Automatic In-network Control Empowered by Programmable Infrastructure

Liangcheng Yu

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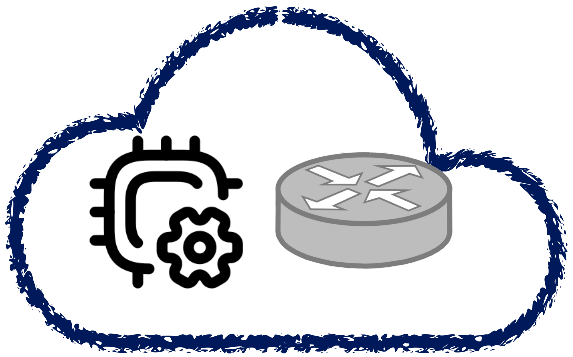
@MSR AFO-OCTO

Penn
University of Pennsylvania

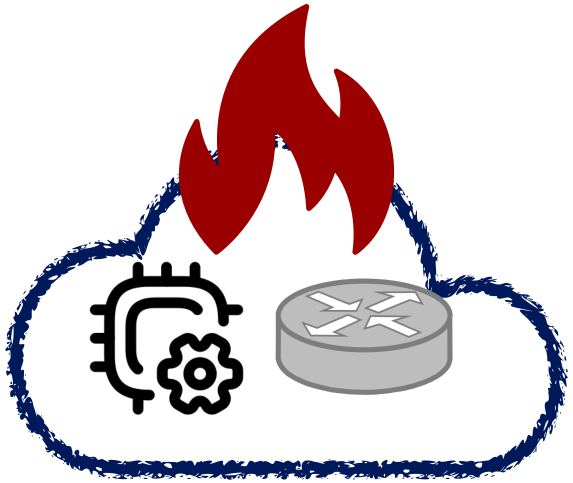
Ubiquitous network control tasks



Ubiquitous network control tasks

Out-of-control events

- Congestion collapse
- TCP incast
- Network hotspot
- DoS attack
- Network failure
- Time drift
- Bandwidth starvation
- …



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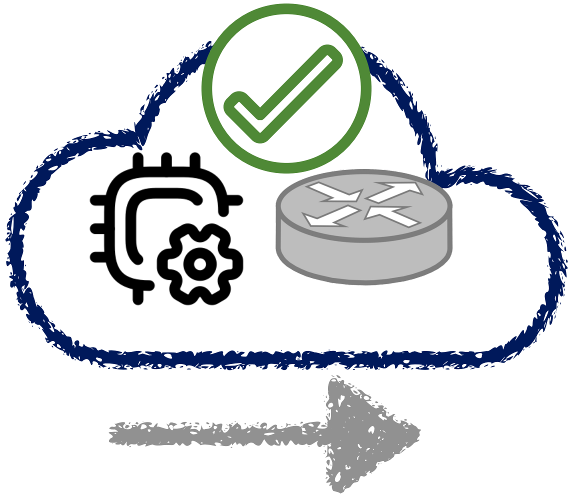
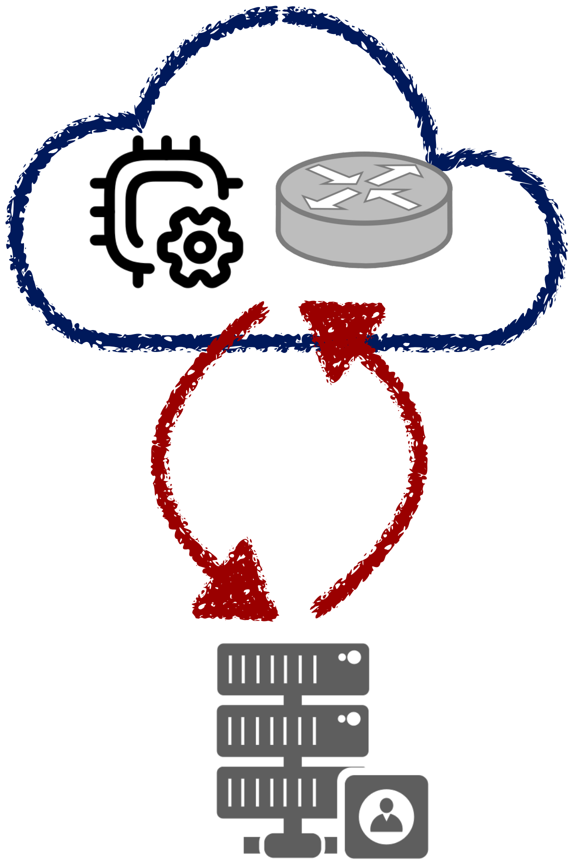


Closed-loop control mechanisms

- Congestion control
- Desynchronization
- Load balancing
- Defense policy
- Failure mitigation
- Clock synchronization
- Fairness control
- …

Anatomy of network control



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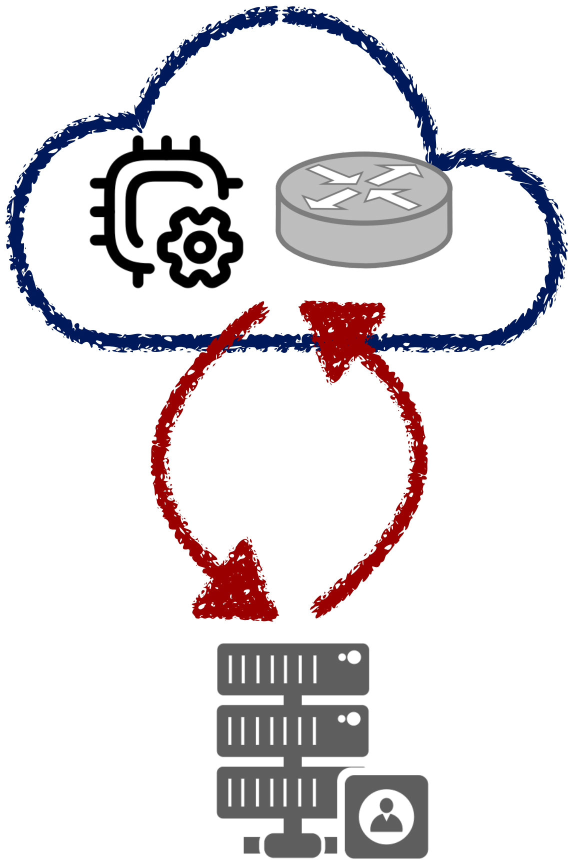

System identification

Linear models? Blackbox? Source of disturbances or misbehaviors?

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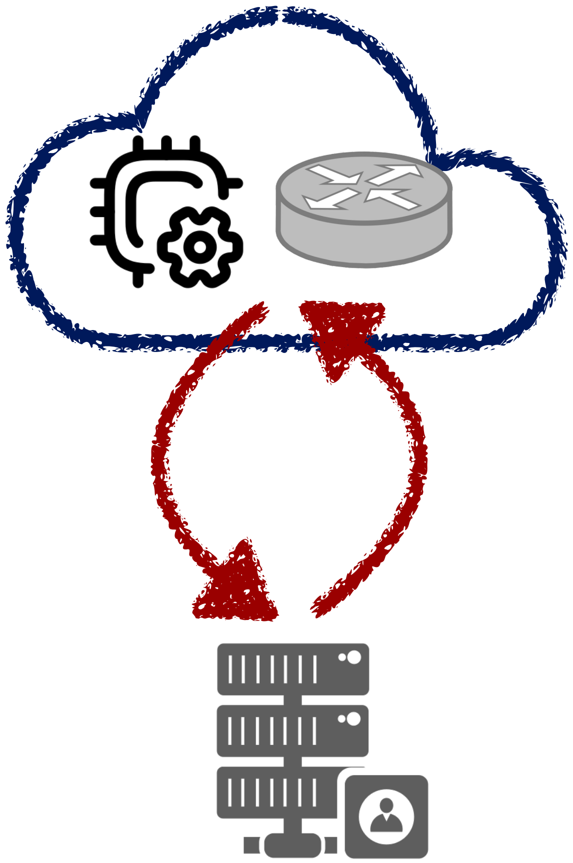

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Target signals? Granularity? Explicit or implicit? Synchronous?

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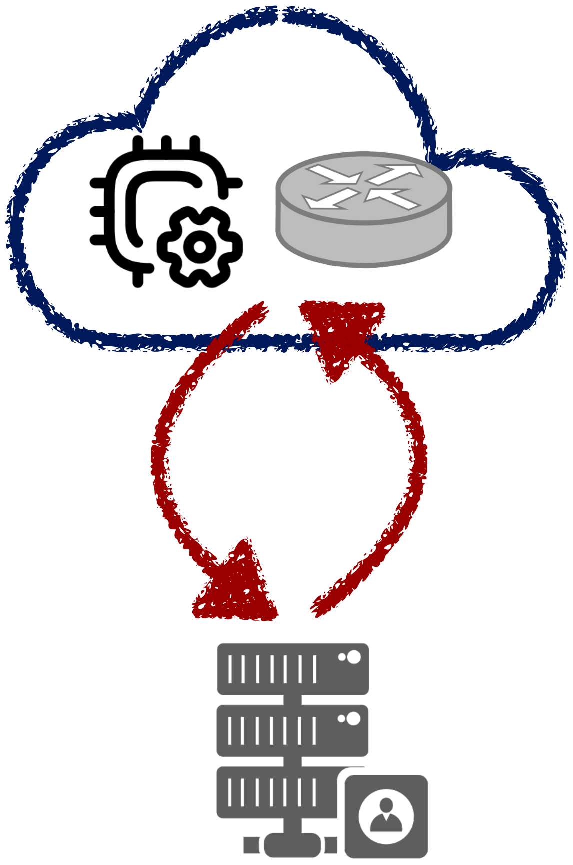

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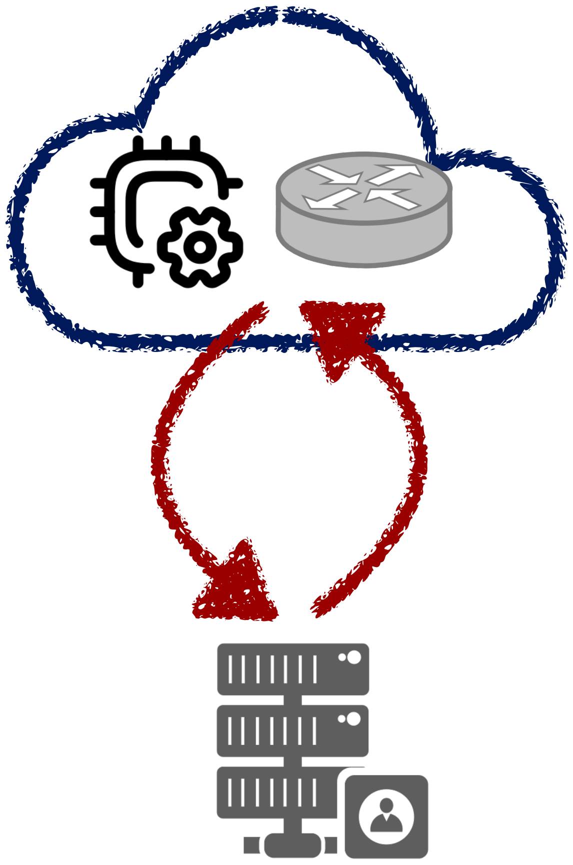

Actuation

Adaptive? Rate limiter config?
Switch weights? Routes? Pacing?

Measurement

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Explicit or implicit? Synchronous?

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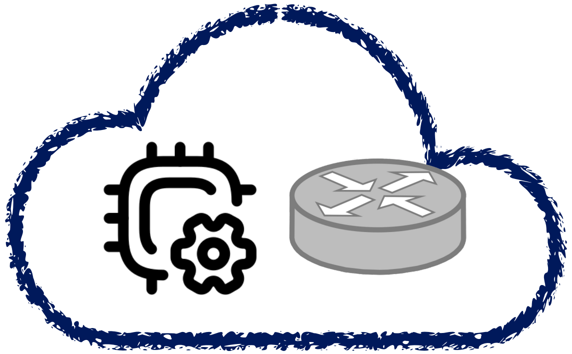
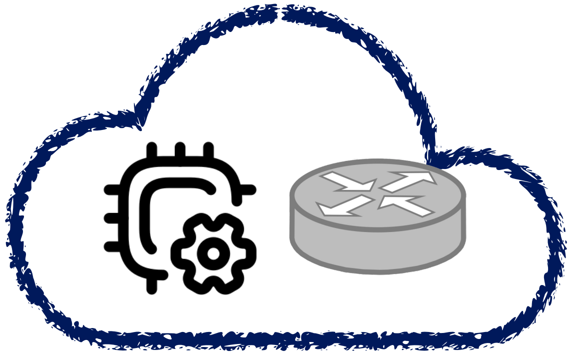
Sustaining network control



Faster networks $< 1 \rightarrow 10 \rightarrow 100 \rightarrow 800 \rightarrow \ldots$[Gbps]

Sustaining network control



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- ***Microscopic*** *(O(μs)) events are prevalent*
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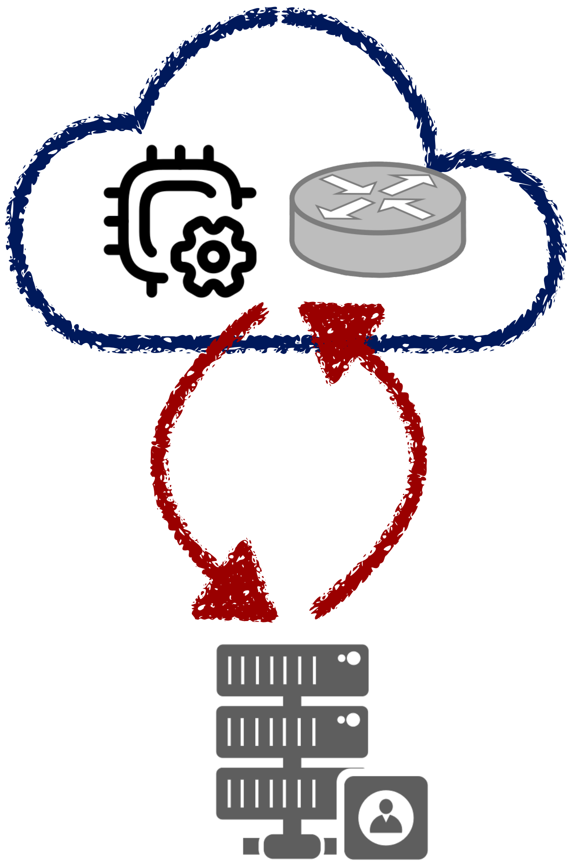

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Traditional network control

- ***Infrequent*** *(O($100\,ms$)),* ***asynchronous****, and* ***manual***

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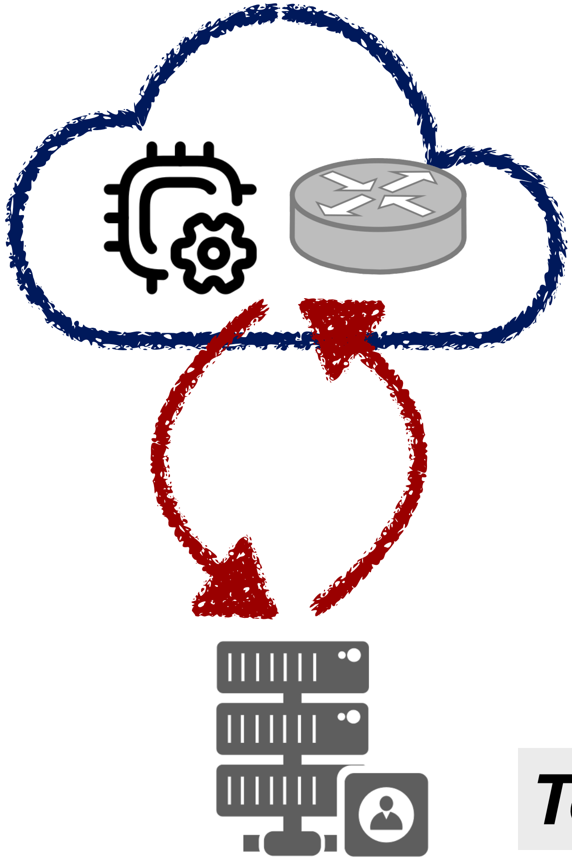

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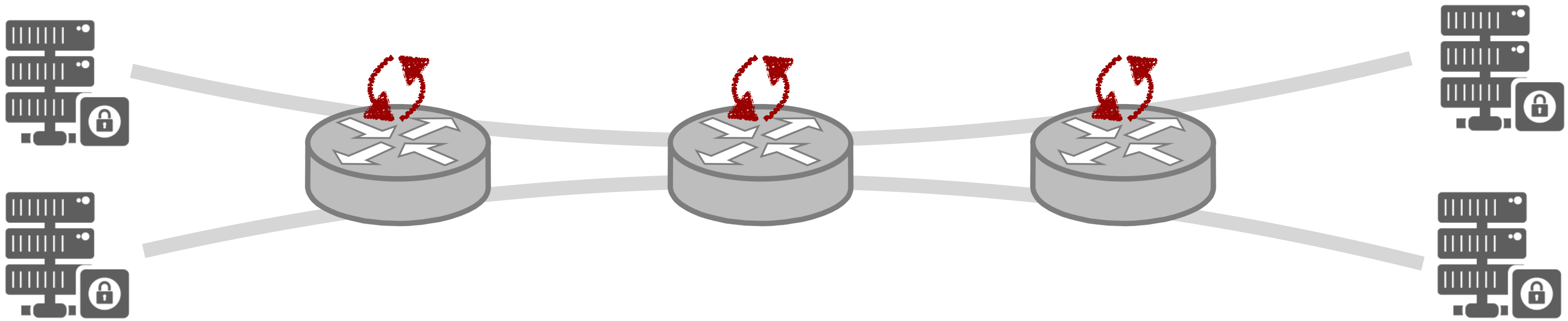
Towards fast, real-time, and automatic control at scale?

Opportunities: in-network control



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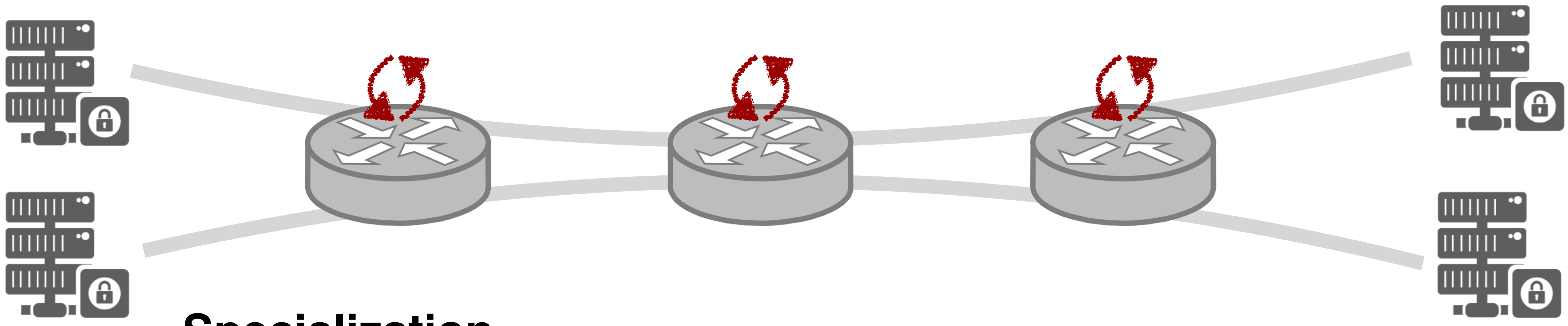

Specialization

- High throughput (>12.8 Tbps, billions of operations/s)
- Little additional overhead with processing logic

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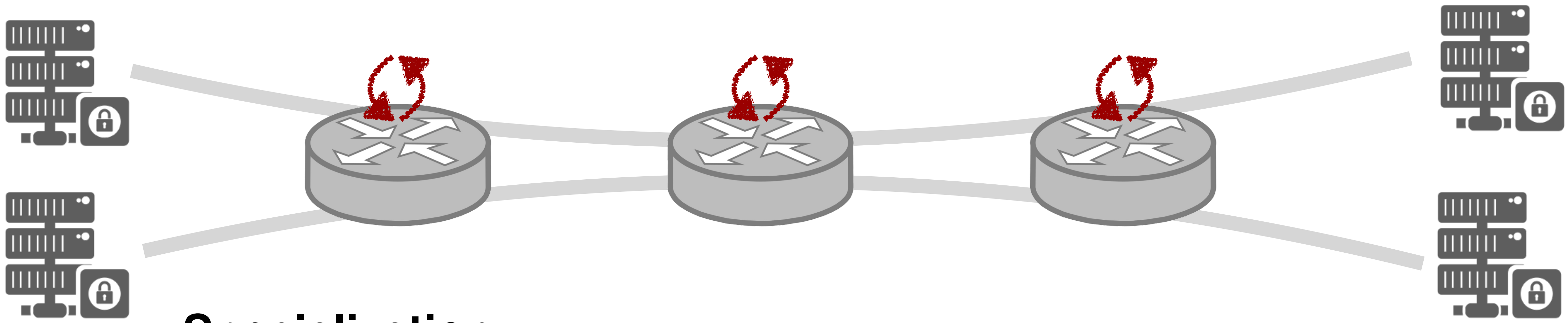


Specialization

- High throughput (>12.8 Tbps, billions of operations/s)
- Little additional overhead with processing logic

Locational benefits

- Customizable line-rate processing to reduce (tail) latency
- Visibility into accurate network information

Opportunities: in-network control

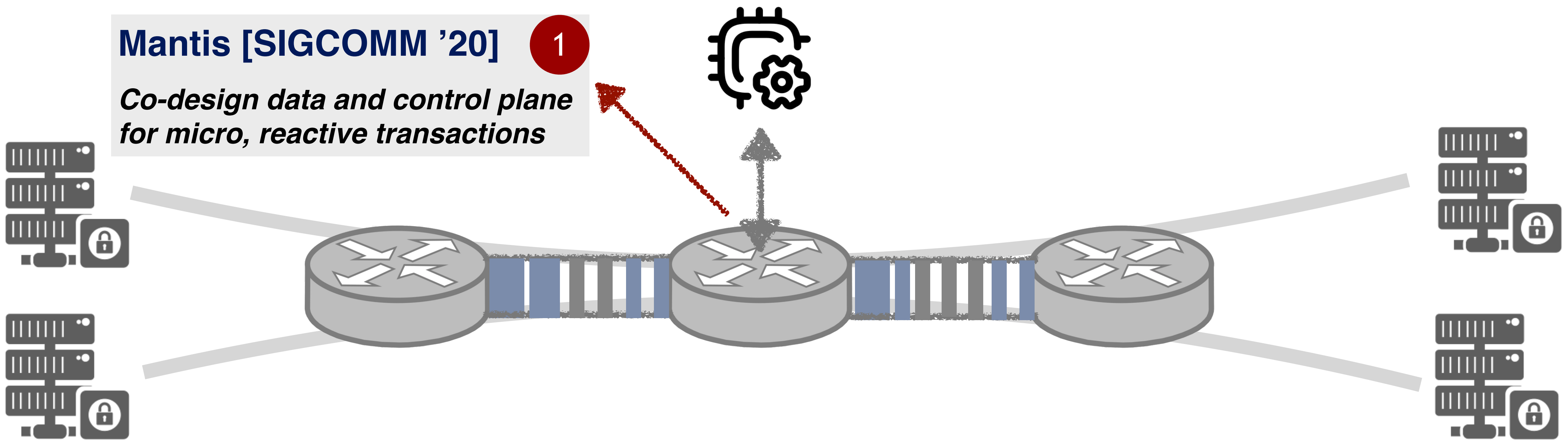
Once you've got a software platform where you can ***change its behavior****, you can start introducing previously absurd-sounding ideas, including fanciful ideas of* ***automatic, real-time, closed-loop control of an entire network****."* — Nick McKeown

- 12.8 Tbps of throughput and beyond
- Low overhead with additional processing logic

Unique locational benefits

- Processing along packet path to reduce (tail) latency
- Visibility into accurate network information

Pushing switches to the limit via tight coupling



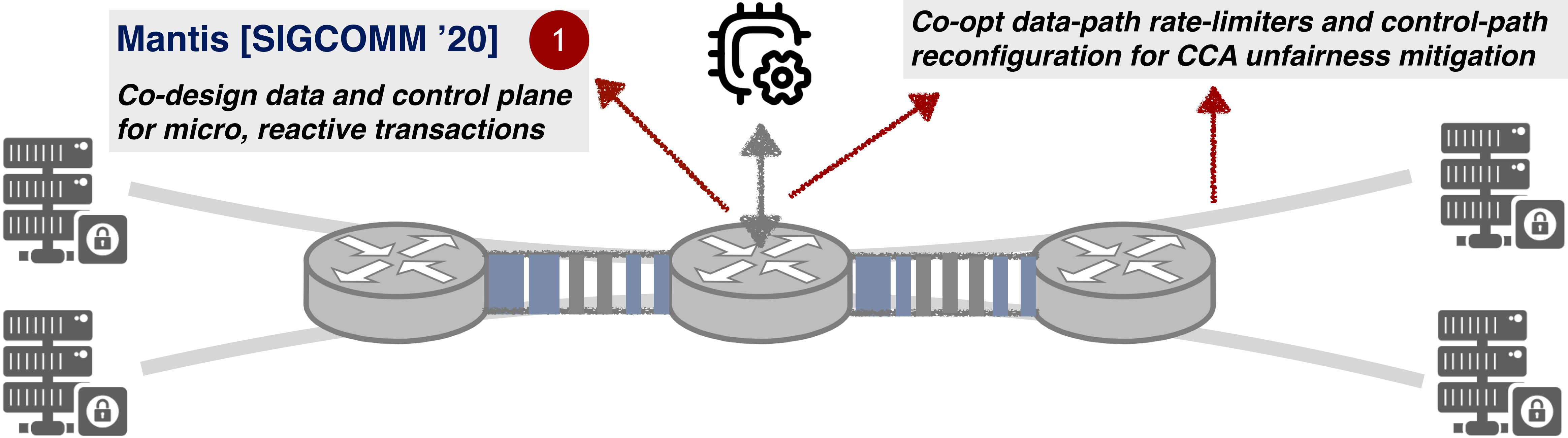
Pushing switches to the limit via tight coupling

Mantis [SIGCOMM '20] 1

Co-design data and control plane for micro, reactive transactions

Cebinae [SIGCOMM '22] 2

Co-opt data-path rate-limiters and control-path reconfiguration for CCA unfairness mitigation



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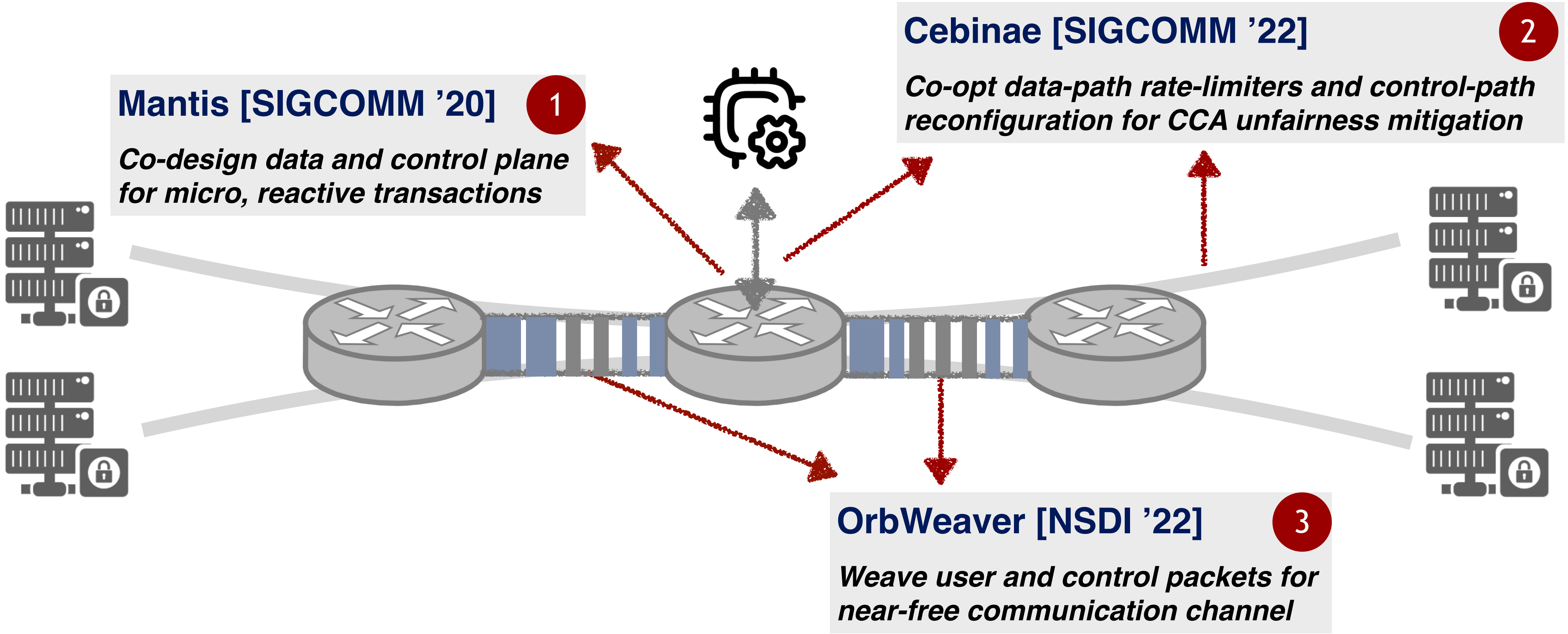

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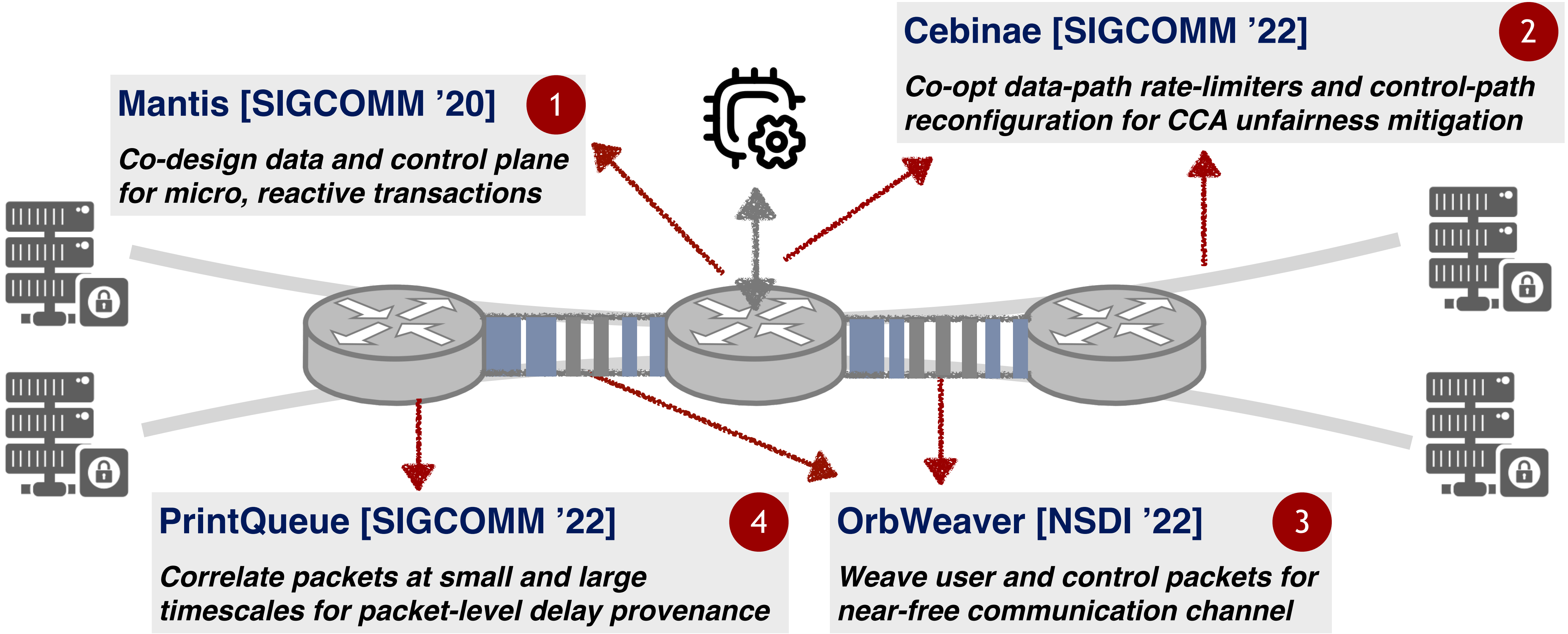

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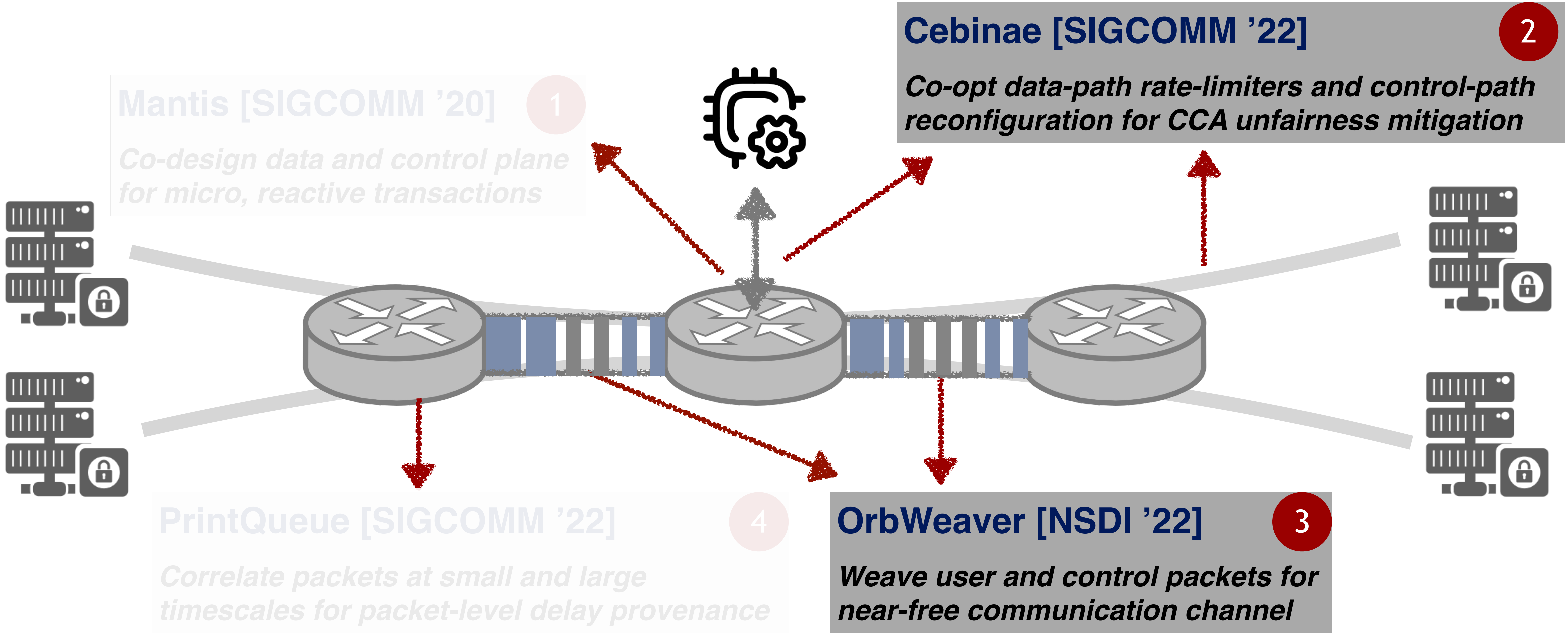
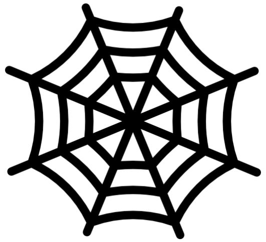


Outline



OrbWeaver:
Using IDLE Cycles in Programmable Networks for Opportunistic Coordination

Cebinae:
Scalable In-network Fairness Augmentation

Networks are woven from packets

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Networks are woven from packets

- A primary goal of computer networks: ***deliver packets***
  - ***User application***: video streaming, web browsing, file transfer…
  - ***Non-user application***: control messages, probes about network state, keep alive heartbeats…

- Often, two classes of traffic ***multiplex*** the same network

When introducing a new in-band application…

To consume ***extra BW*** for ***fidelity*** *(of the control application)*, or not to?

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- *Failure detector*: **keep alive message frequency** → **detection speed**
- *Congestion notification*: **signaling data/rate** → **measurement accuracy**
- *In-band telemetry*: **INT postcard volume** → **post-mortem analysis**

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Is the trade-off between fidelity and overhead necessary?

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Can we coordinate at **high-fidelity** with a **near-zero cost** (to usable bandwidth, latency…)?

Is the trade-off between fidelity and overhead necessary?

Can we coordinate at **high-fidelity** with a **near-zero cost** to usable bandwidth and latency?

Idea: Weaved Stream

- Exploit ***every gap*** (*O(100ns)*) between user packets opportunistically
- Inject customizable ***IDLE packets*** carrying information across devices

Opportunity: $< \mu s$ gaps are prevalent

- *Application-level traffic patterns*
- *TCP effects*
- *Structural asymmetry*
- *…*

Abstraction: weaved stream

- Union of **user** and **IDLE** (injected) packets:

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[R1 Predictability] Interval between ***any two consecutive*** packets $\leq \tau$

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[R1 Predictability] Interval between ***any two consecutive*** packets $\leq \tau$

[R2 Little-to-zero overhead] Not impact user packets or power draw

Abstraction: weaved stream

- Union of user and IDLE (injected) packets:

Implement many ***in-network applications***

(failure detection, clock sync, congestion notification…)

for free!

1. [Predictability] Interval between ***any two consecutive*** packets $\leq \tau$
2. [Little-to-zero overhead] Weaved IDLE packets not impact user packets

Abstraction: weaved stream

- Union of **user** and **IDLE** (injected) packets:

Crazy idea?

Extending IDLE characters to higher layers

- Data plane packet generator
- Replication engine
- Data plane programmability
- Flexible switch configuration (priorities, buffers…)

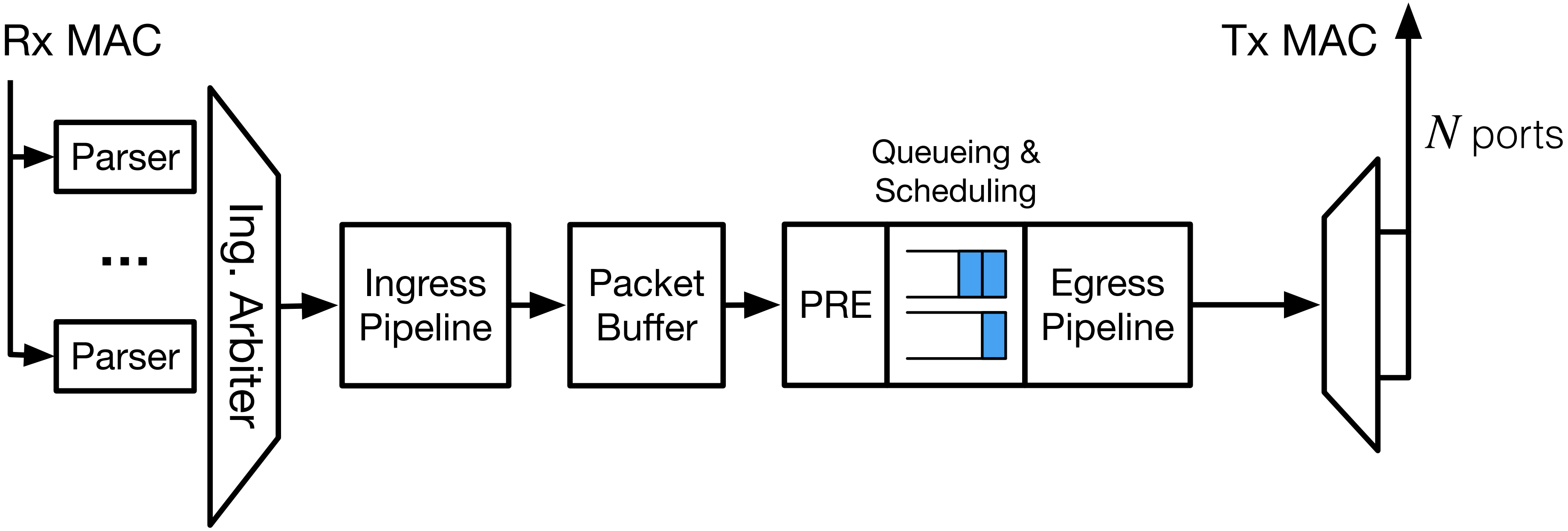
1. Interv

2. Weaved IDLE packets incur ***little-to-zero*** impact to user packets

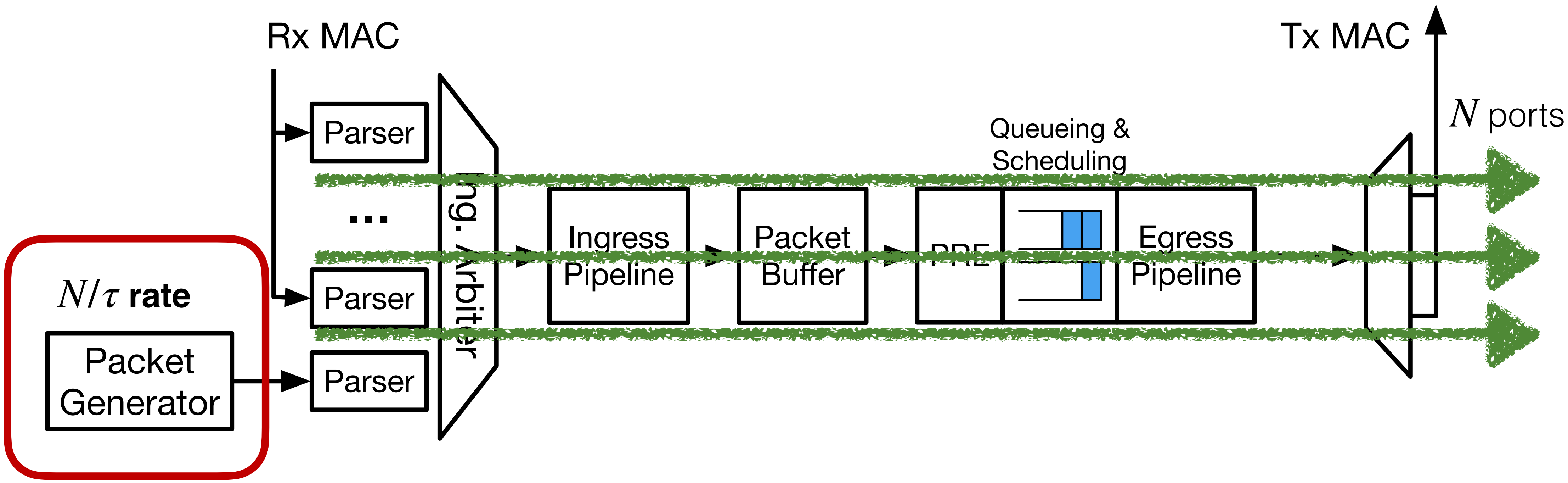
Outline

1. Switch data plane architecture
2. Weaved stream generation
3. OrbWeaver applications

RMT switch model



Naive weaved stream generation



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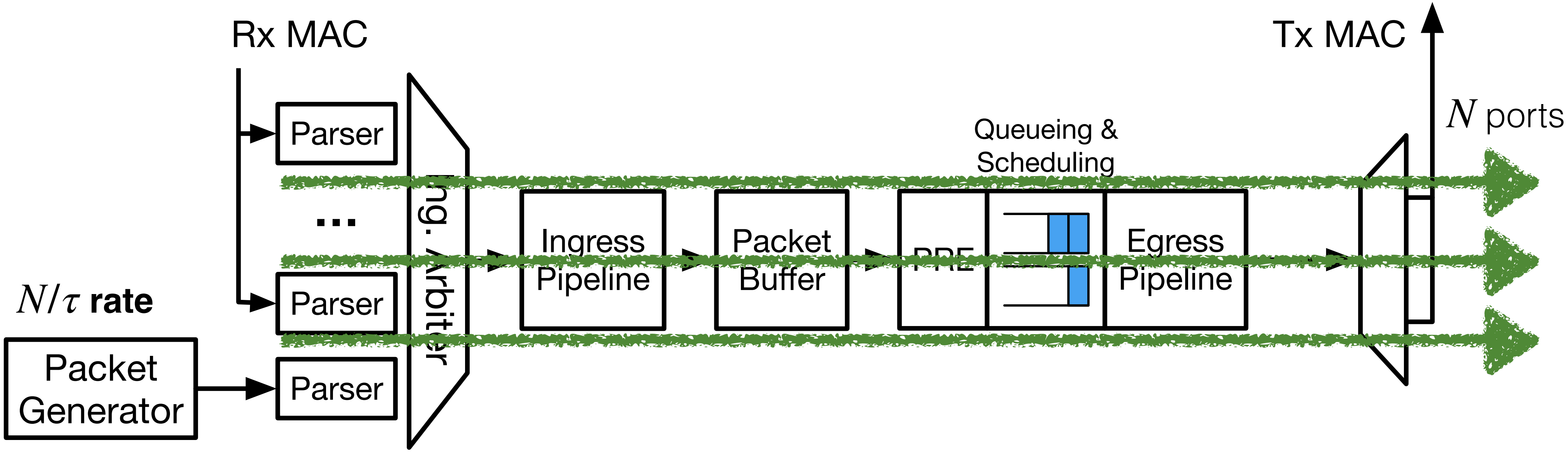
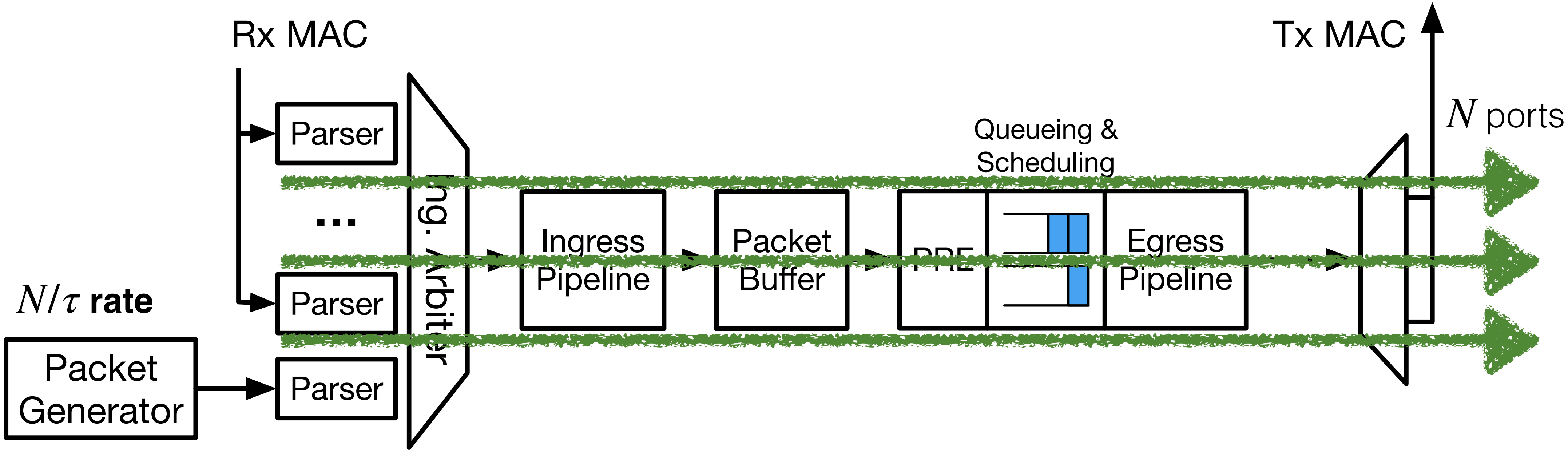


Predictability even there is no user traffic ✔

Problems with blind injection



Scalability: overwhelm packet generator capacity to satisfy target rate

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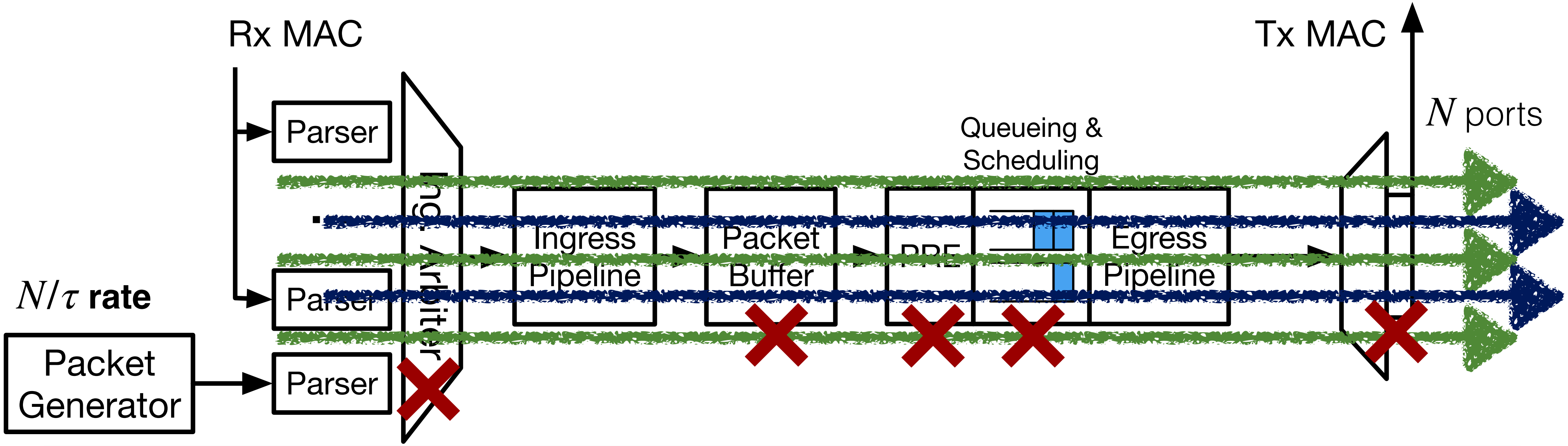
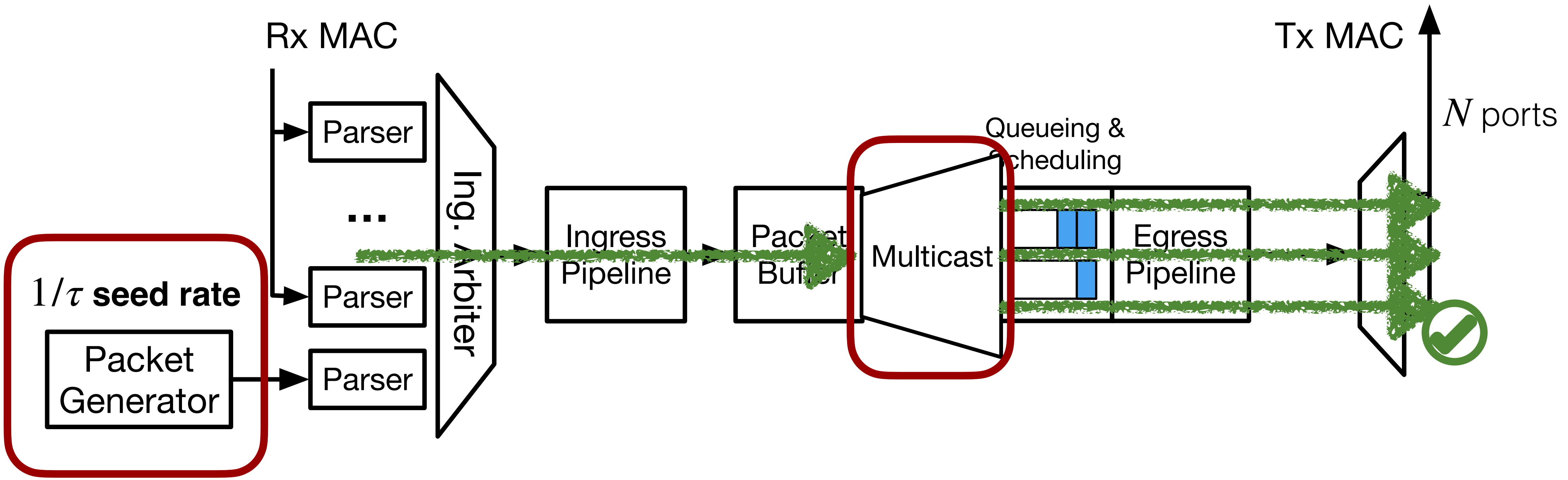


Scalability: overwhelm packet generator capacity to satisfy target rate

Interference upon cross-traffic: throughput, latency, or loss of user traffic!

Amplify seed stream



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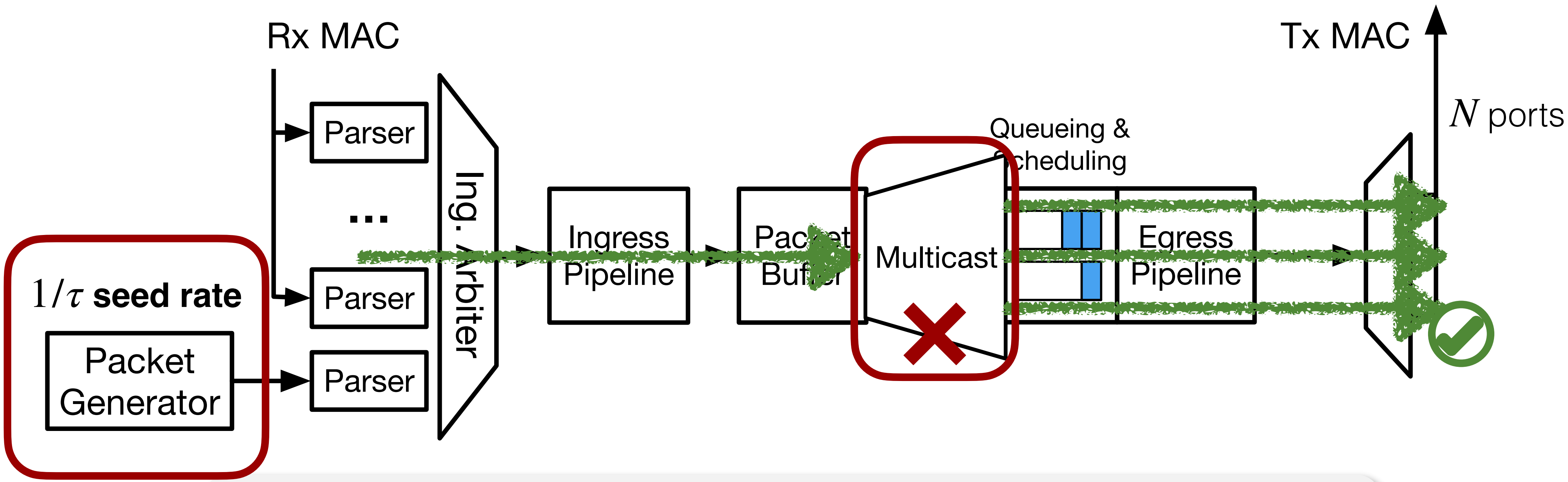
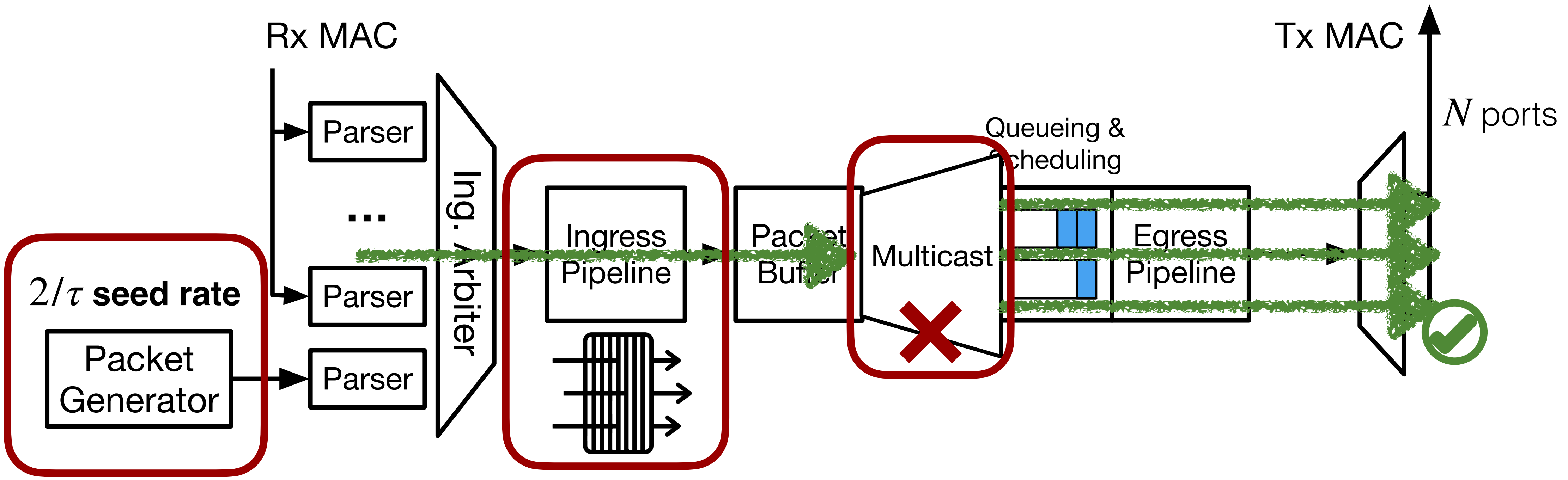


Monopolize usage and waste PRE packet-level BW!

Amplify seed stream <u>on demand</u>



<u>Selective filtering</u>

- (Tiny) sending history state of past cycle to each egress port
- Create an IDLE packet to a port ***only if we need an IDLE packet***

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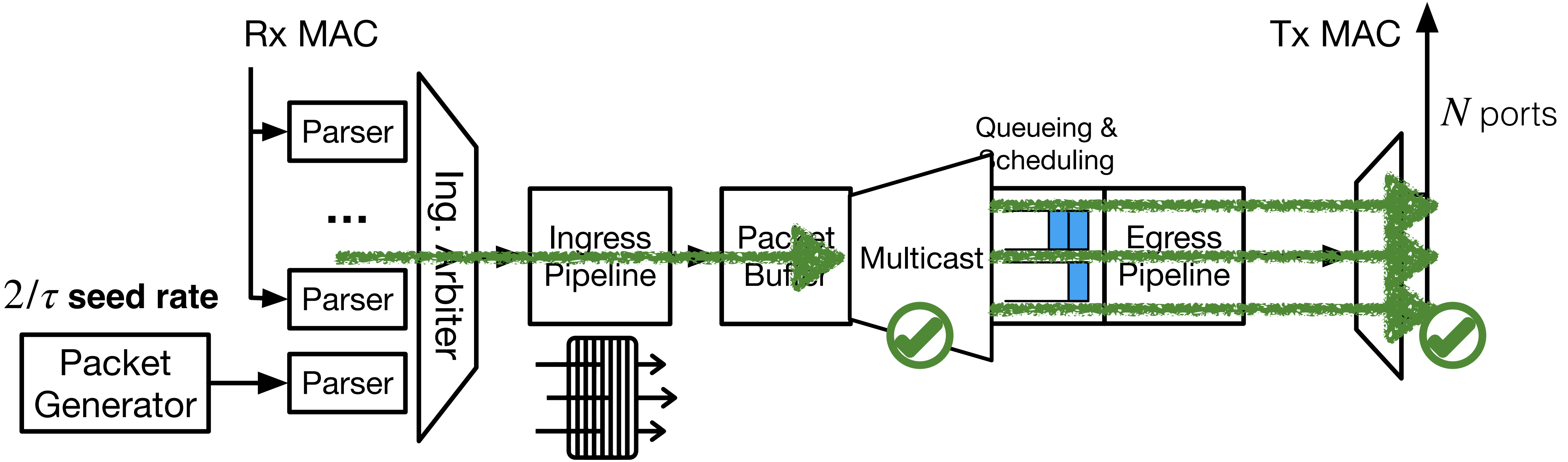

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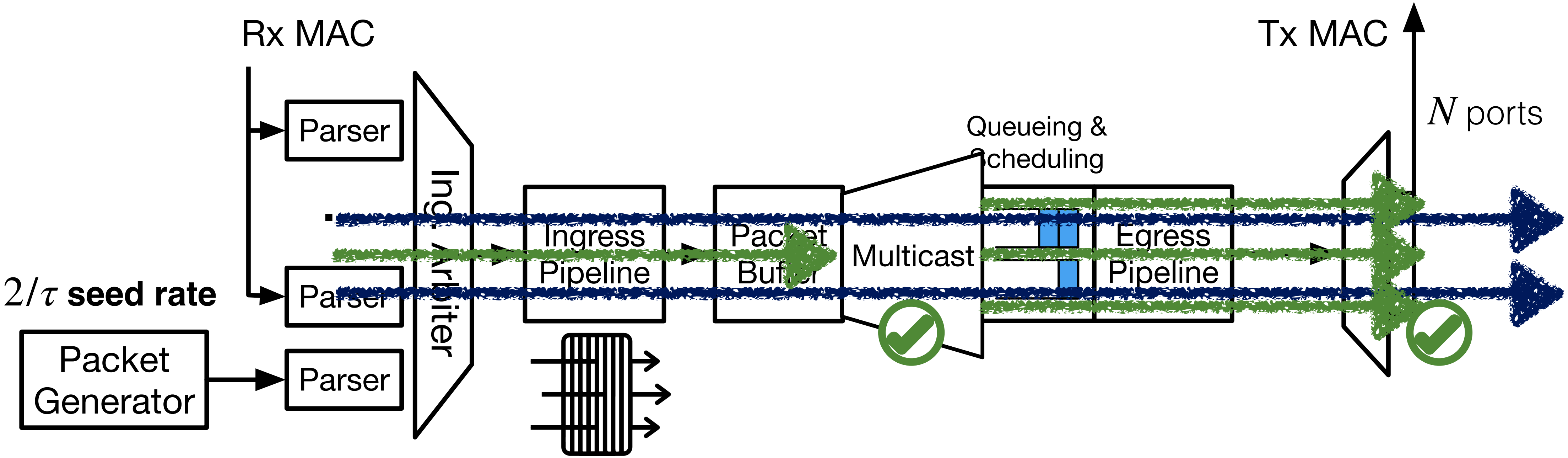
Cross-traffic contention



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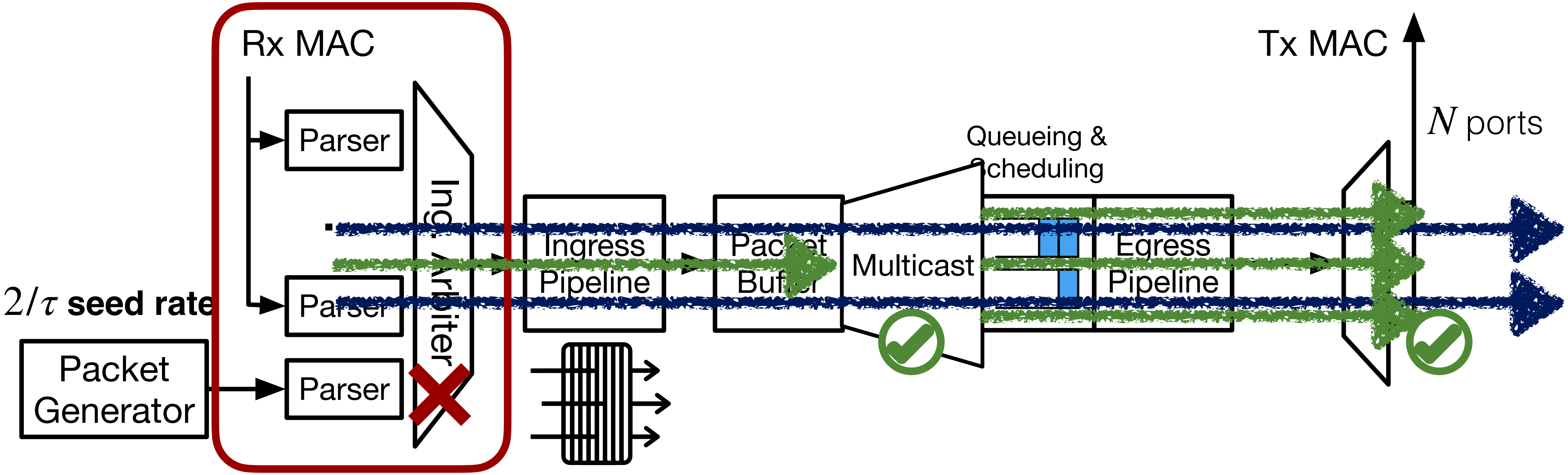
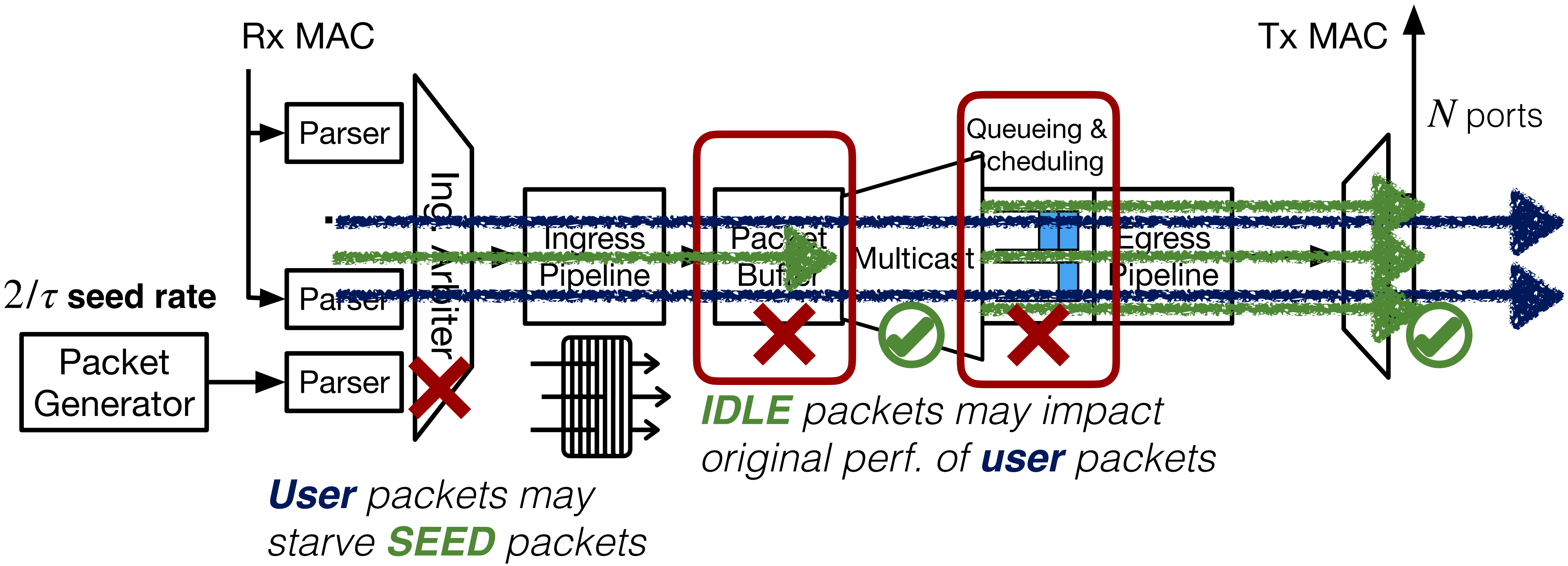
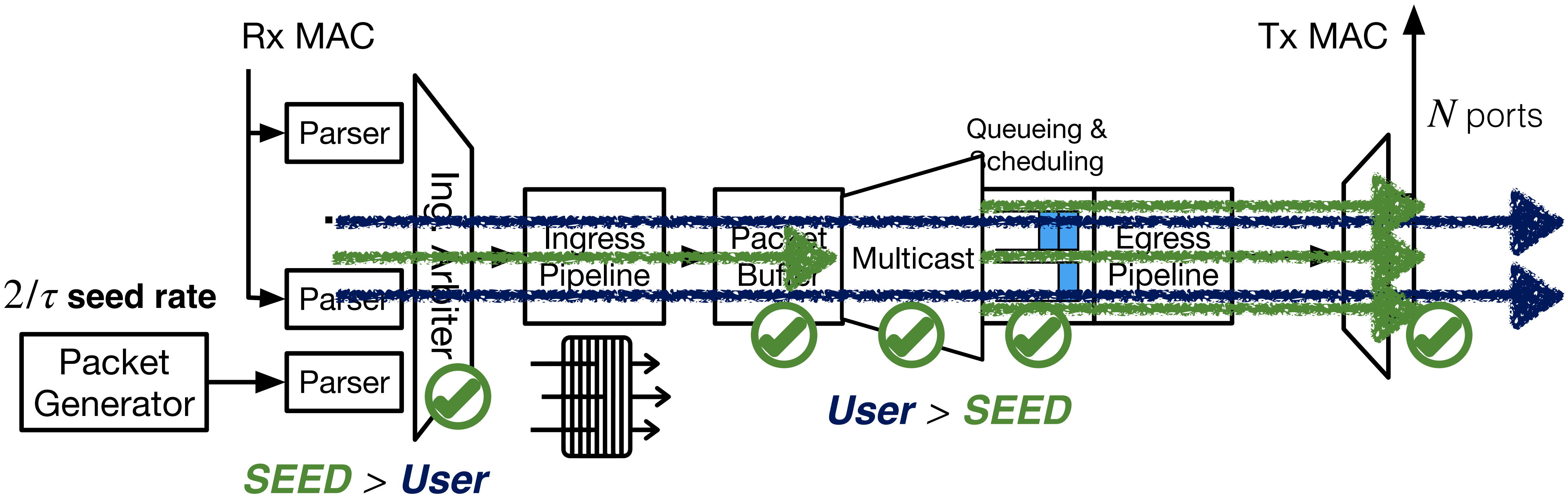


User *packets may starve* ***SEED*** *packets*

Cross-traffic contention

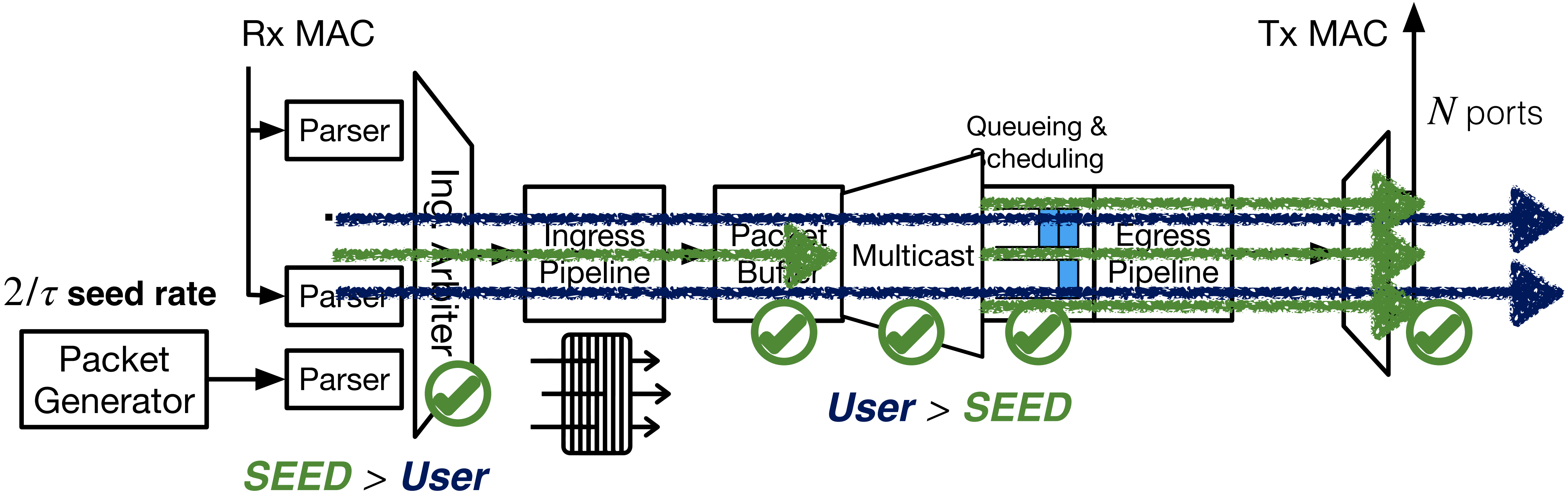


Preventing contention



Rich configuration options for priorities and buffer management

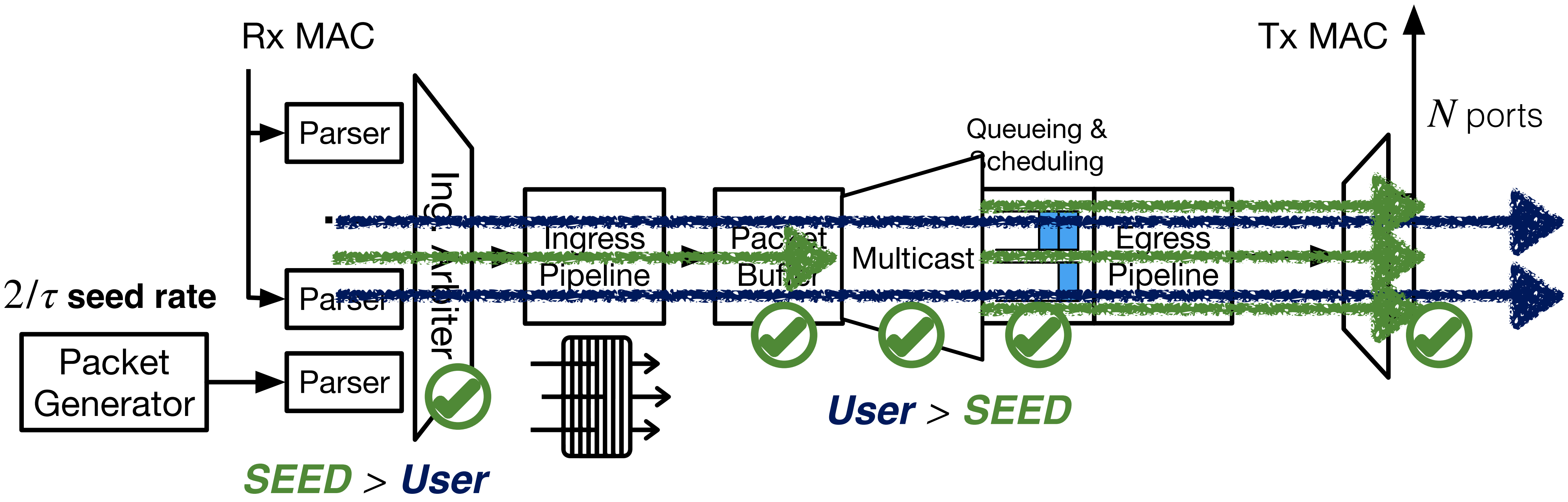
Preventing contention



Rich configuration options for priorities and buffer management

- *Zero impact of weaved stream predictability* ✓
- *Zero impact of* ***user traffic*** *throughput or buffer usage* ✓

Preventing contention

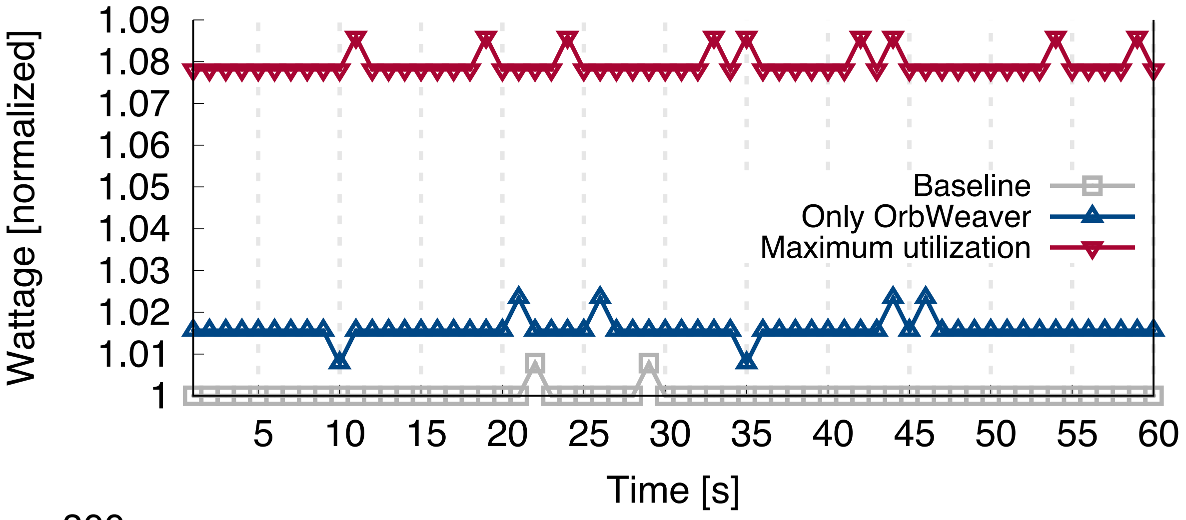


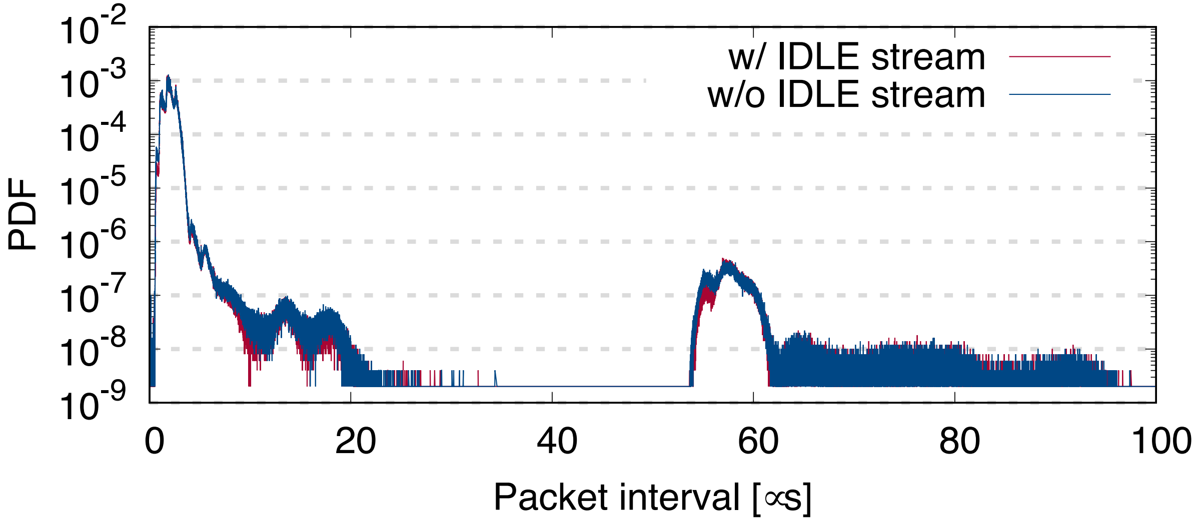
Rich configuration options for priorities and buffer management

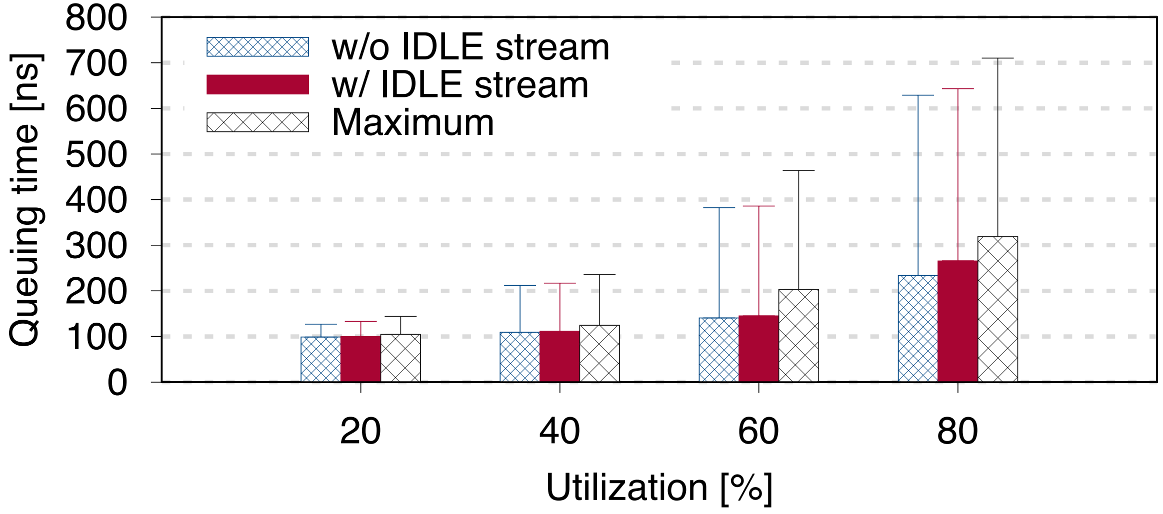
- *Zero impact of weaved stream predictability*
- *Zero impact of **user traffic** throughput or buffer usage*
- *Negligible impact of latency of **user packets***

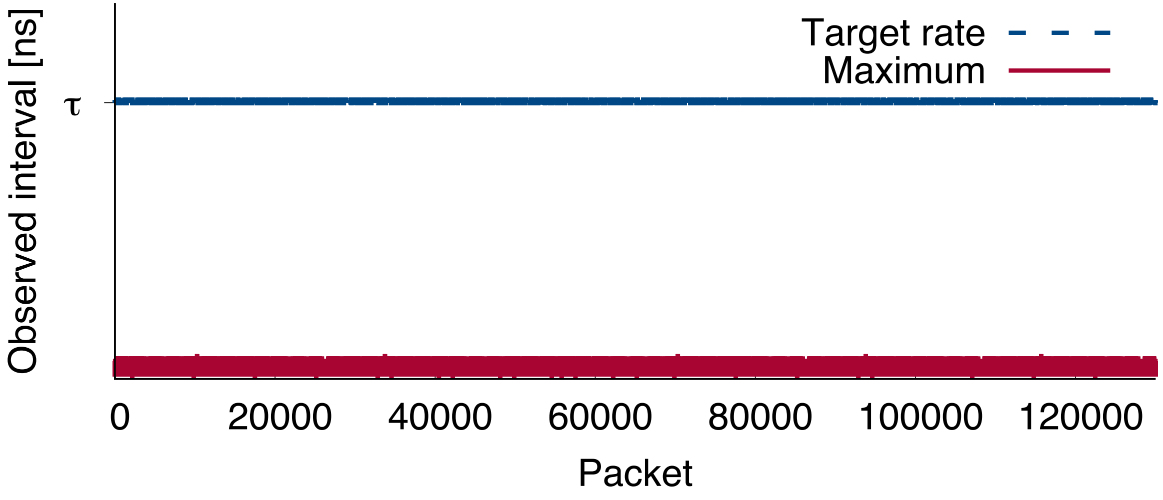
Implementation and evaluation

Hardware prototype on a pair of Wedge100BF-32X Tofino switches









Takeaway: **Little-to-no impact** of power draw, latency, or throughput while guaranteeing **predictability** of the weaved stream!

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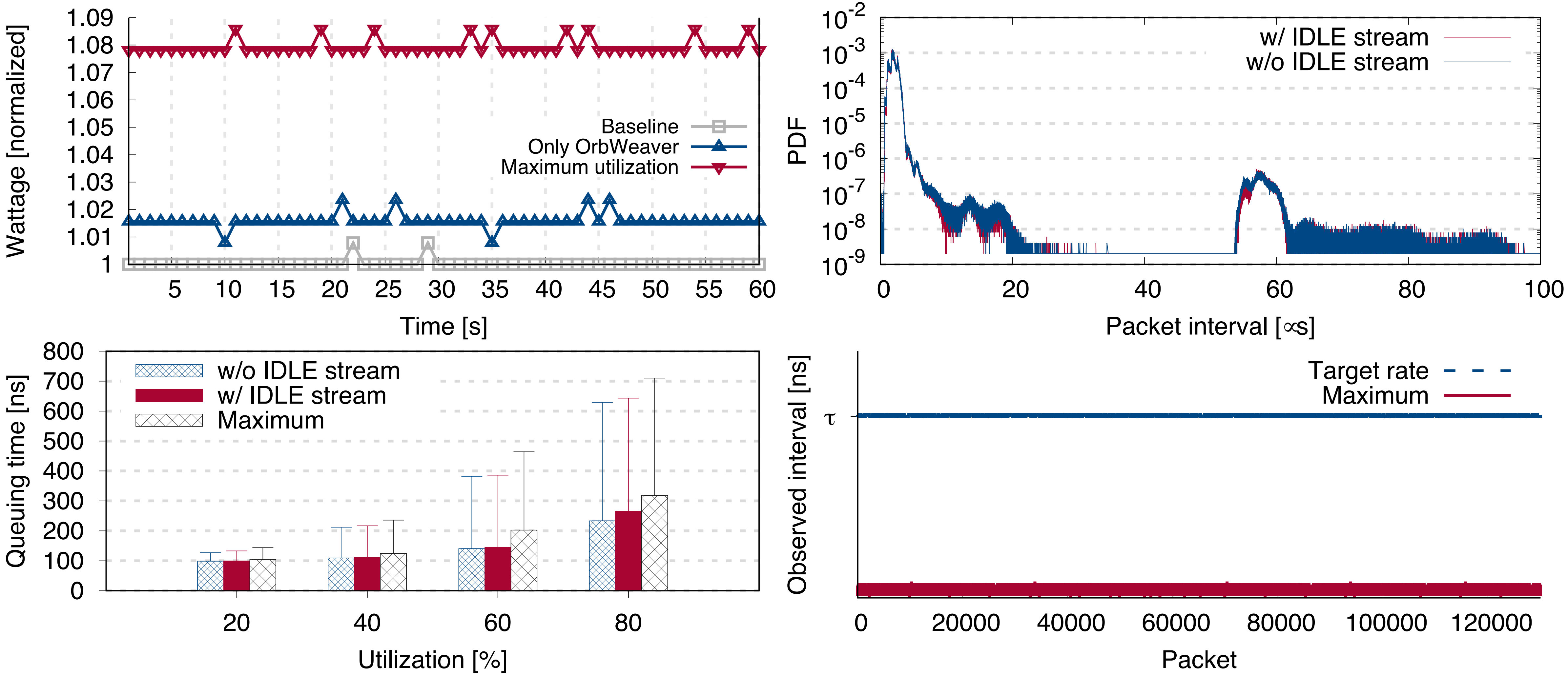

OrbWeaver use cases

- Performance aware routing
- Flowlet load imbalance
- Consistent replicas
- Network queries
- Latency localization
- Header compression
- Microburst detection
- In-band telemetry
- Event-based network control
- Failure detection
- Network queries
- Packet forensics
- Clock synchronization

OrbWeaver use cases

Fine-grained network state inference [R1]

Performance aware routing

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Free information dissemination [R2]

Fine-grained network state inference [R1]

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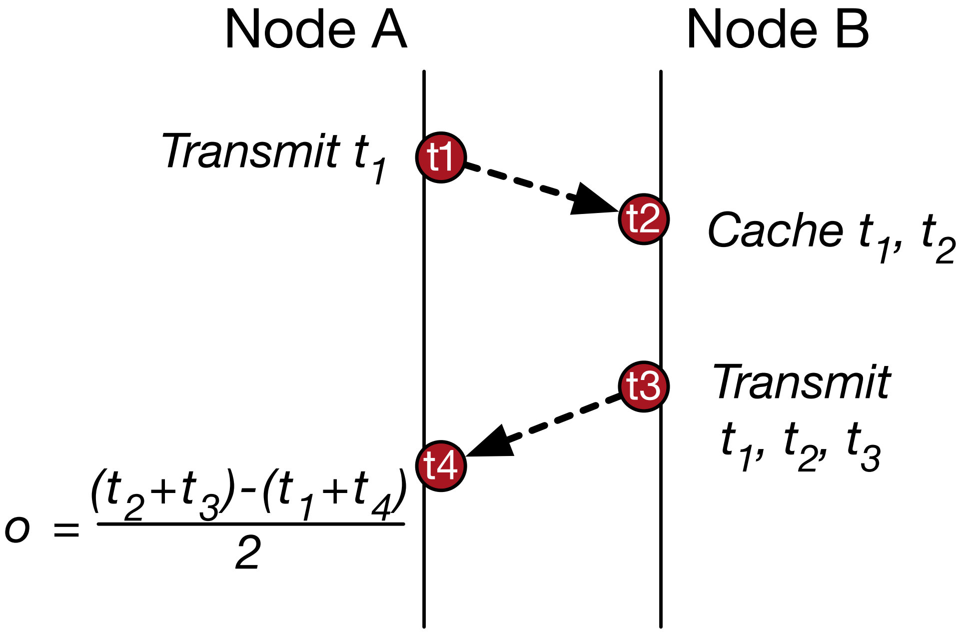
Example: time synchronization



Traditional two-way protocol

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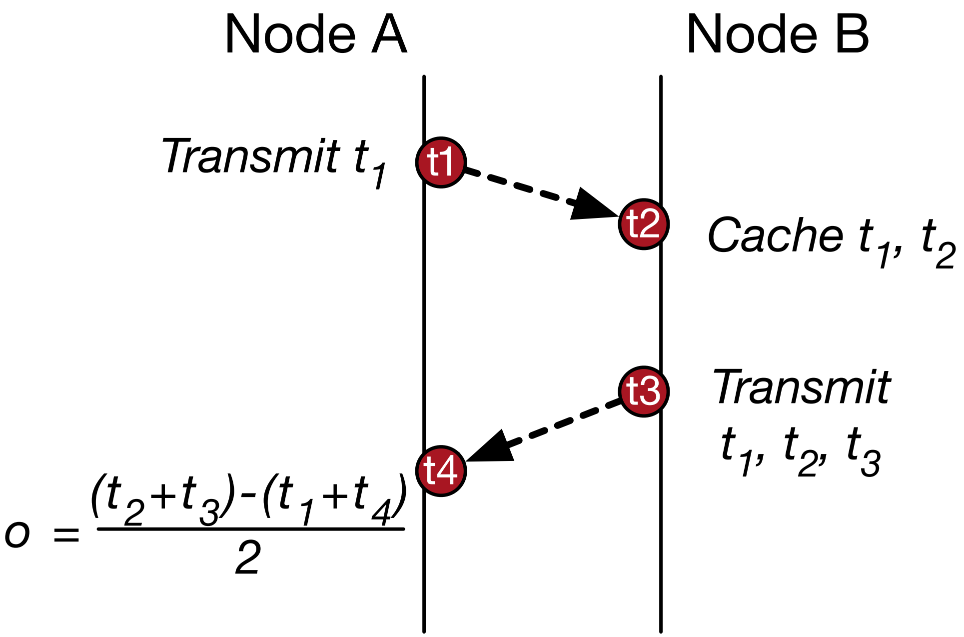

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Existing approaches for high precision

- Require special hardware (such as DTP)
- Require messaging overheads (such as DPTP)

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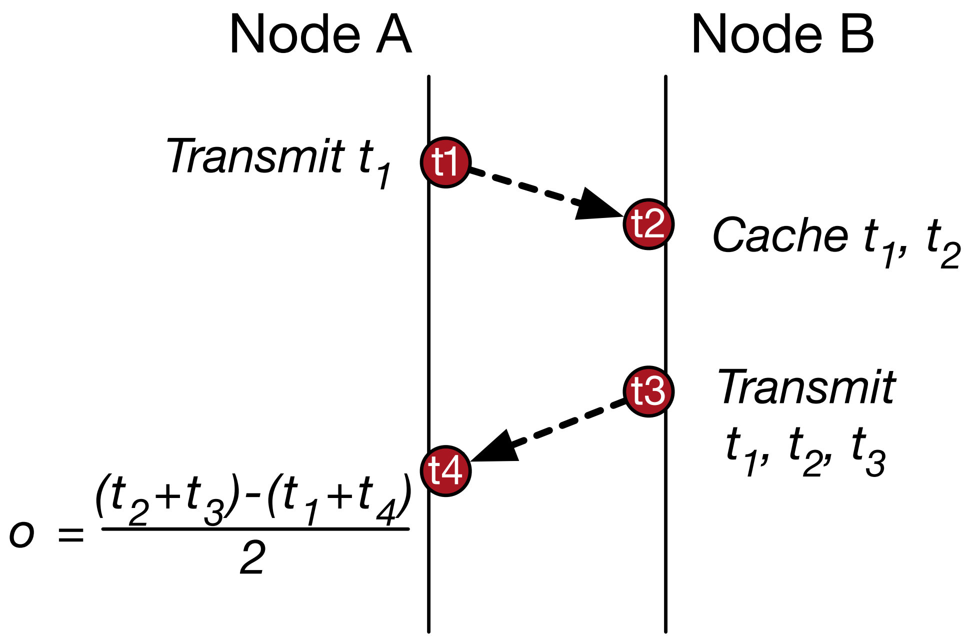

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Challenges to achieve ns precision

- *Messaging frequency v.s. clock precision*
- *Inaccuracies due to queueing delays*

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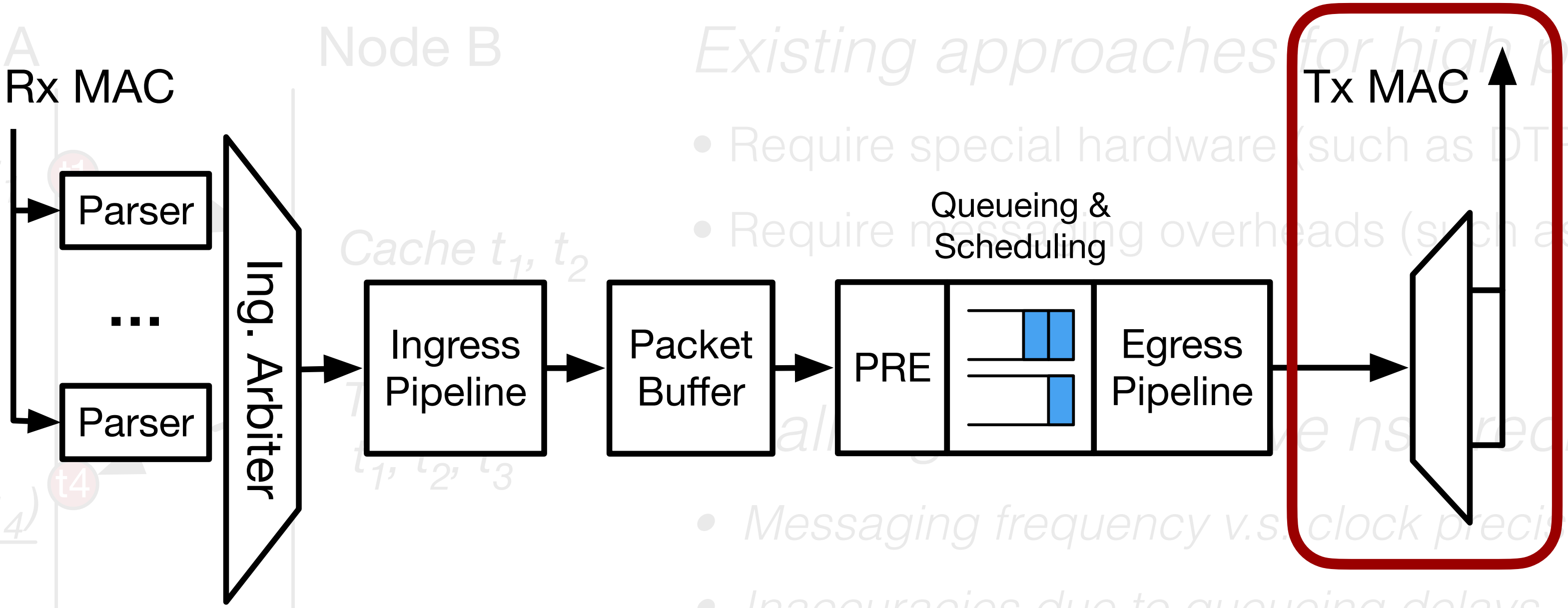

Data plane timestamps don't capture the actual point of serialization

OrbWeaver Redesign

Key ideas:

1. Embed timestamp information in **free IDLE packets** [R2]

OrbWeaver Redesign

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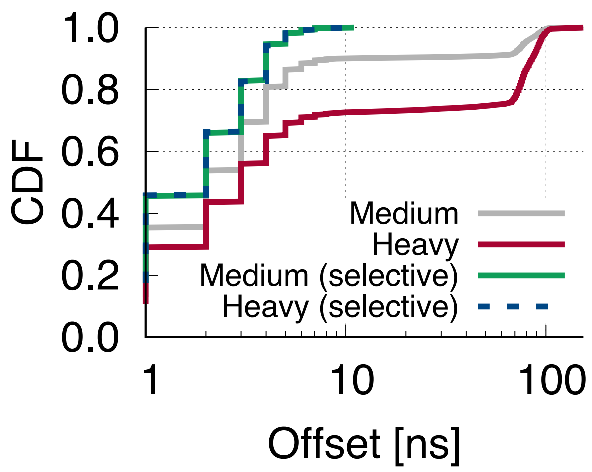
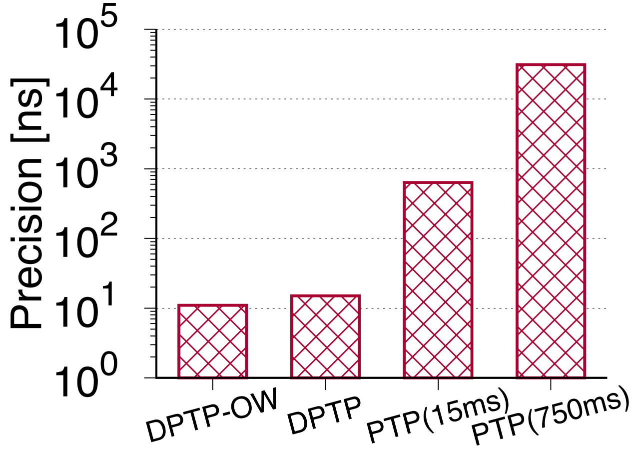
2. Selective synchronization: **infer queue delay** from IDLE gaps and filter out **unreliable messages** [R1]

OrbWeaver Redesign

Key ideas:

1. Embed timestamp information in **free IDLE packets** [R2]
2. Selective synchronization: **infer queue delay** from IDLE gaps and filter out **unreliable messages** [R1]





Achieve same or better performance with close-to-zero overheads

Summary

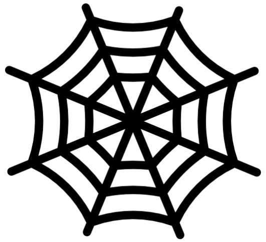
- **Weaved stream abstraction** to harvest IDLE cycles
  - Guarantee predictability with little-to-zero overhead

Summary

- **Weaved stream abstraction** to harvest IDLE cycles
  - Guarantee predictability with little-to-zero overhead
- Generic support of a wide range of data plane applications for free
  - ***Don't*** need to choose between coordination fidelity and bandwidth overhead

https://github.com/eniac/OrbWeaver

Outline



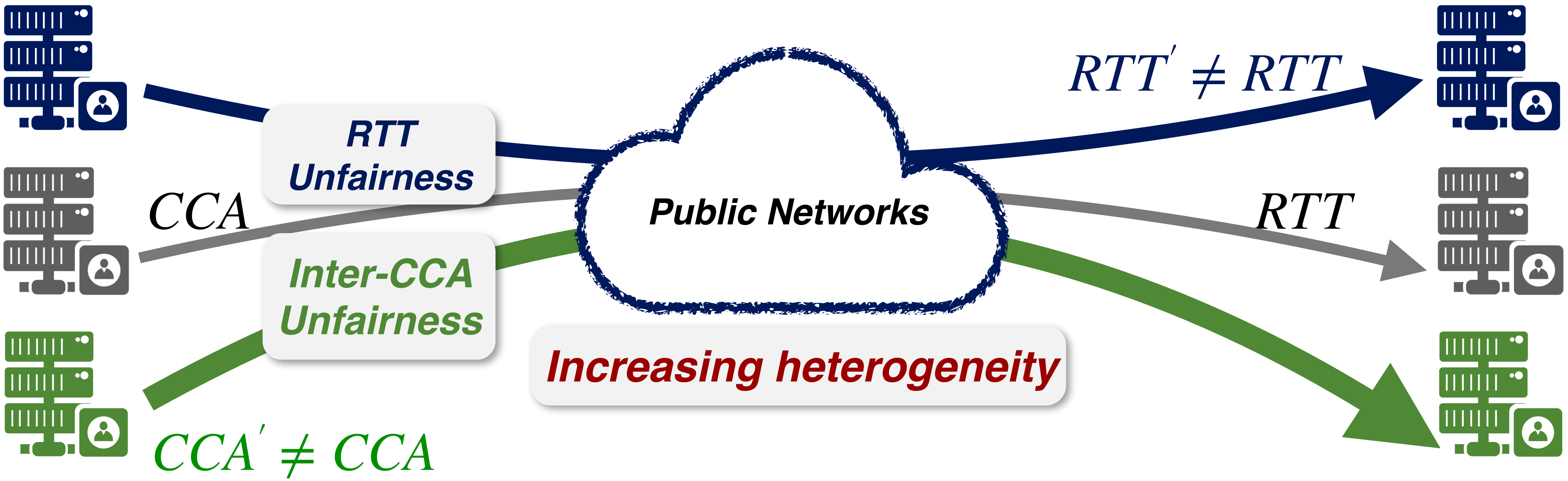
OrbWeaver:

Using IDLE Cycles in Programmable Networks for Opportunistic Coordination

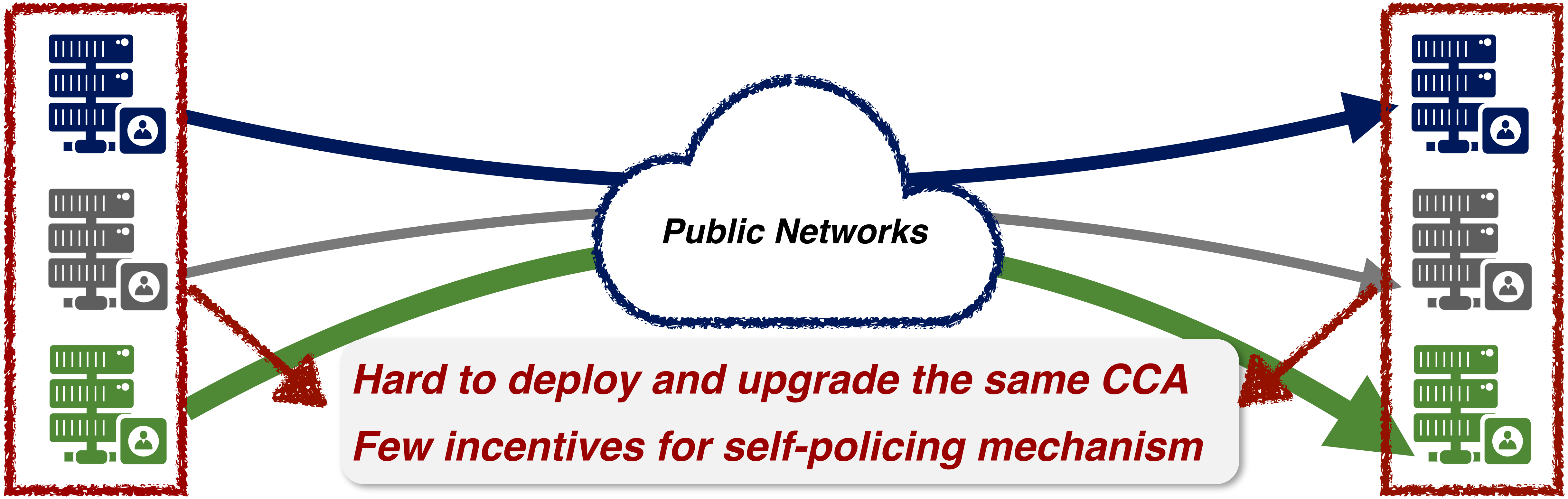
Cebinae:

Scalable In-network Fairness Augmentation

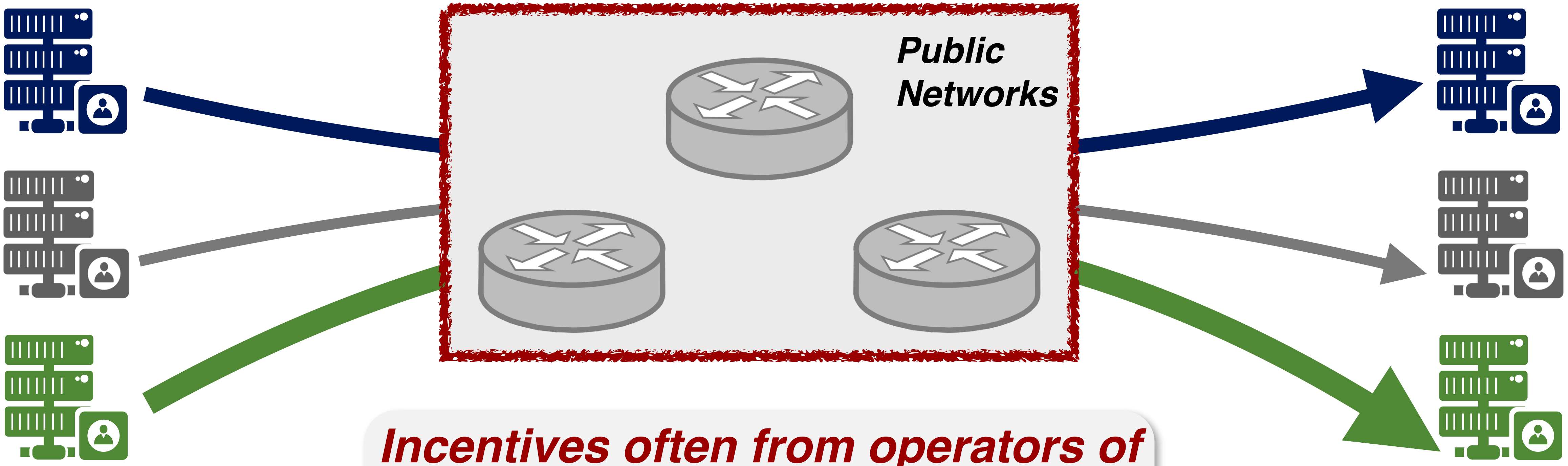
Public networks care about fairness



Fairness enforcement at the end hosts?



In-network fairness enforcement



Incentives often from operators of the in-network devices

In-network fairness enforcement

- Existing approaches suffer from limited practicalities
  - ***Assumption***: *specialized hardware for per-flow queues, end-host cooperation…*

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- AFQ [NSDI '18]: practical emulation of ideal FQ on COTS hardware
  - ***Constraints***: *e.g., # priorities, queues, buffers*

In-network fairness enforcement

- Existing approaches suffer from limited practicalities
  - ***Assumption****: specialized hardware for per-flow queues, end-host cooperation…*
- AFQ [NSDI '18]: practical emulation of ideal FQ on COTS hardware
  - ***Constraints****: e.g., # priorities, queues, buffers*

Challenging to ***strictly*** *enforce FQ on* ***each individual flow***

Cebinae: a simpler approach

- Relaxation of fairness **at every instance in time**
  - *Penalize/redistribute BW from flows exceeding fair share to others*

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- **Binary classification** of flows
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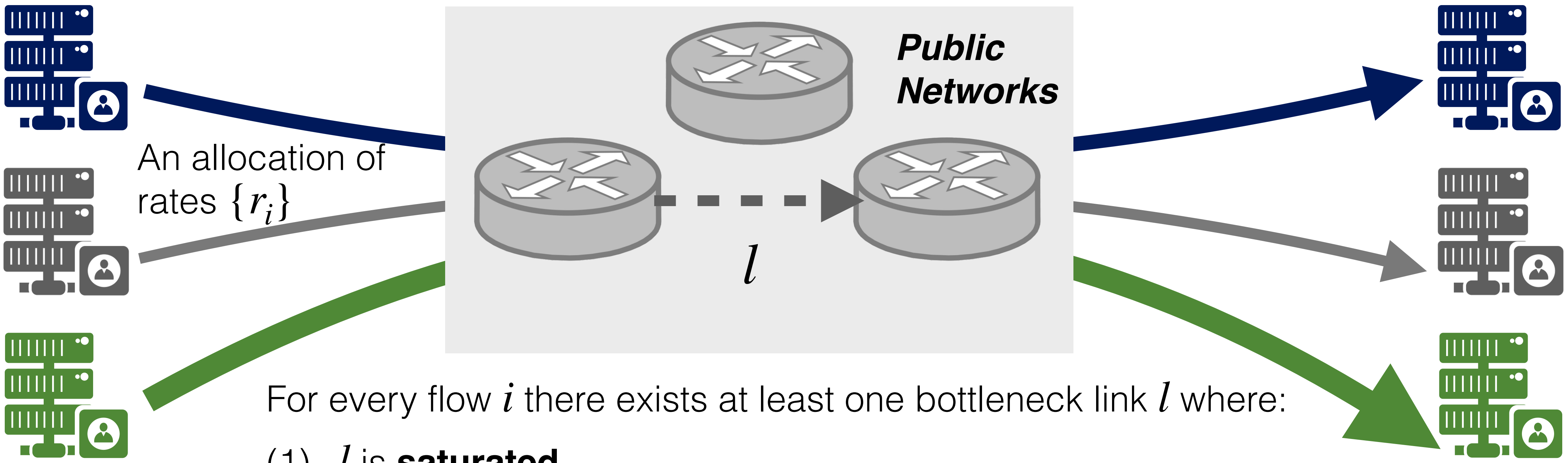
Cebinae router architecture for binary taxation

- **Zero modifications and coordinations** to/with legacy host CCAs
- Requirement of only **two queues/priorities**
- Compatibility with CCAs operating on **both loss and delay** signals

Outline

1. Conceptual foundation for binary classification
2. Cebinae’s taxation mechanism
3. Evaluation

Max-min fairness

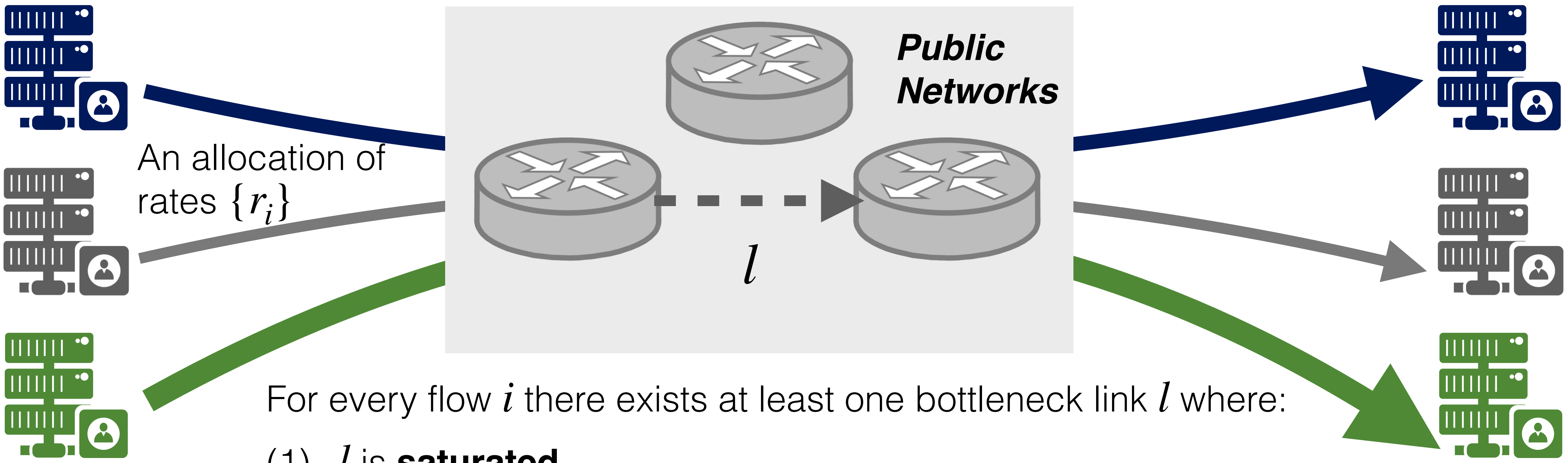


For every flow i there exists at least one bottleneck link l where:

(1) l is **saturated**

(2) r_i is among **the largest** flows sharing the link l

Max-min fairness



For every flow i there exists at least one bottleneck link l where:

(1) l is **saturated**

(2) r_i is among **the largest** flows sharing the link l

<u>Implication:</u> distributed *verification* of max-min fairness

Local verification

Each link l can determine the set of bottlenecked flows:

If l non-saturated:

All flows not bottlenecked

Else, for each flow i:

If i is among l's largest rate(s)

i *is **bottlenecked** at* l

Else

i is **not bottlenecked** at l

Local verification

Each link l can determine the set of bottlenecked flows:

If l non-saturated:

All flows not bottlenecked

Else, for each flow i:

If i is among l's largest rate(s)

i *is* ***bottlenecked*** *at* l

Else

i is **not bottlenecked** at l

Observation:

1. Each conditional can be determined using ***only local information***
2. ***Binary classification***: bottlenecked ($\top$), not bottlenecked ($\perp$)

Naive enforcement

<u>Each link l can determine the set of bottlenecked flows:</u>

If l non-saturated:

NOP

Else, for each flow i:

If i is among l's largest rate(s)

*Drop packets of **all** $\boldsymbol{i}$**s** per their current rate*

Else

NOP

Naive enforcement

Each link l can determine the set of bottlenecked flows:

If l non-saturated:

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Else, for each flow i:

If i is among l's largest rate(s)

Drop packets of ***all*** $\boldsymbol{i}$***s*** *per their current rate*

Else

NOP

Drawbacks:

1. Can not push an already-unfair allocation fair
2. CCAs may not be responsive to loss signals

Cebinae taxation

Each link l can determine the set of bottlenecked flows:

If l non-saturated:

NOP

Else, for each flow i:

If i is among l's largest rate(s)

Penalize *is with their* ***taxed rate***

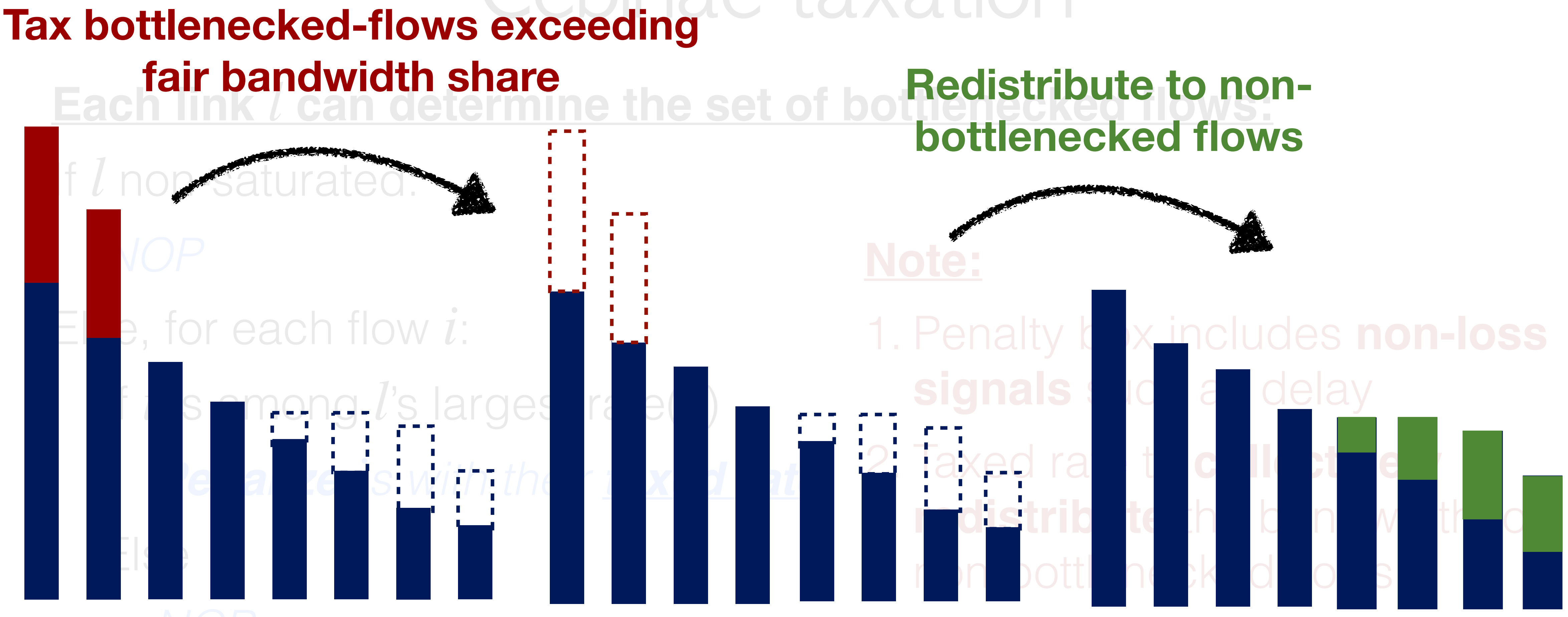
Else

NOP

Note:

1. Penalty box includes **non-loss signals** such as delay
2. Taxed rate to **collectively redistribute** the bandwidth to non-bottlenecked flows

Cebinae taxation



Instantiation: Cebinae router architecture

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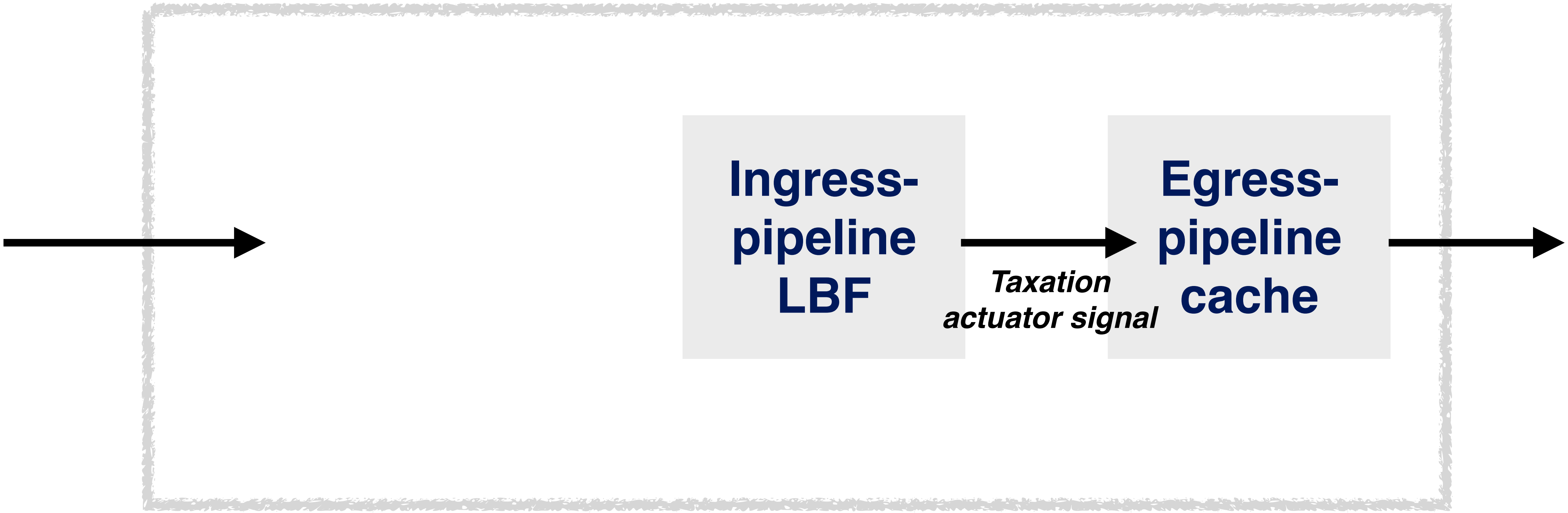

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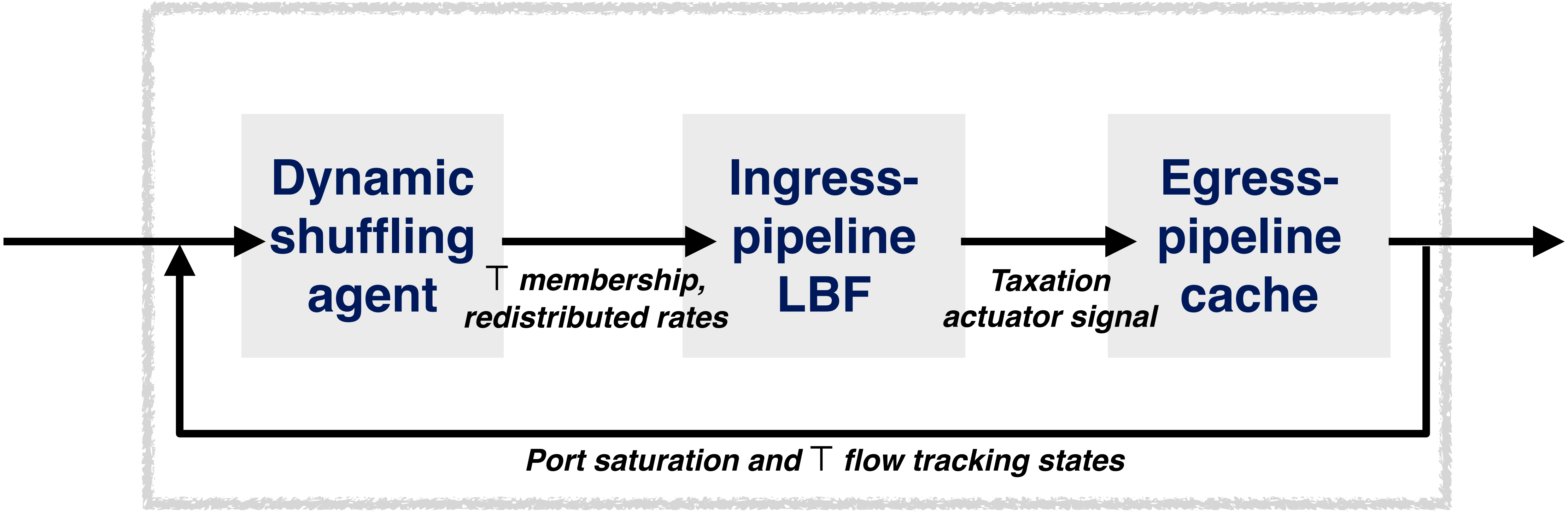
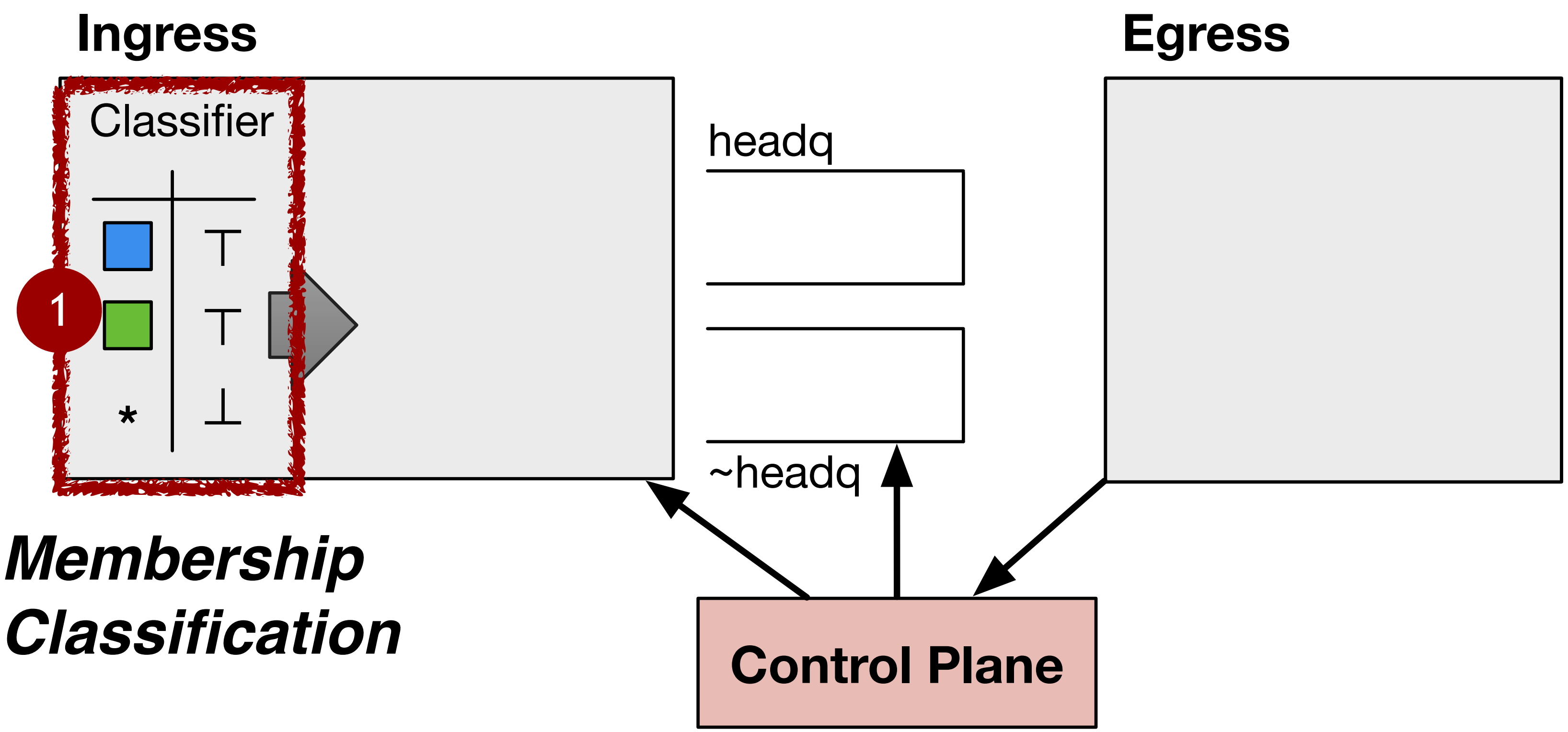


Normal operation



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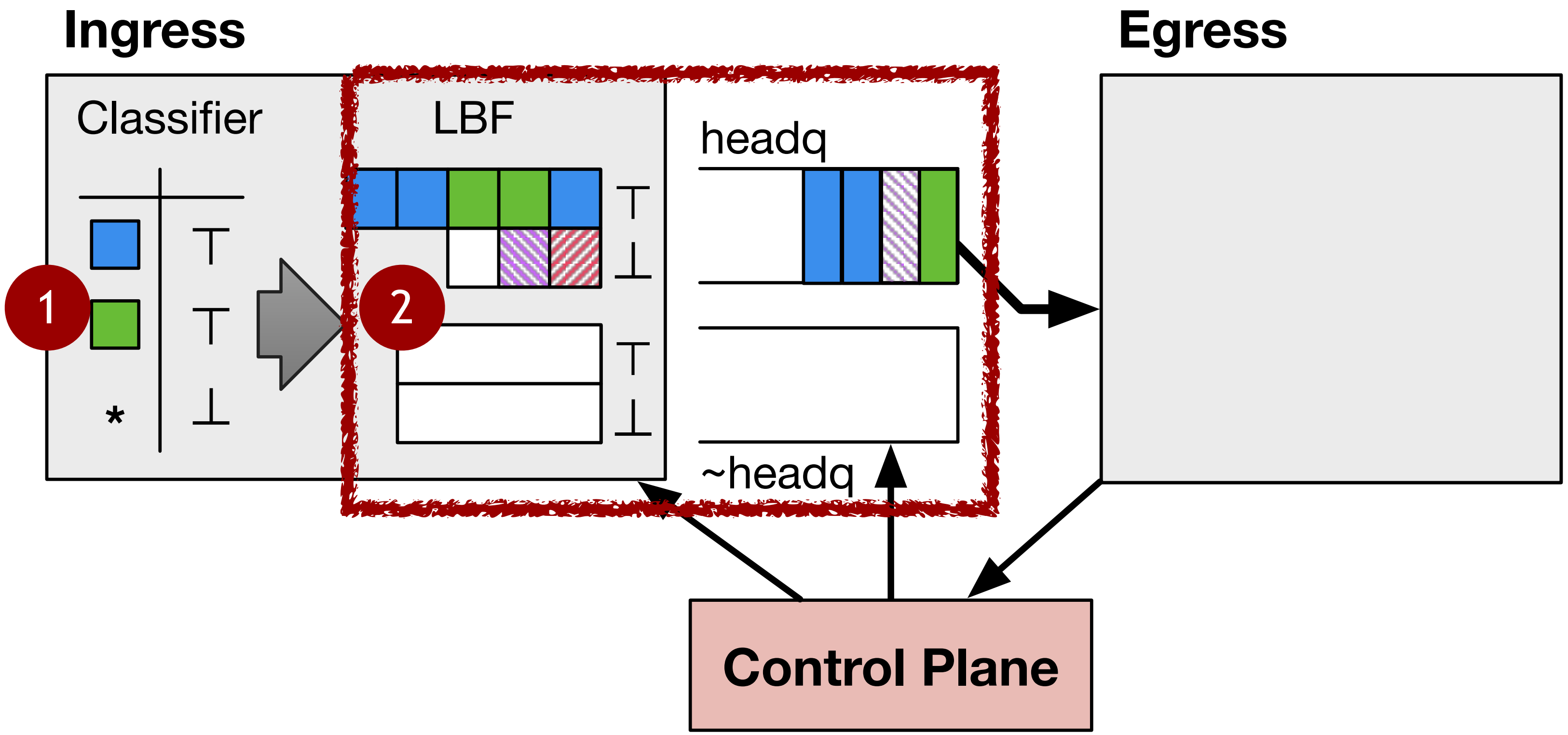
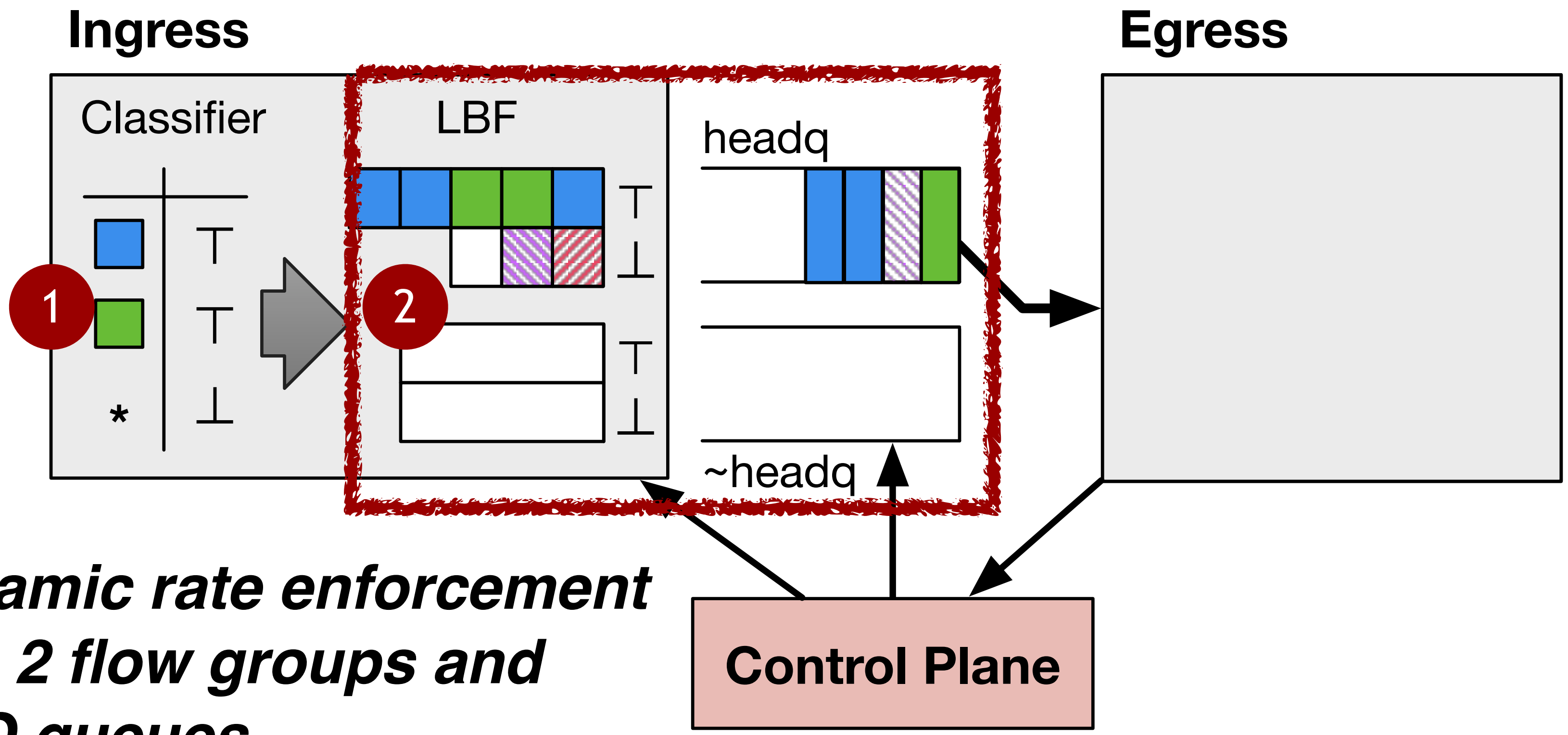
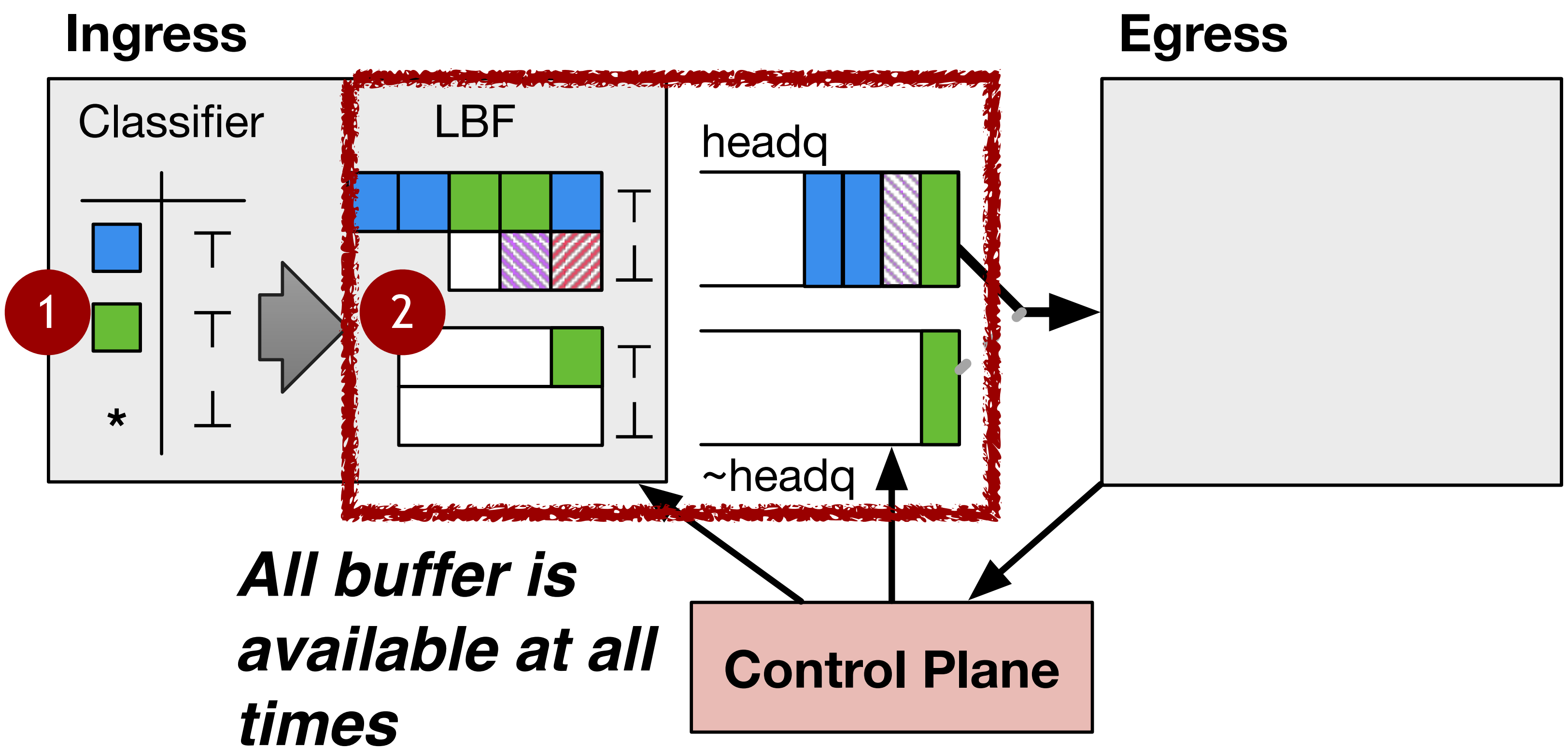


Normal operation



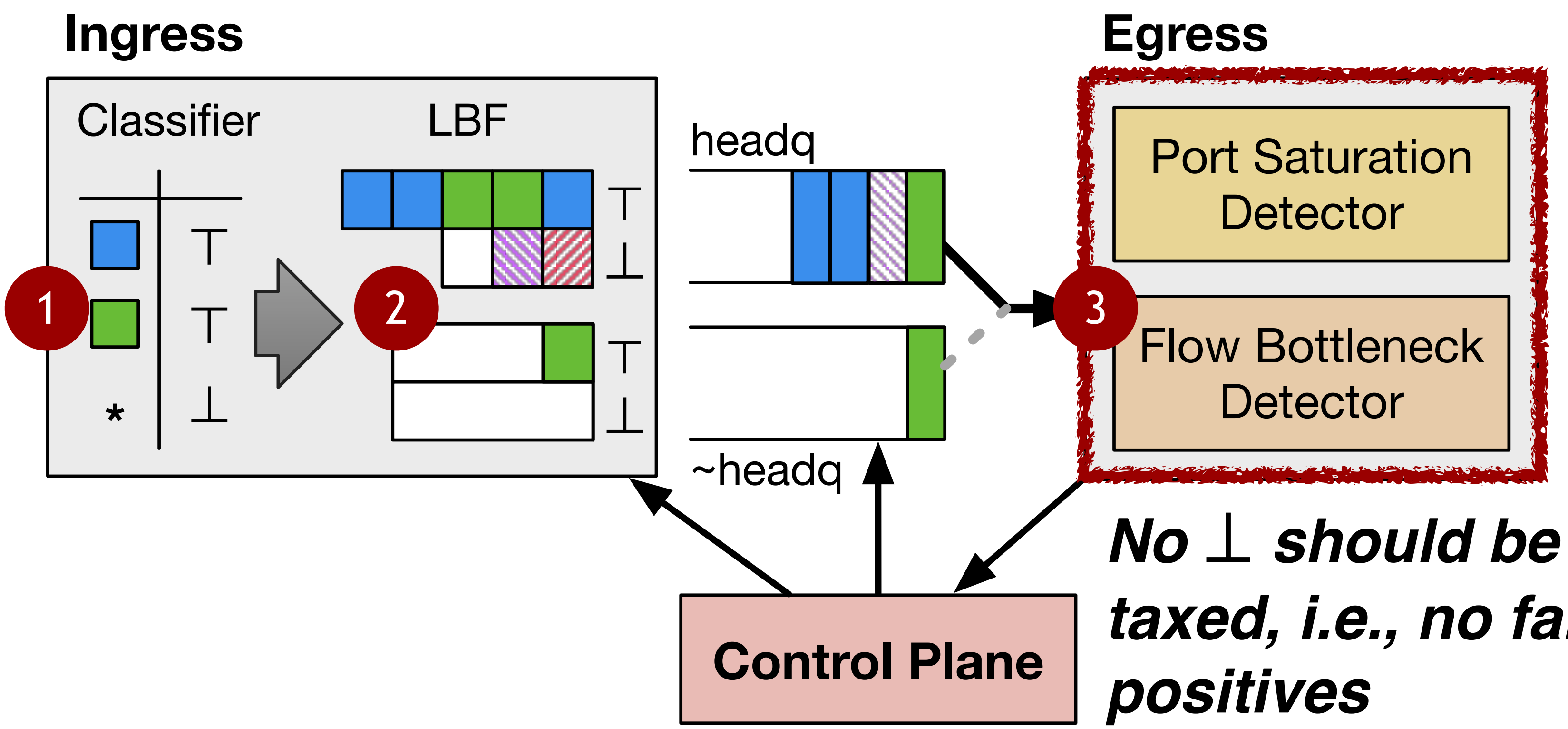
Dynamic rate enforcement with 2 flow groups and FIFO queues

Normal operation



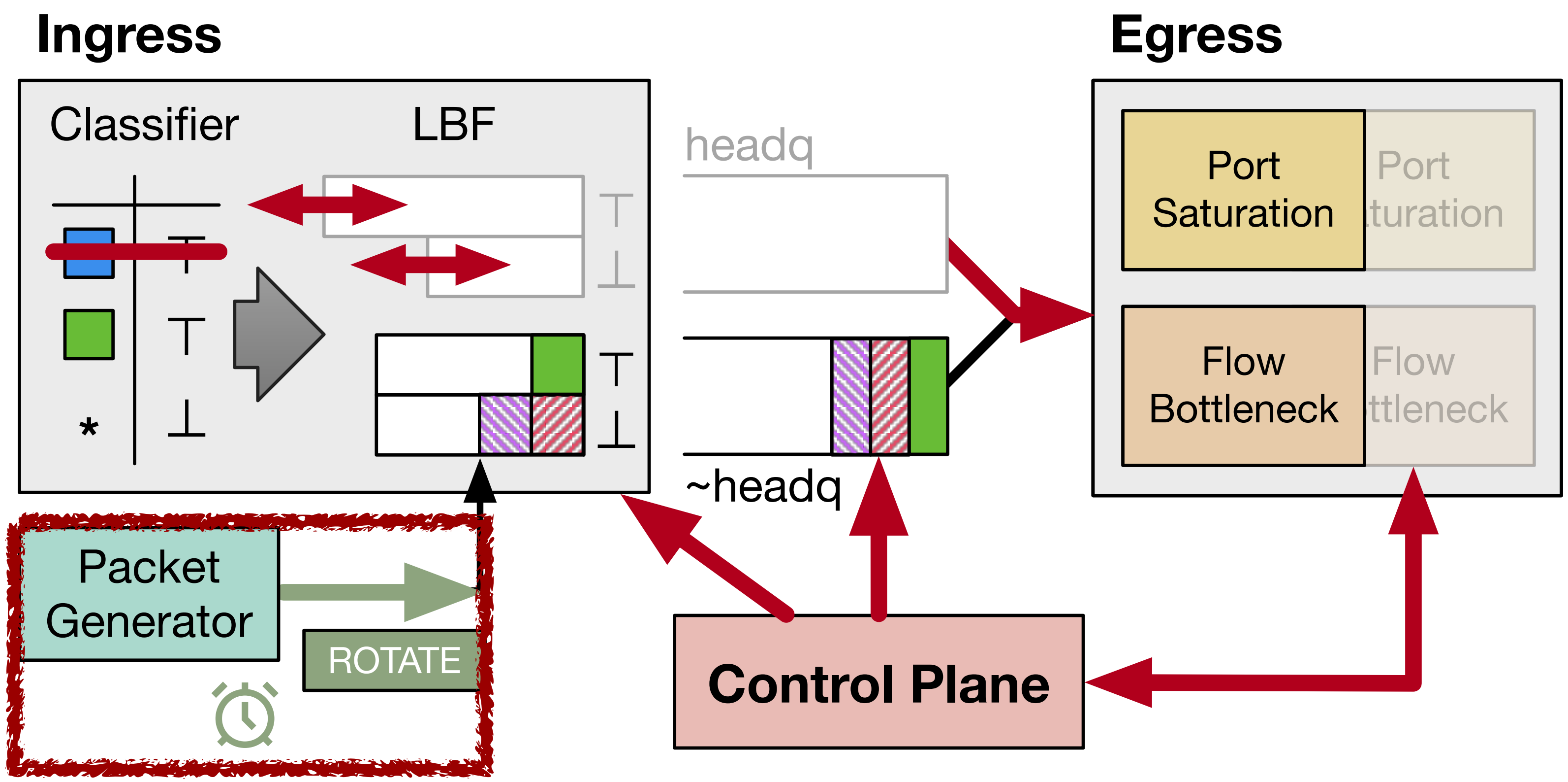
All buffer is available at all times

Normal operation

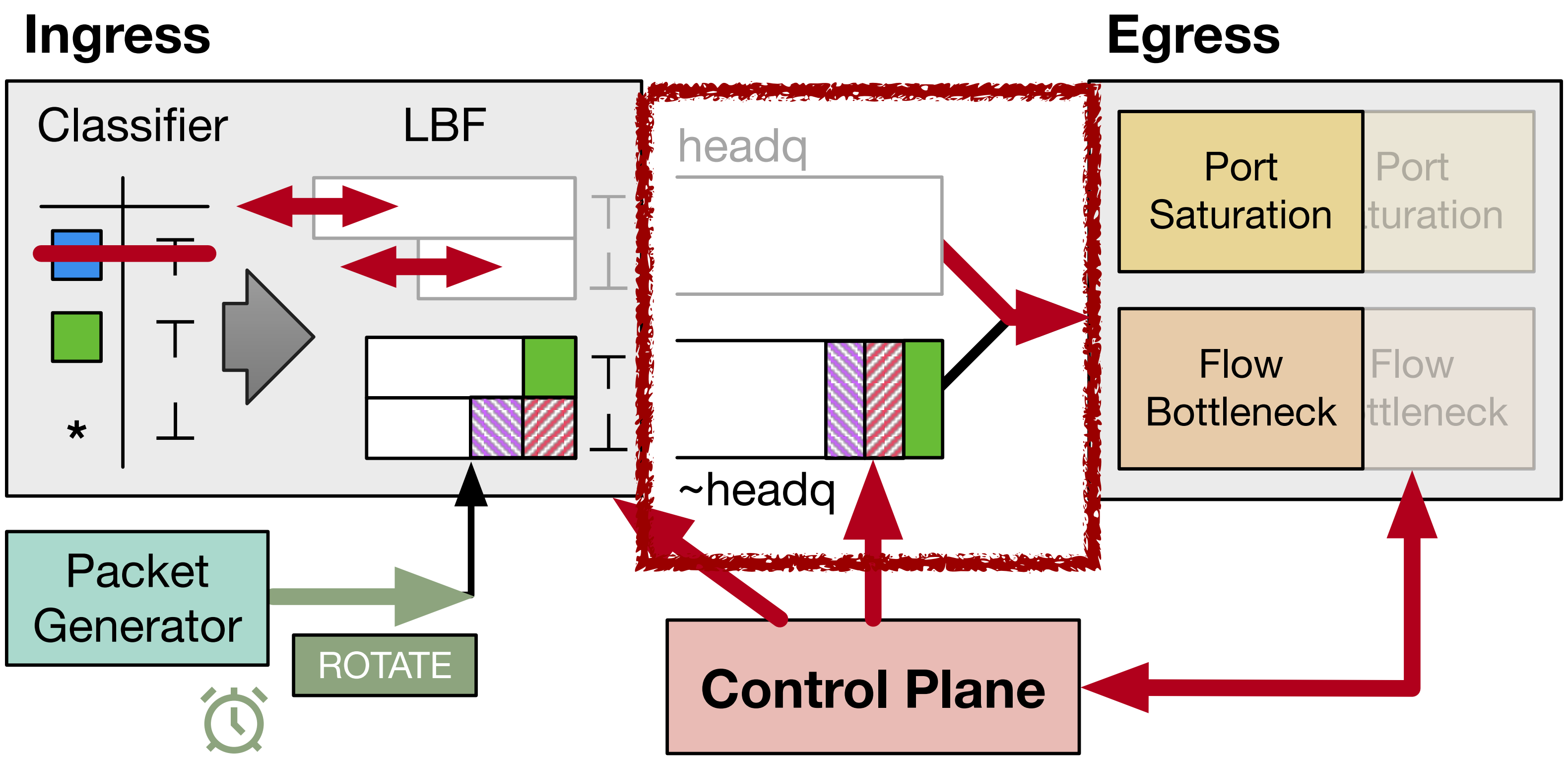


No ⊥ should be taxed, i.e., no false positives

Per-round reconfiguration



Per-round reconfiguration



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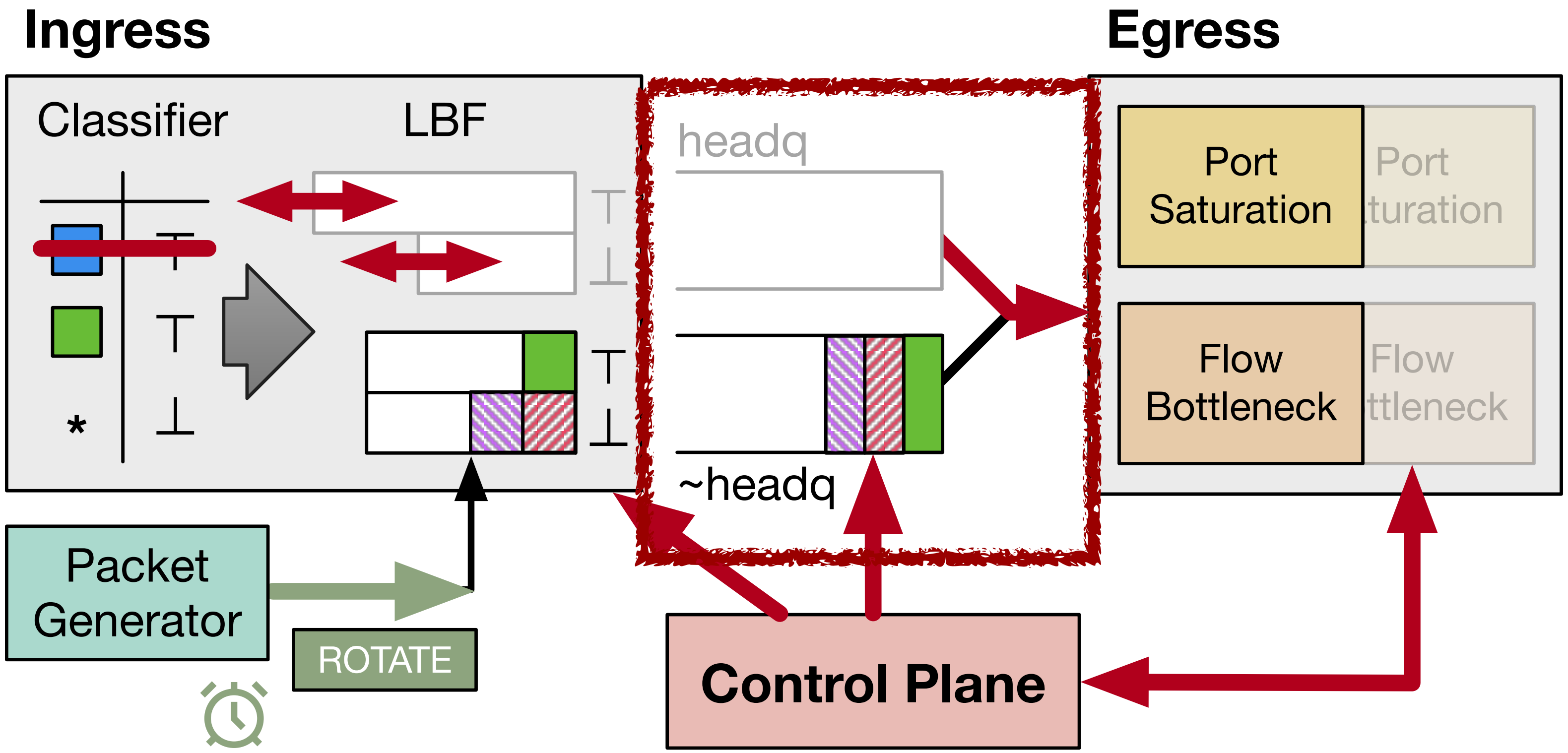
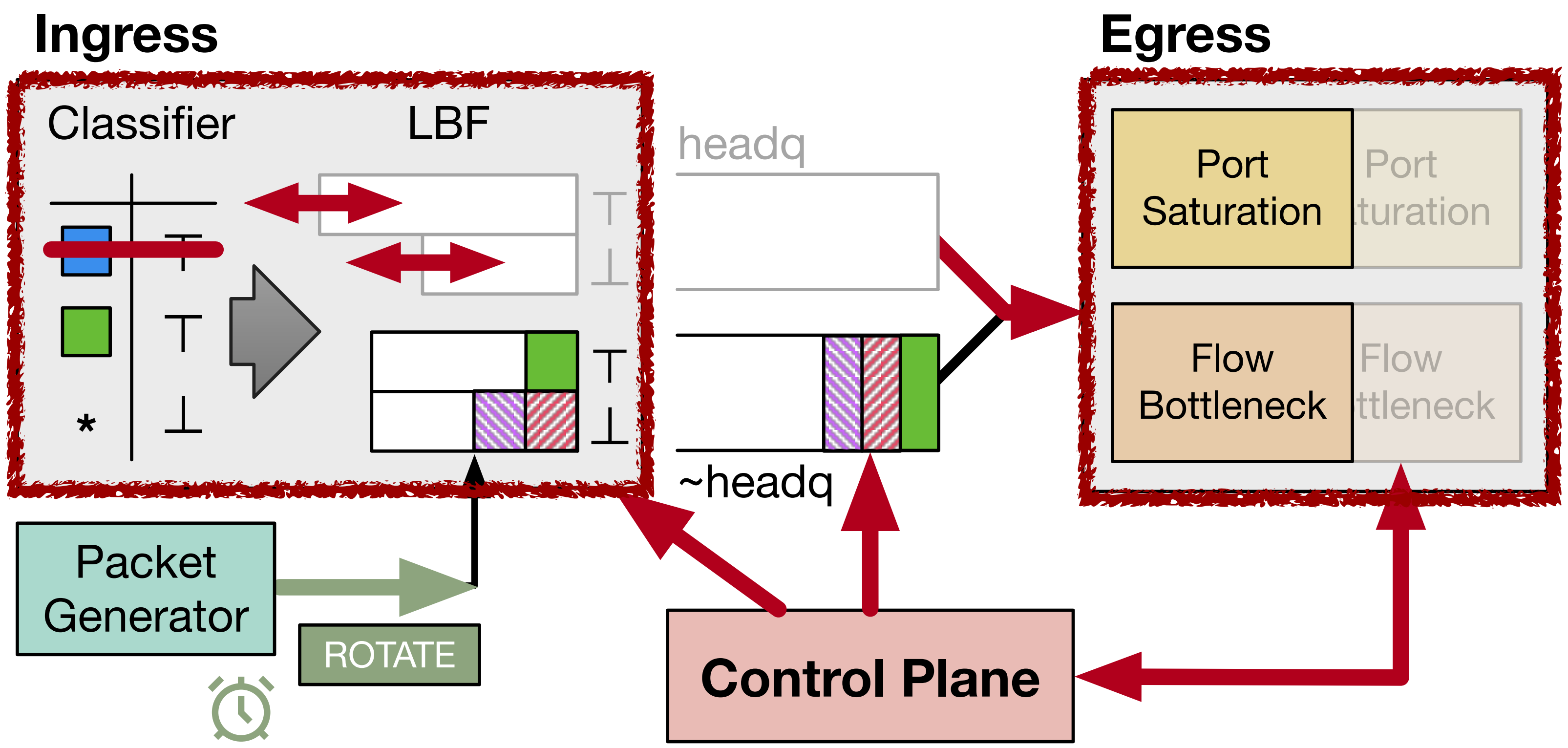


Virtual pacing : *guarantee* ***no reordering*** *and avoid violation of draining deadline in the worst case*

Per-round reconfiguration



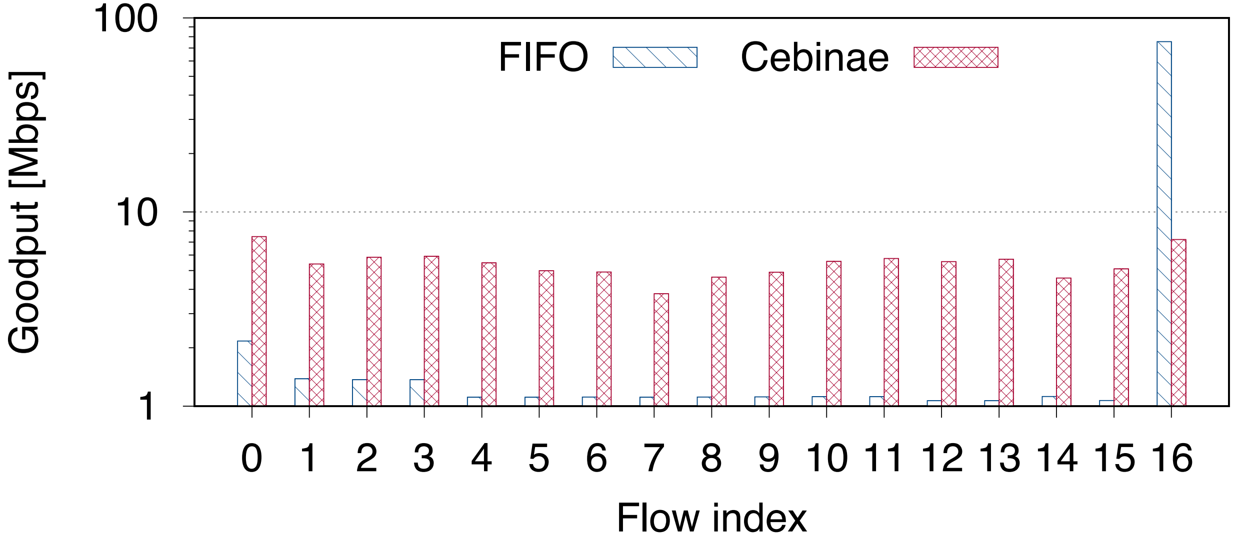
Atomic transactions: *LBF states and egress caches*

Implementation and evaluation

Hardware prototype on a Wedge100BF Tofino switch testbed and NS-3 module

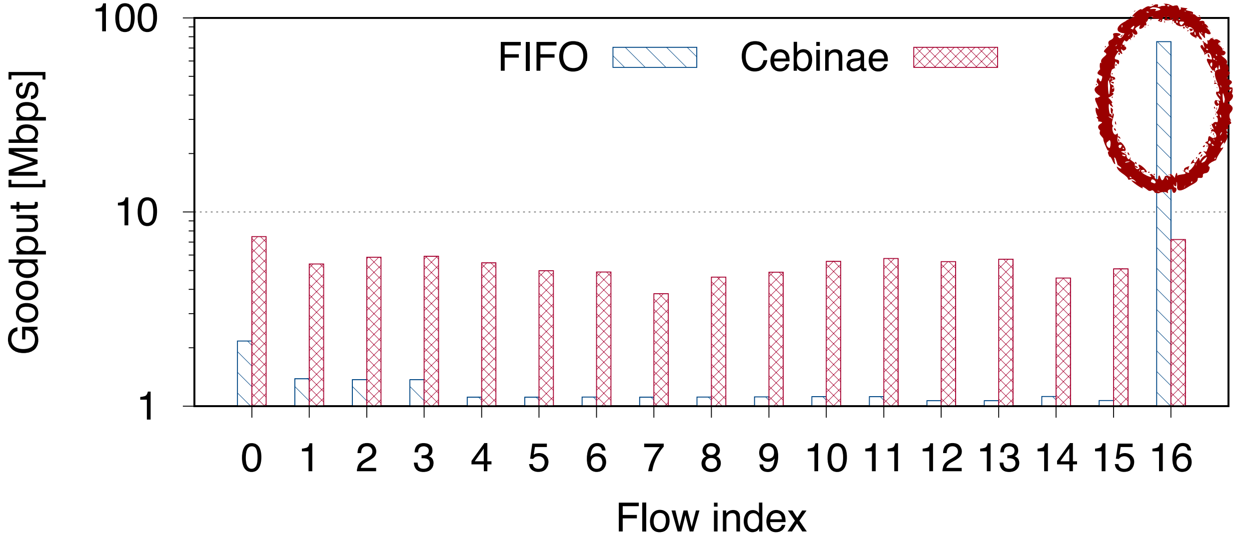
- Is Cebinae agnostic to CCAs?
- Can Cebinae mitigates unfairness (RTT, inter-CCA)?
- Can Cebinae move towards max-min fairness?
- Is Cebinae easy to configure?
- Does Cebinae resource usage scale?
- …

Cebinae mitigates unfairness



16 TCP Vegas (0–15)
v.s. 1 NewReno (16)

Cebinae mitigates unfairness



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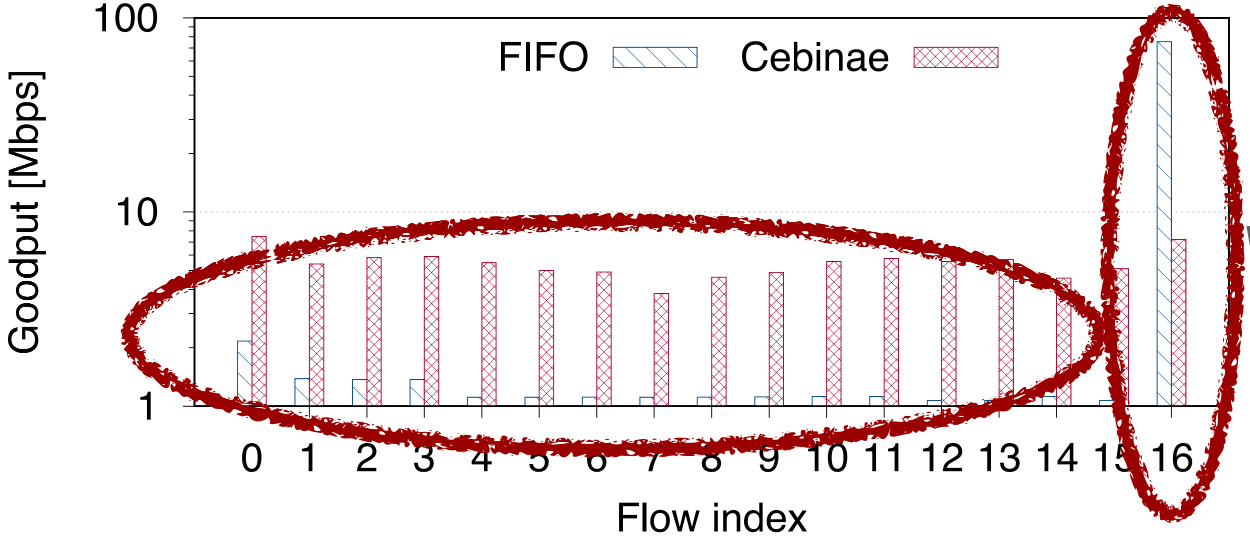

16 TCP Vegas (0–15)
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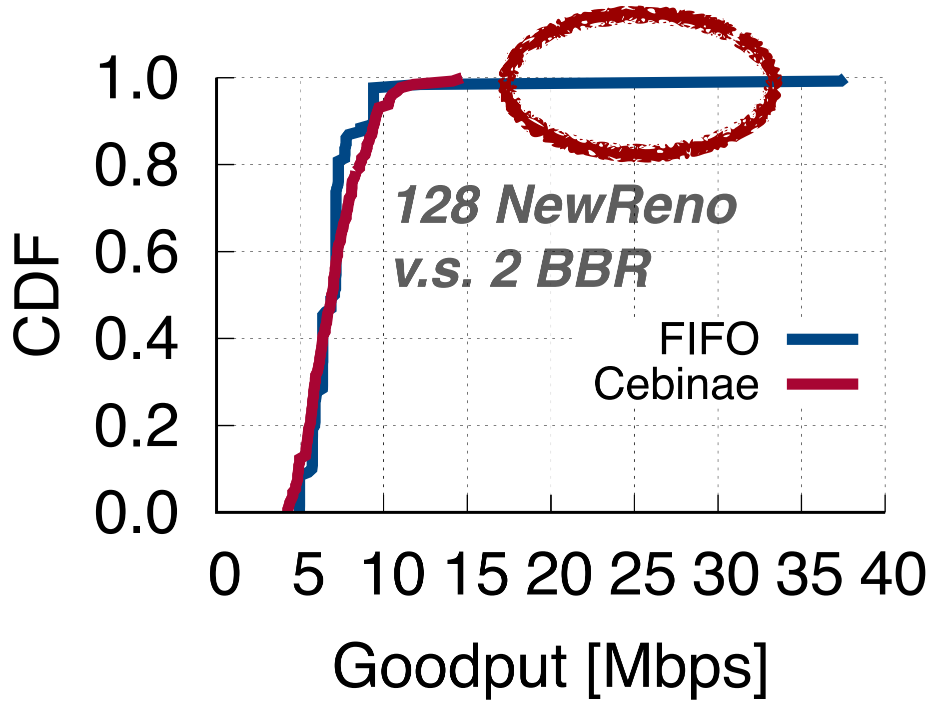
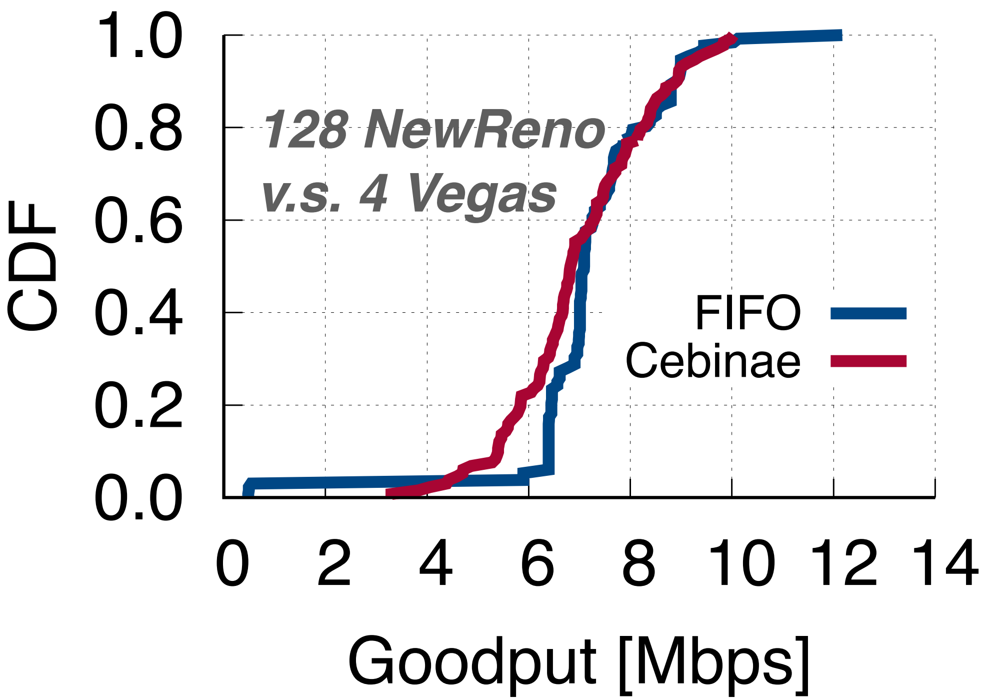
*Mitigates the **skewed and persistent unfairness** with little efficiency impact: **JFI from 0.093 to 0.984***

Cebinae mitigates unfairness

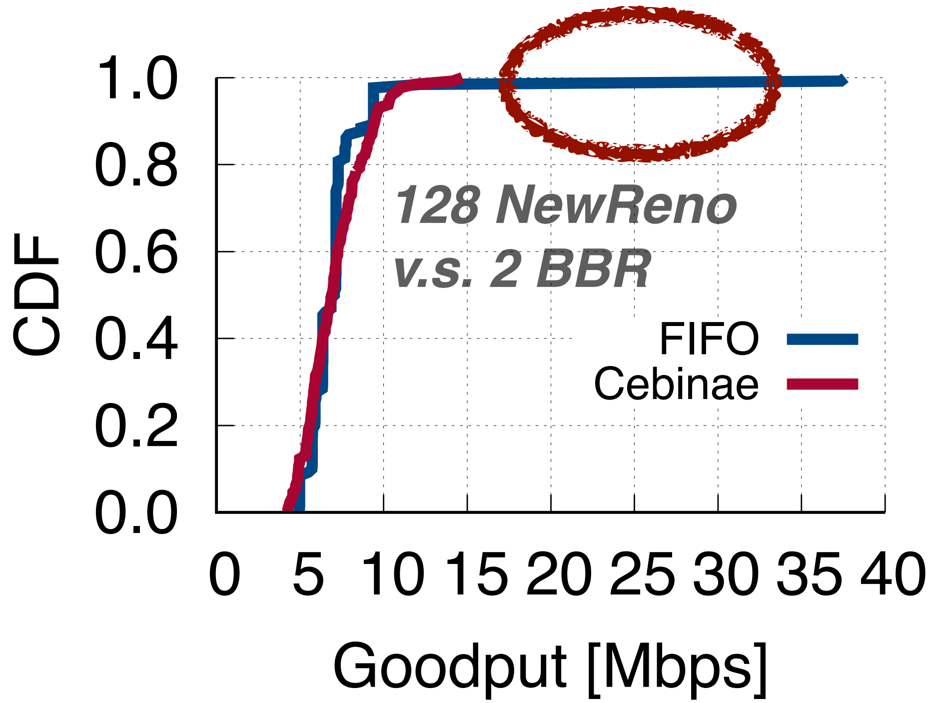


Preventing aggressiveness



Mitigating starvation

Cebinae mitigates unfairness



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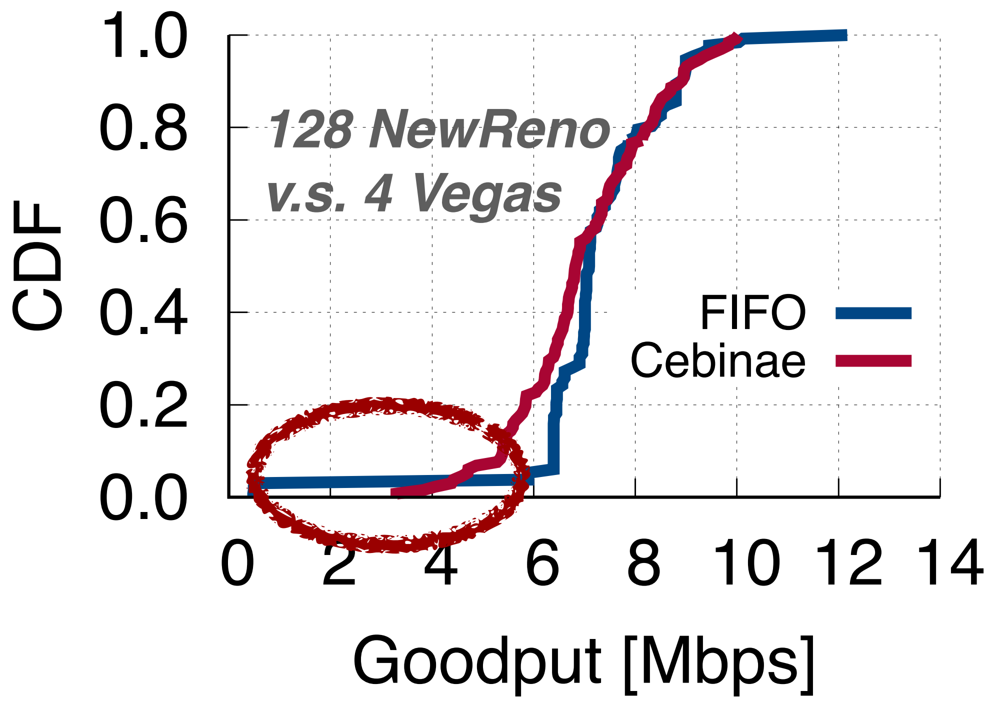

Mitigating starvation

Cebinae mitigates unfairness

				Throughput [Mbps]			Goodput [Mbps]			JFI		
Btl. BW	**RTTs [ms]**	**Buf. [MTU]**	**CCAs**	**FIFO**	**FQ**	**Cebinae**	**FIFO**	**FQ**	**Cebinae**	**FIFO**	**FQ**	**Cebinae**
100 Mbps	{20.8, 28}	250	{NewReno:2, NewReno:8}	98.95	95.62	95.92	95.35	92.16	92.44	0.740	0.982	0.999
100 Mbps	{20.4, 40}	350	{Cubic:8, Cubic:2}	98.96	98.95	98.00	95.37	95.37	94.45	0.539	1.000	0.980
100 Mbps	{20.4, 60}	500	{Vegas:2, Vegas:8}	98.88	98.83	98.88	95.29	95.24	95.29	0.873	1.000	0.993
100 Mbps	{200}	1700	{NewReno:16, Cubic:1}	98.28	90.99	94.53	94.38	87.61	91.02	0.446	0.995	0.925
100 Mbps	{100}	850	{NewReno:16, Cubic:1}	98.72	91.45	95.58	95.11	88.10	92.08	0.857	0.998	0.960
100 Mbps	{50}	420	{NewReno:16, Cubic:1}	98.90	93.86	95.37	95.30	90.45	91.90	0.936	0.999	0.993
100 Mbps	{50}	420	{Vegas:16, Cubic:1}	98.90	98.90	95.47	95.30	95.30	91.99	0.096	1.000	0.988
100 Mbps	{100}	850	{Vegas:16, NewReno:1}	98.71	97.77	95.67	95.07	94.19	92.16	0.093	0.999	0.985
100 Mbps	{100}	850	{Vegas:128, NewReno:1}	98.88	98.74	97.45	95.26	95.10	93.88	0.189	0.966	0.976
100 Mbps	{60}	500	{Vegas:8, NewReno:8, Cubic: 2}	98.87	98.02	96.52	95.27	94.45	93.00	0.510	0.991	0.973
1 Gbps	{5}	420	{NewReno:32, Cubic:8}	989.8	989.8	985.4	954.0	954.0	949.7	0.844	0.988	0.955
1 Gbps	{10}	850	{Vegas:128, Cubic:1}	989.8	989.8	968.0	954.0	954.0	932.9	0.048	0.966	0.953
1 Gbps	{10}	850	{Vegas:1024, Cubic:2}	989.8	989.8	949.2	953.6	953.6	914.1	0.275	0.833	0.846
1 Gbps	{50}	4200	{NewReno: 128, BBR: 1}	988.7	923.6	981.6	952.7	890.0	945.8	0.992	0.975	0.990
1 Gbps	{50}	4200	{NewReno: 128, BBR: 2}	988.9	953.9	979.9	952.8	919.2	944.2	0.951	0.963	0.981
1 Gbps	{50}	21000	{NewReno: 128, BBR: 2}	988.8	953.9	963.8	952.7	919.2	928.7	0.773	0.963	0.936
1 Gbps	{100}	8350	{NewReno: 128, BBR: 2}	986.9	938.2	956.3	950.7	903.9	921.1	0.884	0.968	0.967
1 Gbps	{10}	850	{Vegas:64, NewReno:1}	989.8	989.8	976.2	953.8	954.0	940.7	0.042	0.967	0.976
1 Gbps	{100}	8500	{Vegas:4, NewReno:128}	986.9	917.6	957.3	950.8	884.1	922.2	0.946	0.970	0.971
1 Gbps	{100, 64}	8500	{Vegas:4, NewReno:128}	988.4	941.1	959.8	952.4	906.8	924.7	0.956	0.970	0.964
1 Gbps	{100}	8500	{Vegas:8, NewReno:128}	987.0	936.1	964.4	950.8	901.8	929.0	0.921	0.968	0.969
1 Gbps	{10}	850	{Vegas:128, BBR:1}	989.8	989.8	987.3	954.0	954.0	951.5	0.886	0.965	0.985
1 Gbps	{100}	8500	{Bic:2, Cubic:32}	985.1	960.3	952.6	944.9	924.9	911.3	0.799	0.999	0.946
10 Gbps	{50, 44}	41667	{NewReno:128, Cubic:16}	9876	9705	9780	9514	9352	9420	0.917	0.969	0.968
10 Gbps	{28, 28}	25000	{NewReno:128, Cubic:128}	9891	9856	9787	9532	9498	9432	0.863	0.942	0.952

Cebinae is agnostic to CCAs

Btl. BW	RTTs [ms]	Buf. [MTU]	CCAs	Throughput [Mbps] FIFO	Throughput [Mbps] FQ	Throughput [Mbps] Cebinae	Goodput [Mbps] FIFO	Goodput [Mbps] FQ	Goodput [Mbps] Cebinae	JFI FIFO	JFI FQ	JFI Cebinae
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1 Gbps	{50}	4200	{NewReno: 128, BBR: 1}	988.7	923.6	981.6	952.7	890.0	945.8	0.992	0.975	0.990
1 Gbps	{50}	4200	{NewReno: 128, BBR: 2}	988.9	953.9	979.9	952.8	919.2	944.2	0.951	0.963	0.981
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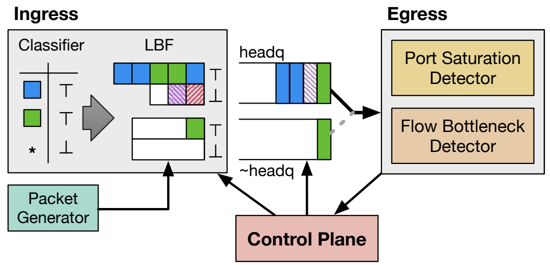
10 Gbps	{50, 44}	41667	{NewReno:128, Cubic:16}	9876	9705	9780	9514	9352	9420	0.917	0.969	0.968
10 Gbps	{28, 28}	25000	{NewReno:128, Cubic:128}	9891	9856	9787	9532	9498	9432	0.863	0.942	0.952

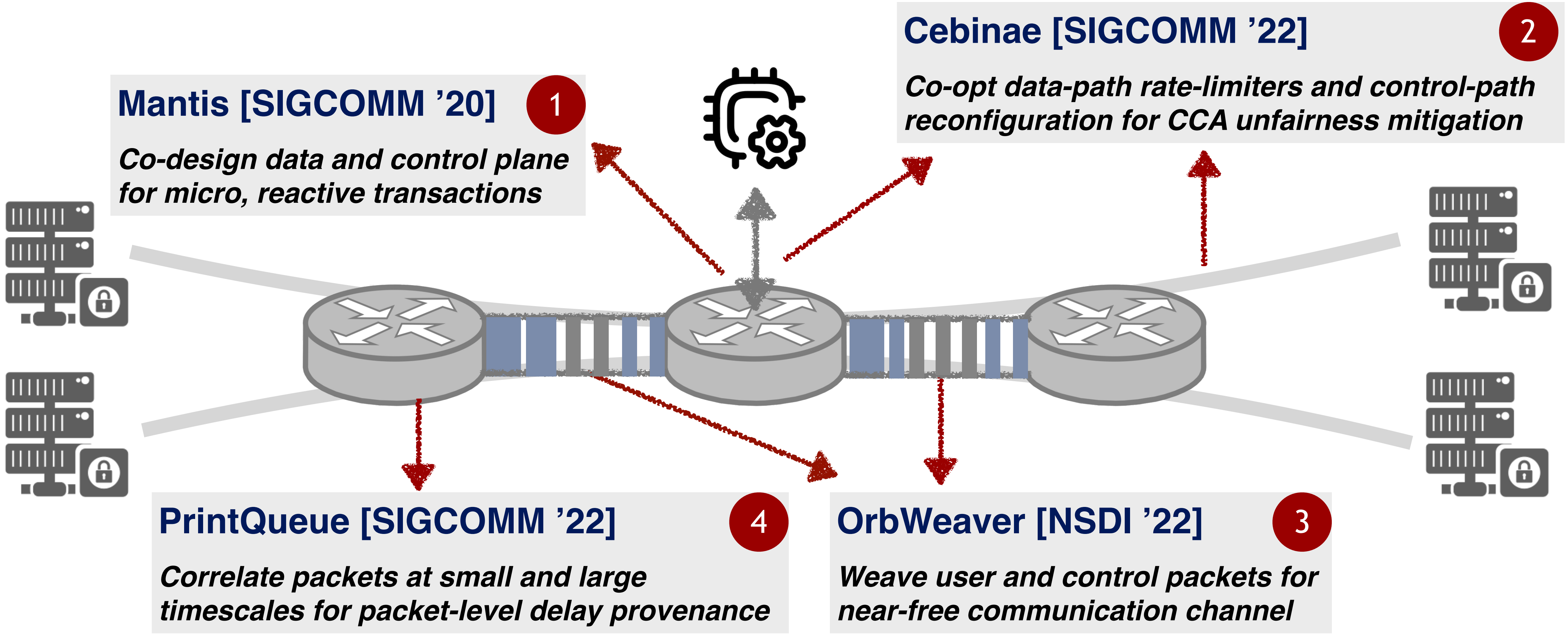


Summary

- **No modifications nor coordinations** to/with legacy host CCAs
  - *Real-time switch architecture serializing in-network compute modules*
- COTS hardware and **minimal resource requirements**
  - *Two queues/priorities are sufficient*
- Compatible with CCAs using **both loss and non-loss signals**
  - *Generic support of a wide range of Internet CCAs and environments*

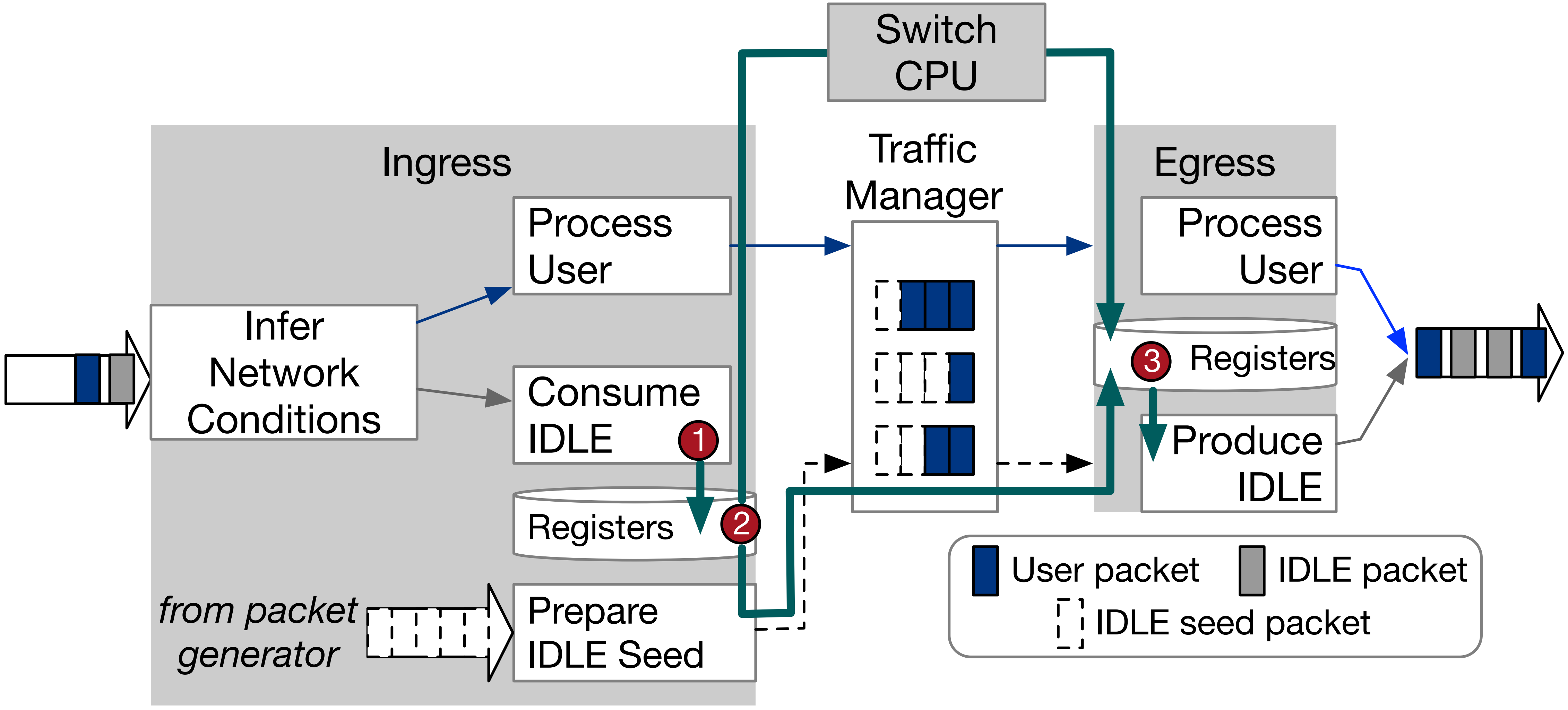
https://github.com/eniac/Cebinae

More details



Q & A

Using weaved stream



Optimal value of τ

$$\tau = B_{100Gbps}/MTU_{1500B} = 120ns$$