fairness
- In the datacenter, the OS **statically** chooses a TSO size

Titan Design:

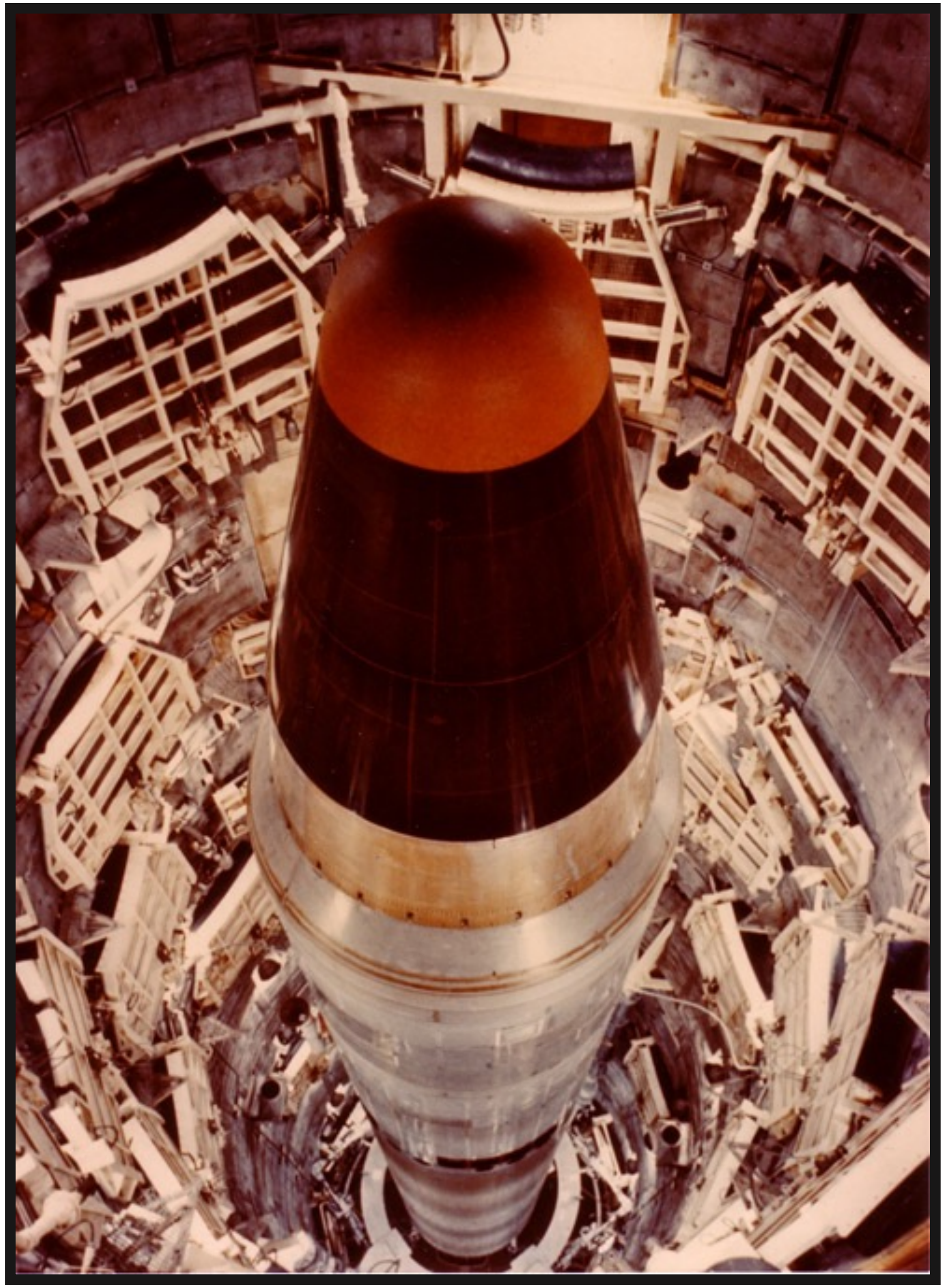
As flows **dynamically** arrive and complete, in Titan:

The OS **dynamically**:

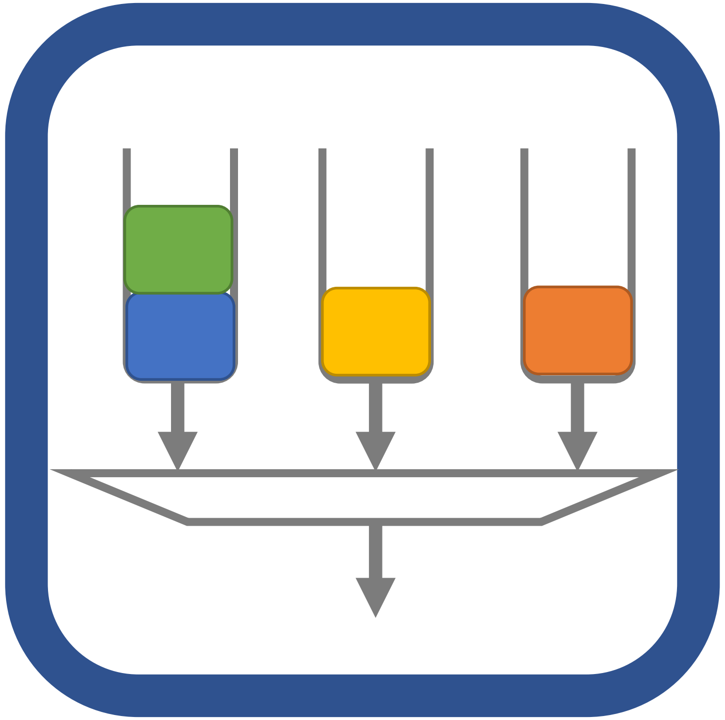
- Assigns weights to flows
- Tracks the flow occupancy of queues
- Picks queues for flows
- Updates the NIC with queue weights

The NIC **dynamically**:

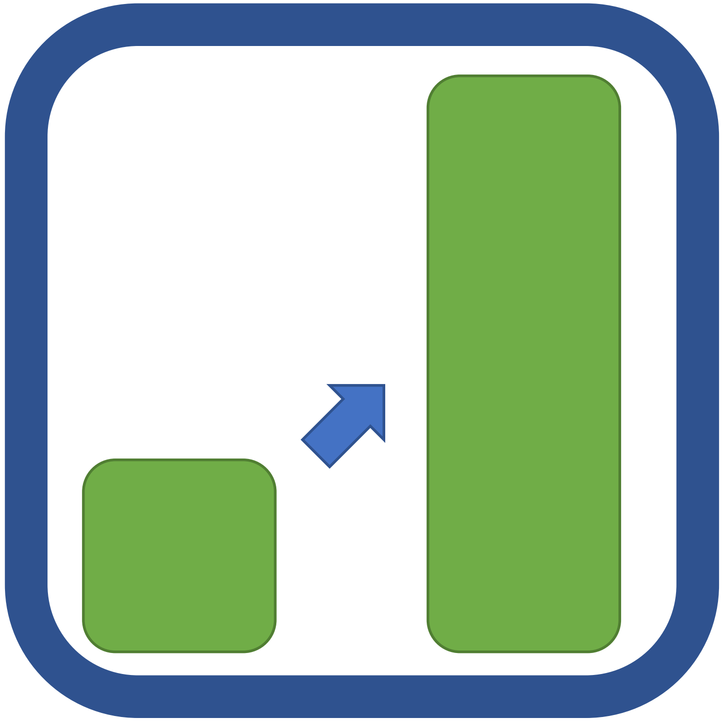
- Applies queue weights from the OS



Causes of Unfairness:

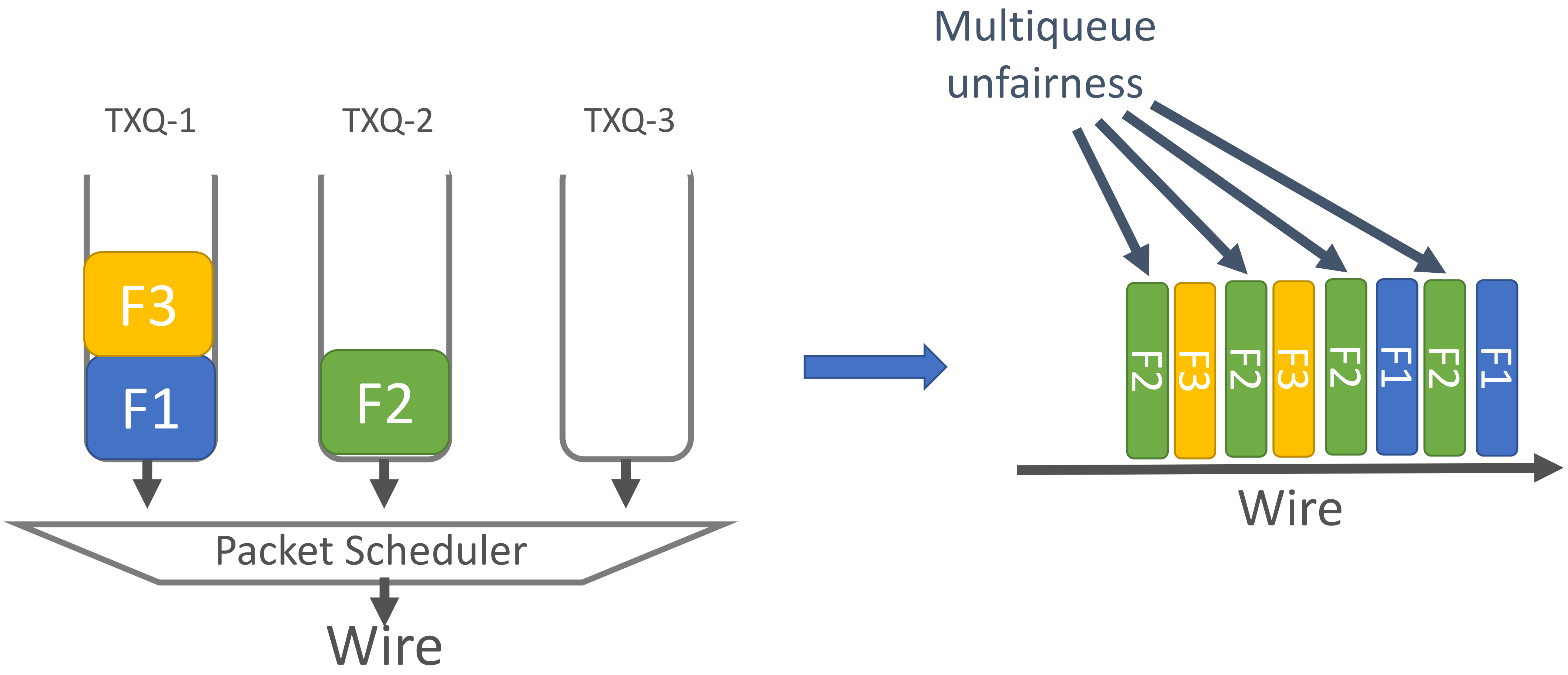


Multiqueue unfairness



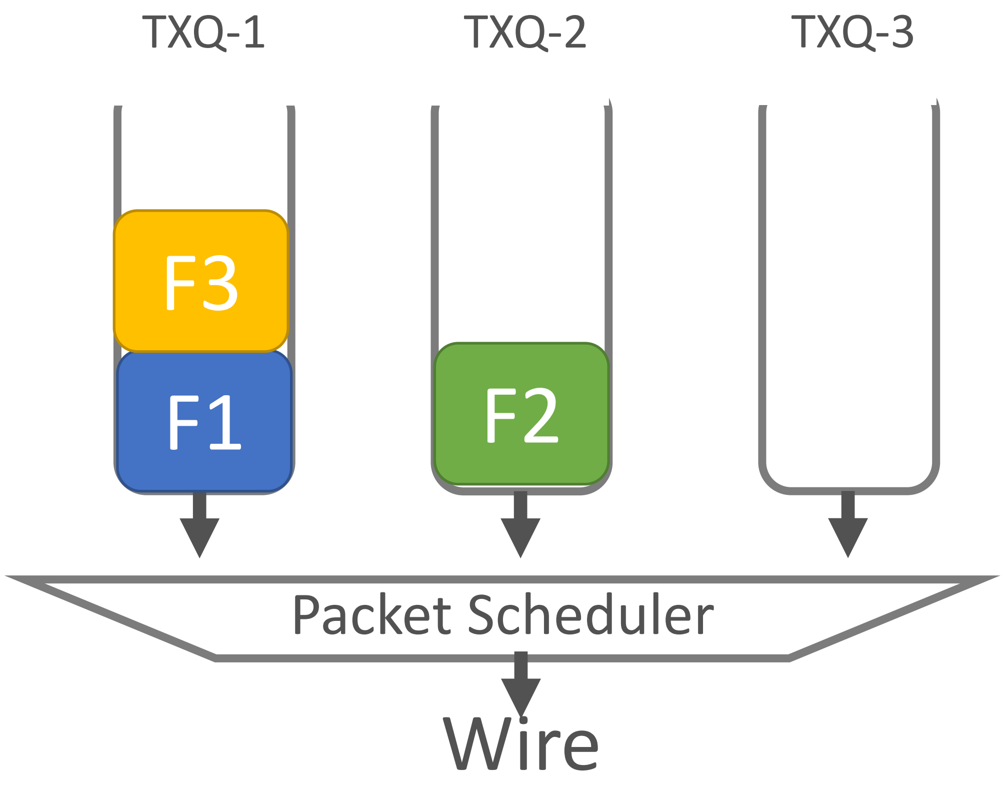
TSO unfairness

Problem: Hash collisions



Problem: Hash collisions

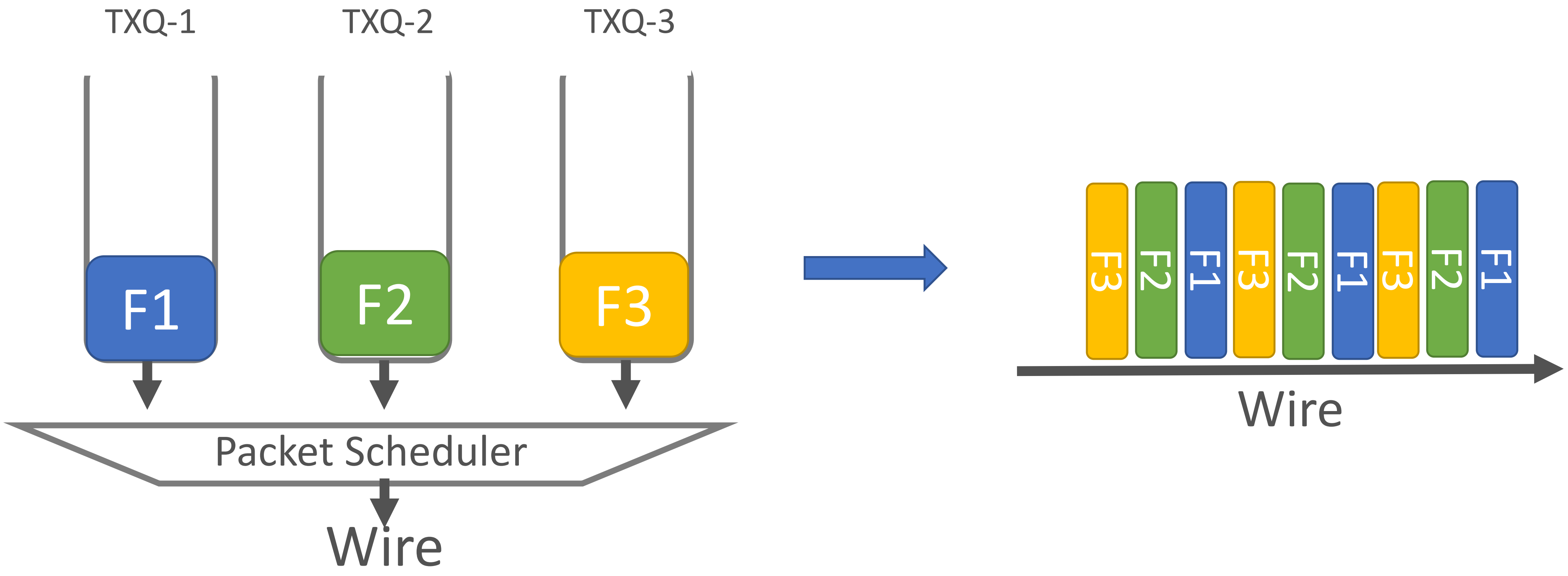
Solution: Dynamic Queue Assignment (DQA)



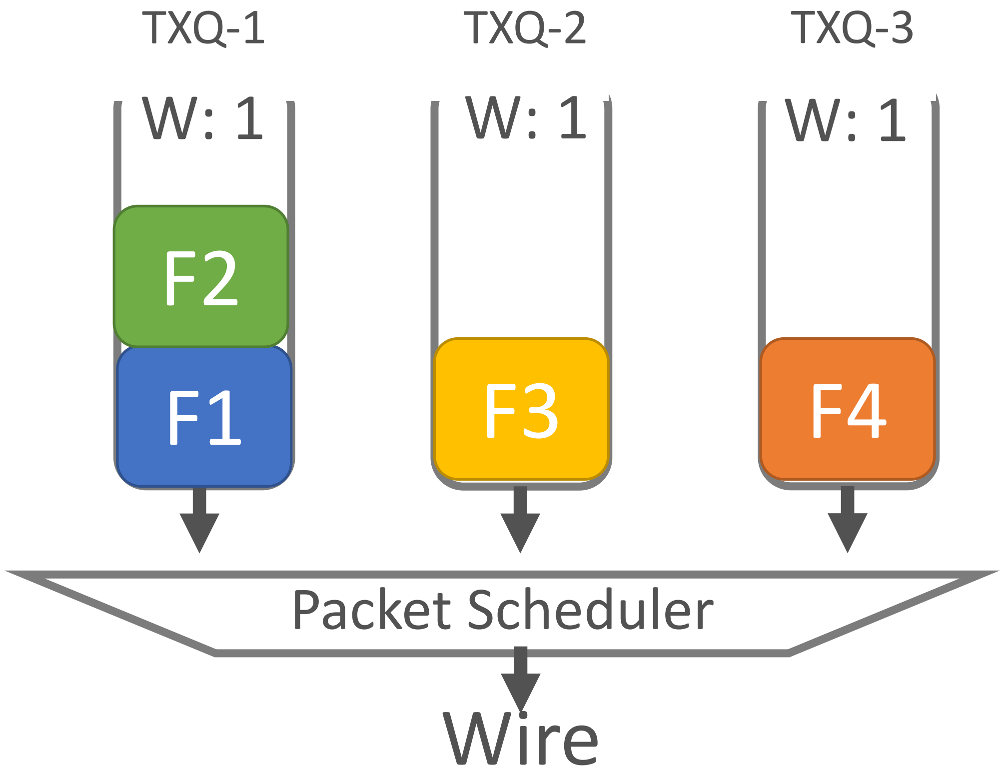
- OS assigns a weight to each flow
- DQA picks the queue with the lowest occupancy when a flow starts
- Queue occupancies are updated:
  - Any time a flow starts enqueuing data
  - Any time a flow has no enqueued bytes (at most each TX interrupt)

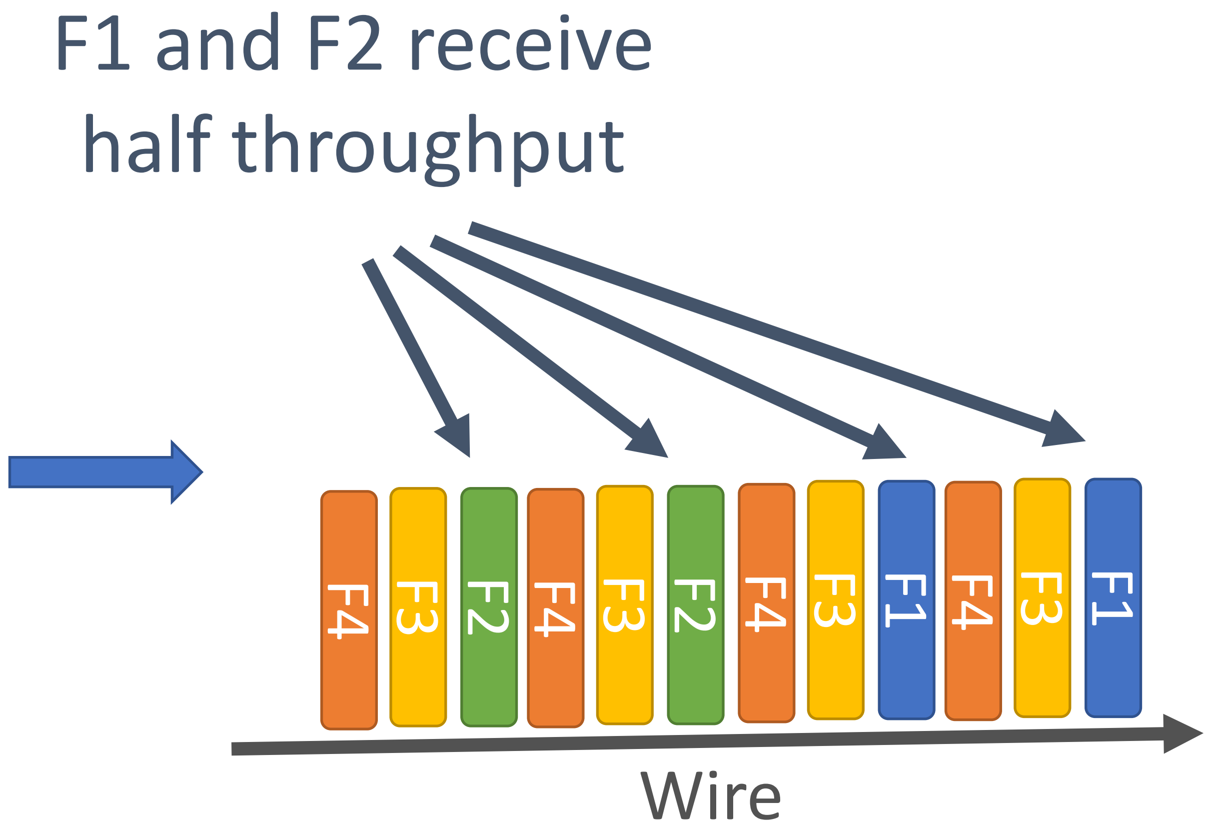
Problem: Hash collisions

Solution: Dynamic Queue Assignment (DQA)



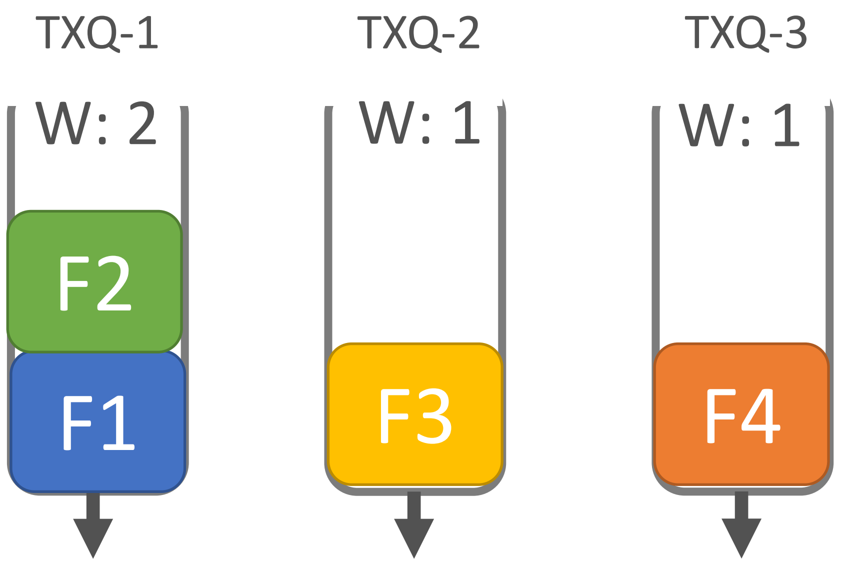
Problem: Asymmetric Oversubscription





Problem: Asymmetric Oversubscription

Solution: Dynamic Queue Weight Assignment (DQWA)

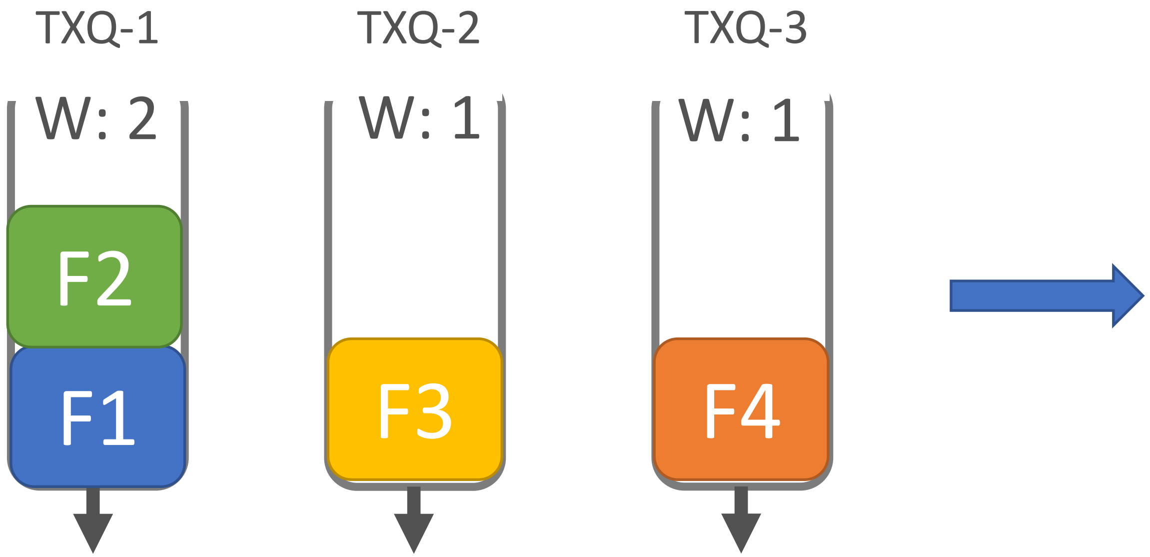


- OS assigns weights to flows
- OS updates the NIC scheduler with queue occupancies as flows start and stop (at most each TX interrupt)
- NIC updates DRR weights

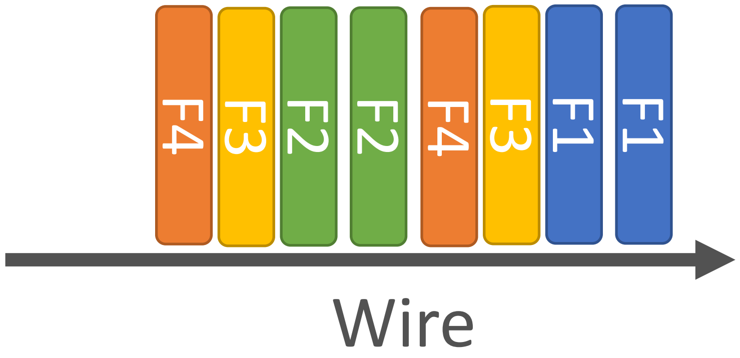
This is implementable on existing commodity NICs because it only needs to update DRR weights!

Problem: Asymmetric Oversubscription

Solution: Dynamic Queue Weight Assignment (DQWA)



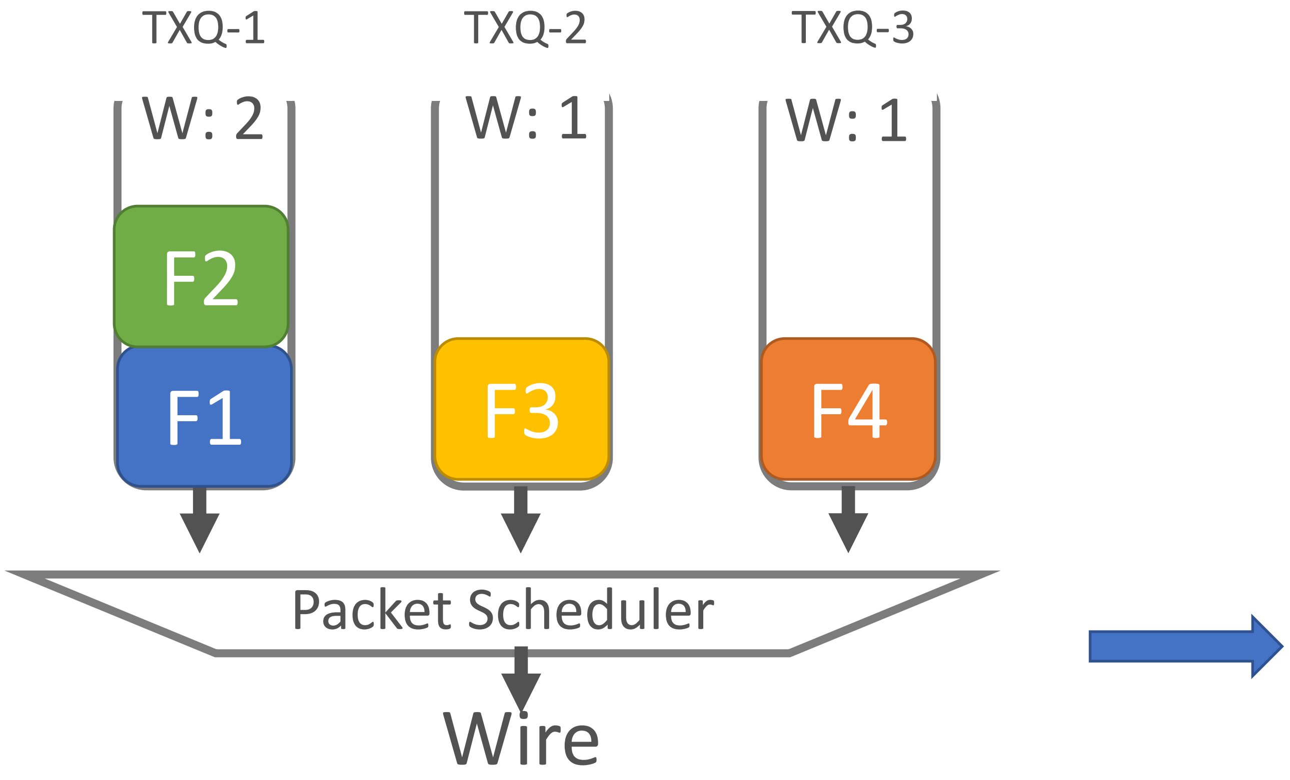
DQA and DQWA provide long-term fairness

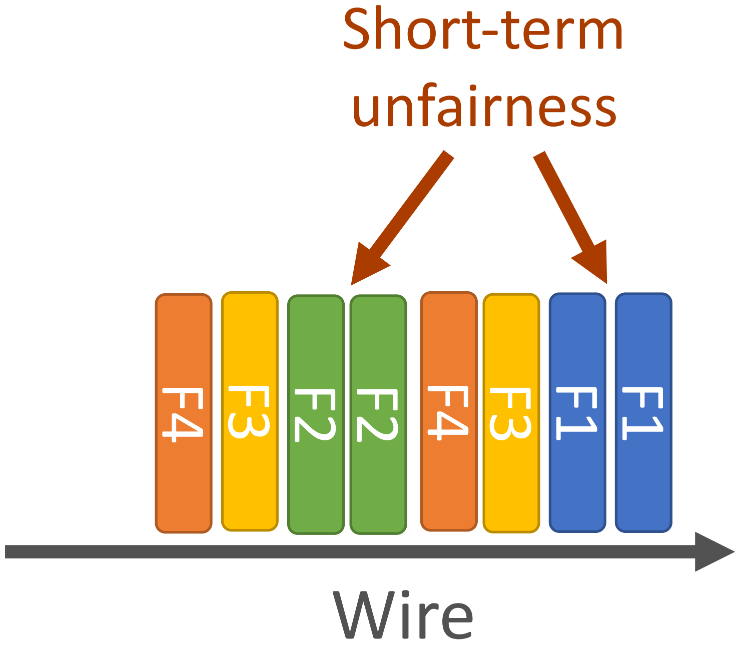


This is implementable on existing commodity NICs because it only needs to update DRR weights!

Problem: TSO Unfairness

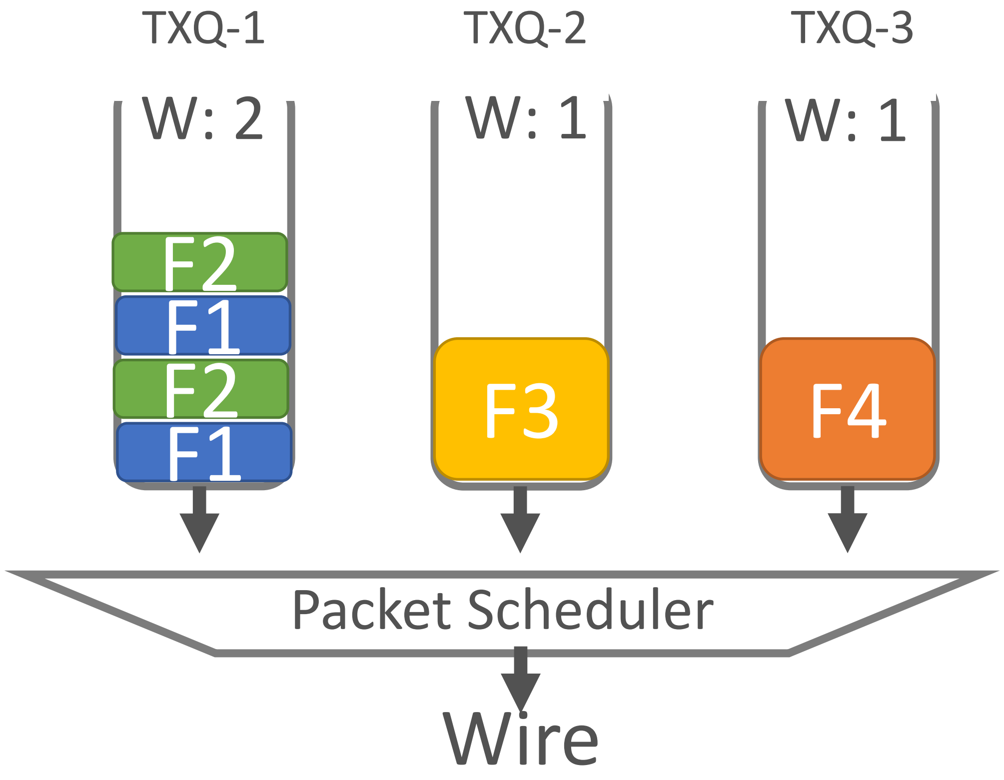
- Short-term unfairness can cause bursts of congestion in the network
- Short-term unfairness can increase latency



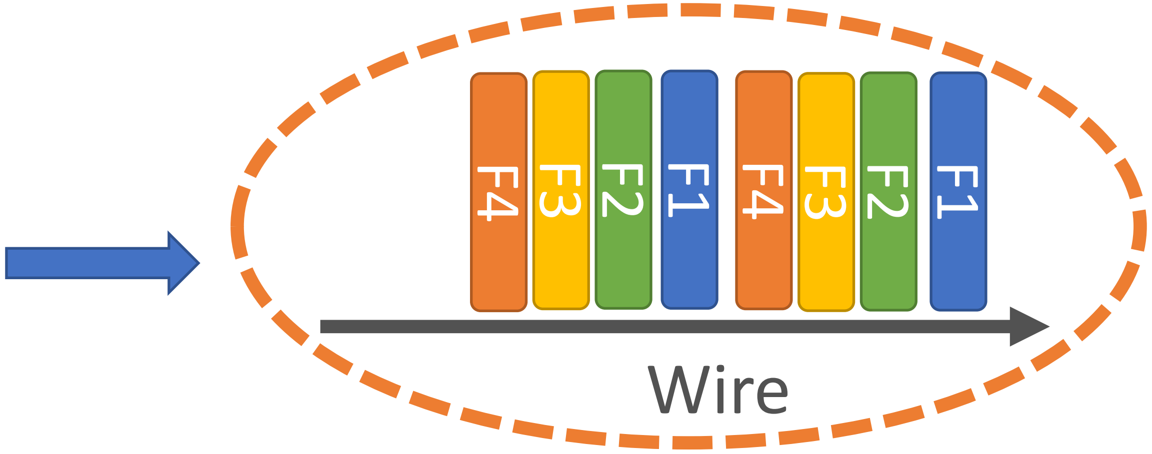


Problem: TSO Unfairness

Solution: Dynamic Segmentation Offload Sizing (DSOS)



- DSOS dynamically changes the segment size during oversubscription
  - Same implementation as GSO
- CPU vs fairness tradeoff
  - Segmenting after the TCP/IP stack reduces CPU costs



Implementation

- DQA, DQWA, and DSOS are implemented in Linux 4.4.6
- Support for `ndo_set_tx_weight` is implemented in the Intel `ixgbe` driver for the Intel 82599 10Gbps NIC
- Titan is open source!

https://github.com/bestephe/titan

Evaluation

- Microbenchmarks
  - 2 servers, 1 switch
  - 8 queue NICs
  - Vary number of flows (level of oversubscription)
- Incremental fairness benefits of DQA, DQWA, and DSOS
  - DQA and DQWA: expected to improve long-term fairness
  - DSOS: expected to improve short-term fairness

Evaluation – Fairness Metric

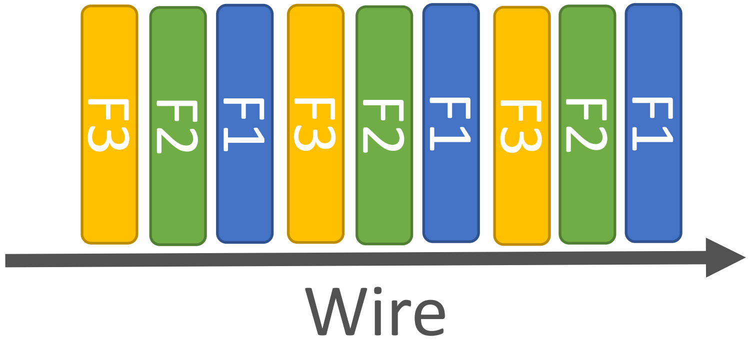
Metrics:

- Normalized fairness metric (NFM) inspired by Shreedhar and Varghese:
  - NFM = 0 is fair
  - NFM > 1 is very unfair

```
NFM =
(Bytes(MaxFlow) -
Bytes(MinFlow)) /
Bytes(FairShair)
```

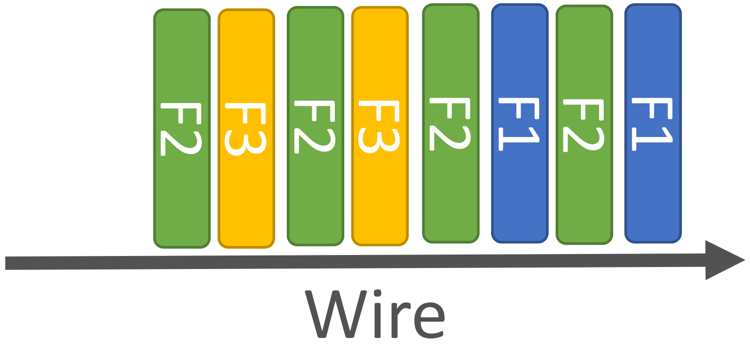
Ideal packet schedule:

NFM = 0



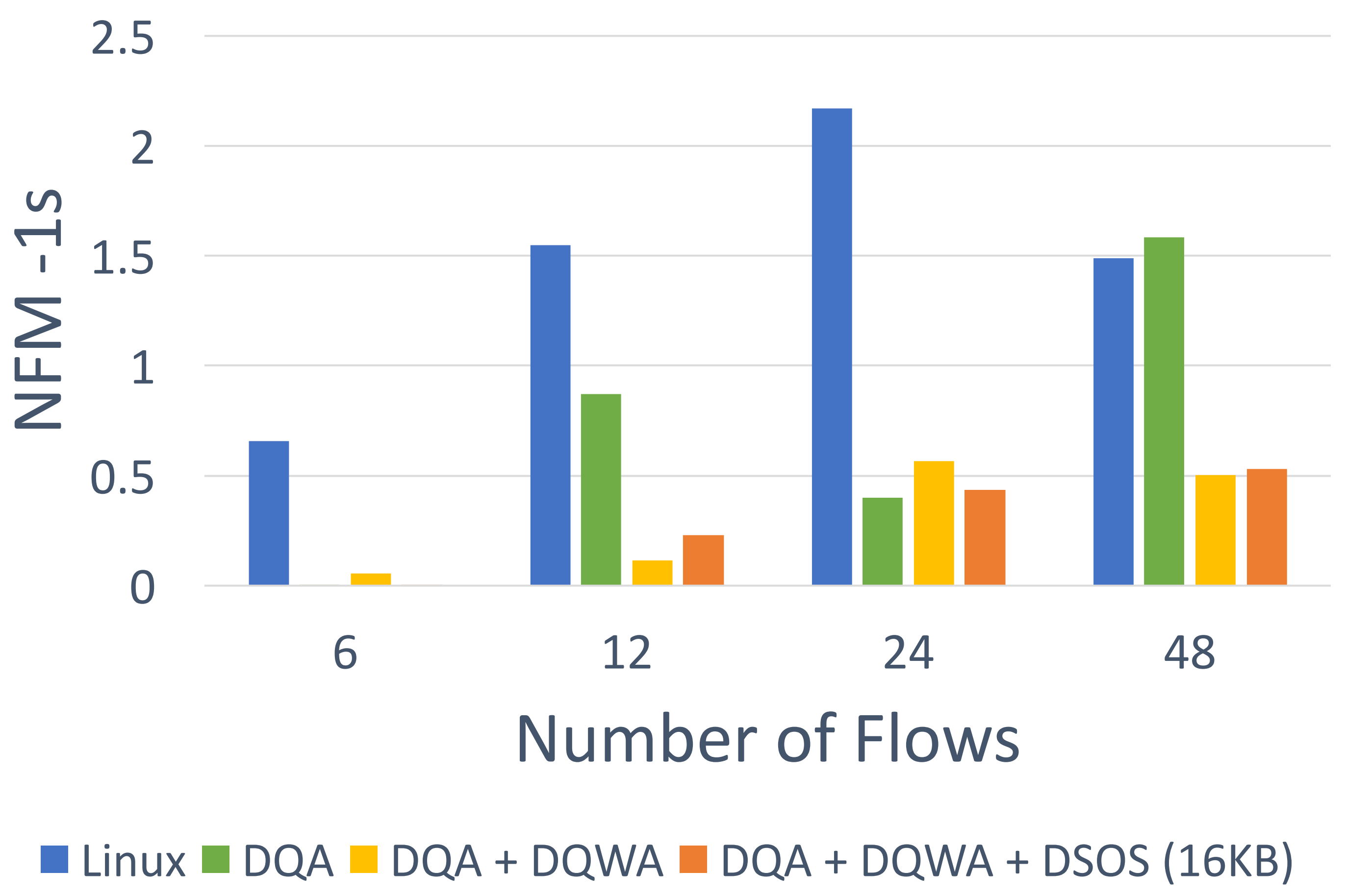
Unfair packet schedule:

NFM = 1



Microbenchmarks – 1s Timescale

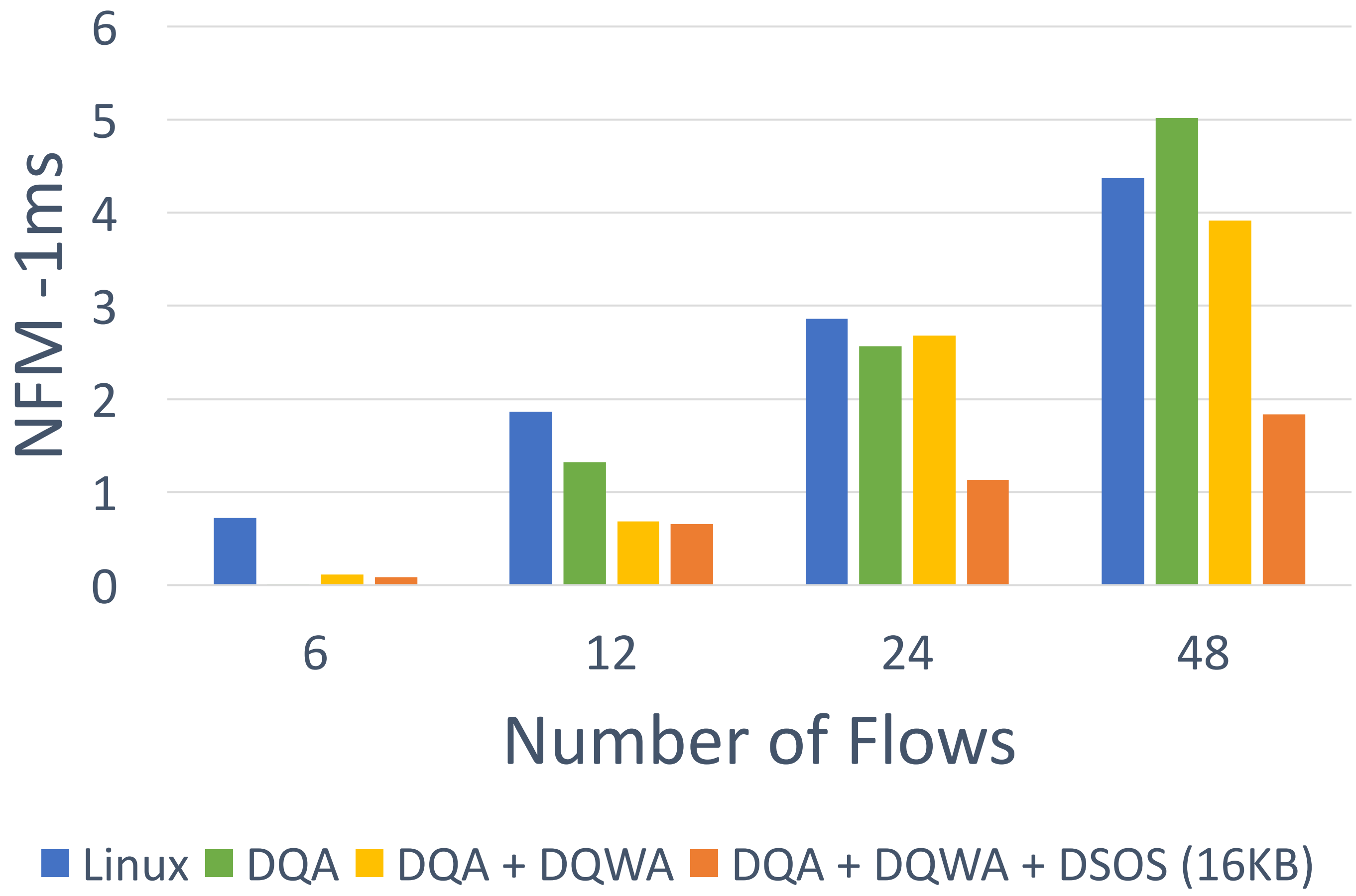
- Linux is unfair at all subscription levels
- DQA often significantly improves fairness
  - At 48 flows, flow churn prevents DQA from evenly spreading flows
- DQWA improves fairness when DQA cannot evenly spread flows across queues
- DSOS does not have a significant impact on long-term fairness



Microbenchmarks – 1ms Timescale

- At short timescales and under oversubscription, DQA and DQWA do not significantly improve fairness
  - TSO is the primary cause of unfairness

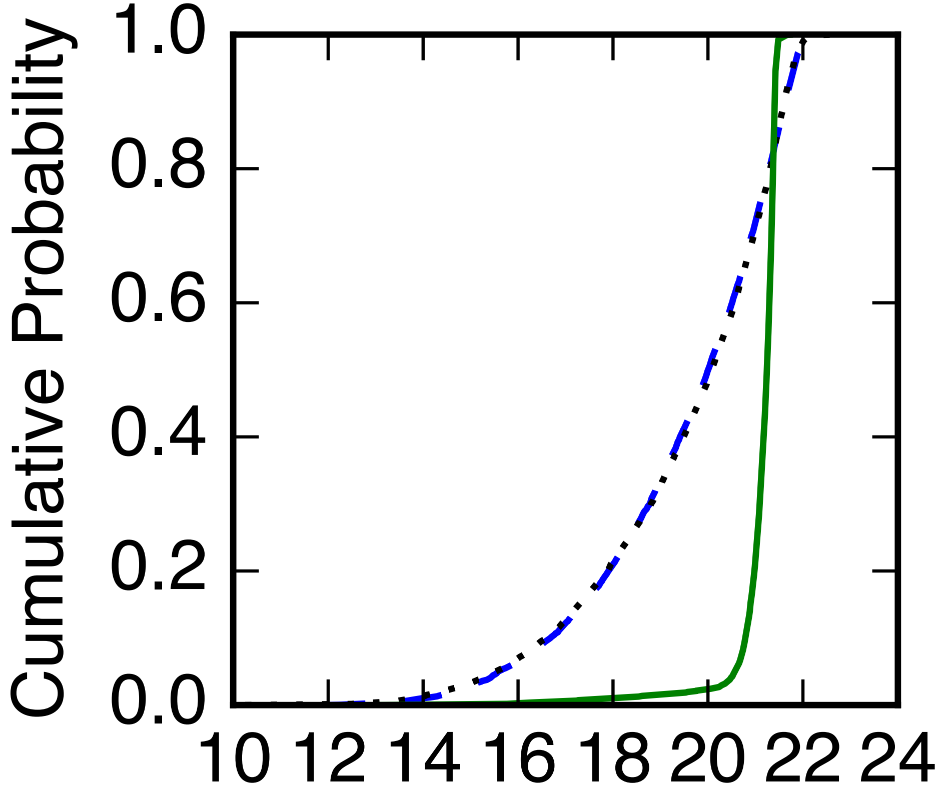
- DSOS (16KB) often reduces unfairness by >2x



Cluster Experiments

CDF of completion times in a 1GB all-to-all shuffle (24 servers)

- Ideal CDF would be a vertical line
- Titan makes performance more predictable
- Titan improves tail performance (>90th percentile)



Titan improves fairness without changing the network core!

Additional Evaluation

Additional performance metrics:

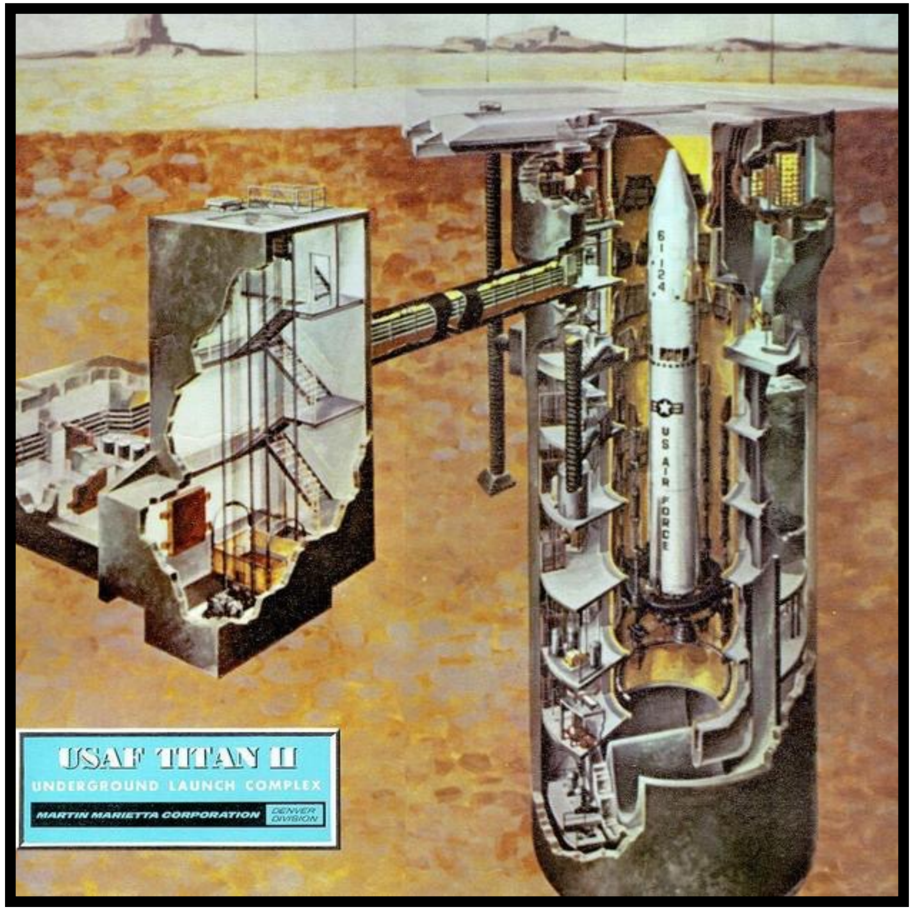
- Throughput: line-rate
- Latency: no significant change
- CPU Utilization:
  - DQA and DQWA: increase < 10%
  - DSOS is better than statically decreasing the TSO size
    - DSOS motivates creating a better TSO implementation (zero-copy)

Linux network configuration trade-off study

- See paper

Summary

- Multi queue NICs can lead to significant flow-level unfairness
  - Titan significantly improves fairness by allowing the OS to *dynamically* interact with the NIC packet scheduler
  - Titan is implementable on commodity NICs!



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