Automatic In-network Control Empowered by Programmable Infrastructure

Liangcheng Yu

09/2022

Penn
UNIVERSITY *of* PENNSYLVANIA

Ubiquitous network control tasks

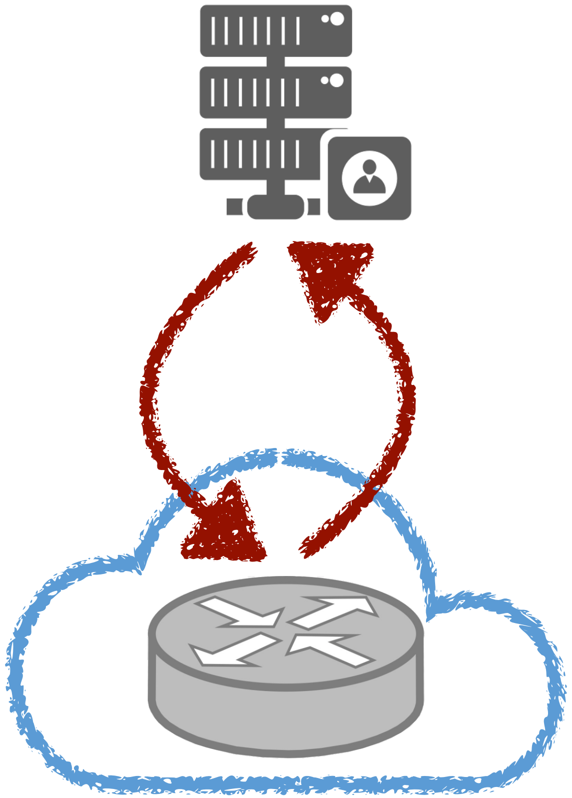
Out-of-control events

- Congestion collapse
- Network hotspots
- DoS attacks
- Effects of failure events
- Time drifts
- Bandwidth starvation
- …

Network control mechanisms

- Congestion control
- Load balancing
- Security policies
- Failure mitigation
- Clock synchronization
- Fairness control
- …

Network control



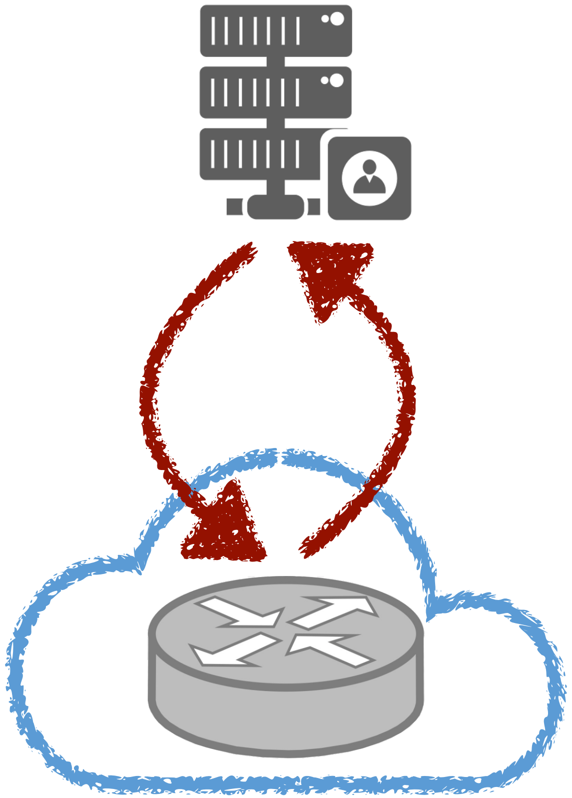
Need for **fast, real-time, and automatic** control at scale

- *Networks are getting fast:* $< 1 \rightarrow 10 \rightarrow 100 \rightarrow 800 \rightarrow \ldots$*[Gbps]*
- *Implication:* ***microscopic*** *(e.g., O(μs)) event, harder management*
- *Closed-loop reactions: e.g., rate control, load balancing, …*

Traditional network control

- *Mode of operation: infrequent (O(100 ms)), asynchronous, and manual*

Network control



Need for fast, real-time, and automatic control at scale

- *Networks are getting fast:* $< 1 \rightarrow 10 \rightarrow 100 \rightarrow 800 \rightarrow \ldots$*[Gbps]*
- *Implication: microscopic (e.g., O(*μs*)) event, harder management*
- *Closed-loop reactions: e.g., rate control, load balancing, …*

Traditional network control

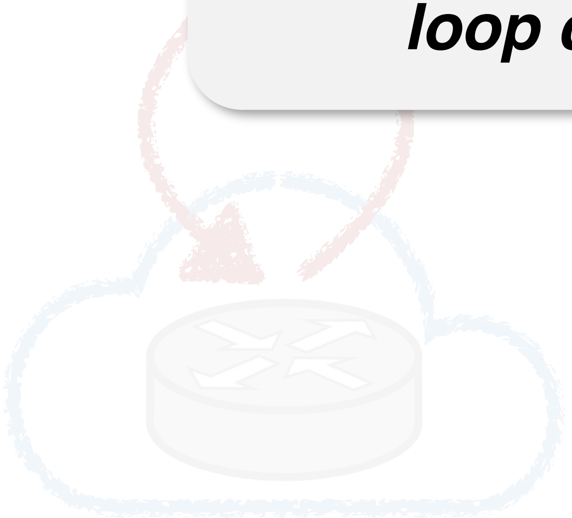
- *Mode of operation: infrequent (O(100* ms*)), asynchronous, and manual*

Fill the gap towards high-frequency network control?

Network control

Need for fast, real-time, and automatic control at scale

*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

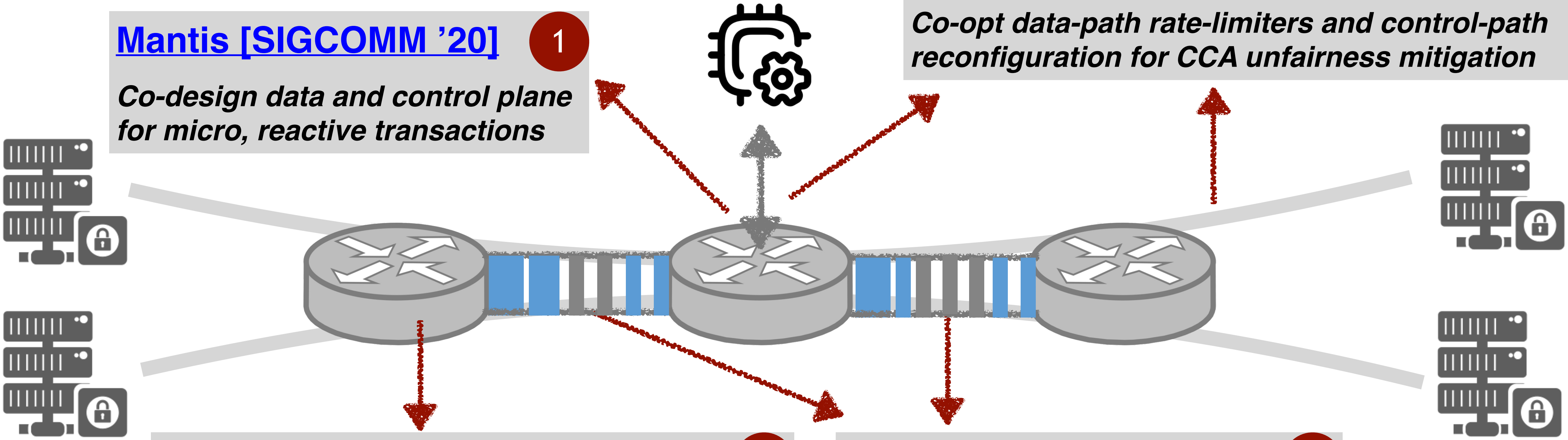


Traditional network control

- *Mode of operation: infrequent ($O(100\,ms)$), asynchronous, and manual*

Fill the gap towards high-frequency network control?

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

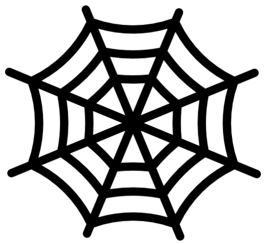
OrbWeaver [NSDI '22] 3

Weave user and control packets for near-free communication channel

PrintQueue [SIGCOMM '22] 4

Correlate packets at small and large timescales for packet-level delay provenance

Outline



OrbWeaver:

Using IDLE Cycles in Programmable Networks for Opportunistic Coordination

Cebinae:

Scalable In-network Fairness Augmentation

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…

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?

- *Time synchronization*: clock-sync rate → precision
- *Failure detector*: keep alive message frequency → detection speed
- *Congestion notification*: signaling data and rate → measurement accuracy

When introducing a new in-band application…

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

- *Time synchronization*: clock-sync rate → precision
- *Failure detector*: keep alive message frequency → detection speed
- *Congestion notification*: signaling data and rate → measurement accuracy

Is the trade-off between fidelity and overhead necessary?

When introducing a new in-band application…

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

- Failure detector: keep alive message frequency → detection speed

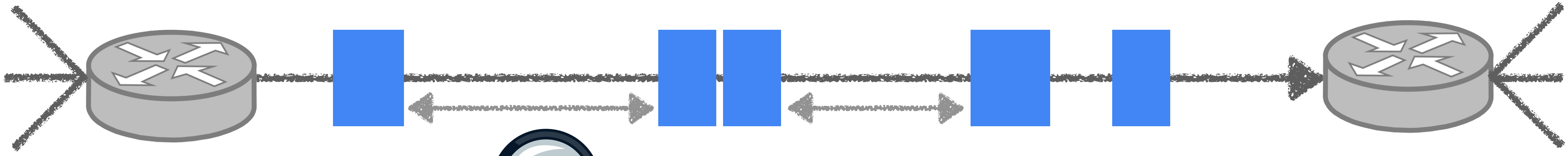
Can we coordinate at **high-fidelity** with a **near-zero cost** (to usable bandwidth, latency…)?

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

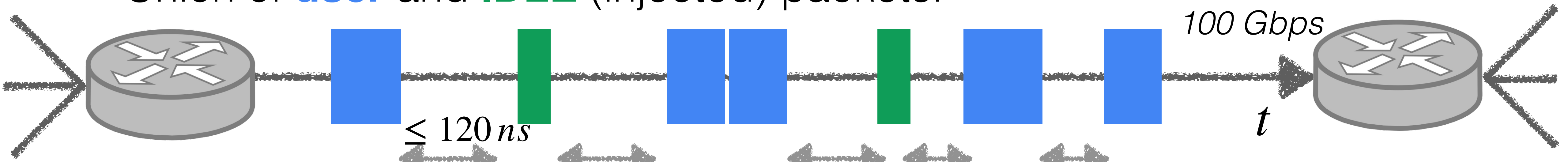
Opportunity: $< \mu s$ gaps are prevalent



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

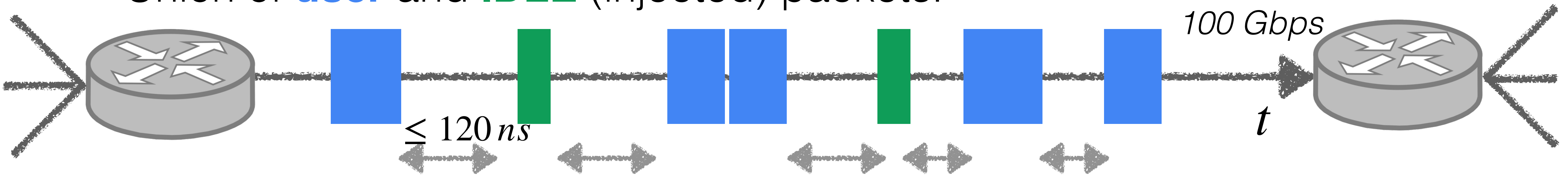
Abstraction: weaved stream

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



Abstraction: weaved stream

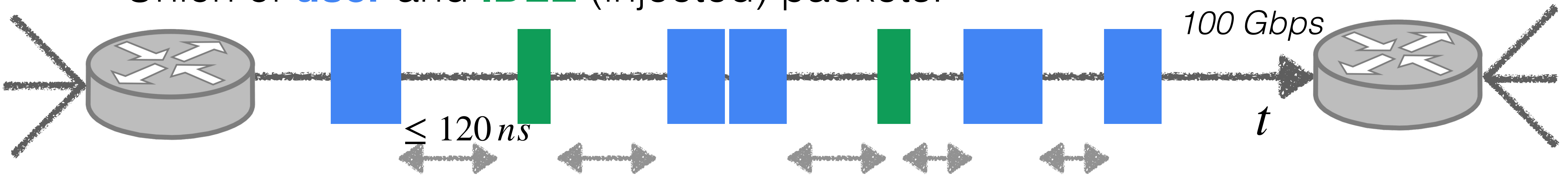
- Union of **user** and **IDLE** (injected) packets:



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

Abstraction: weaved stream

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



[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:

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

Crazy idea?

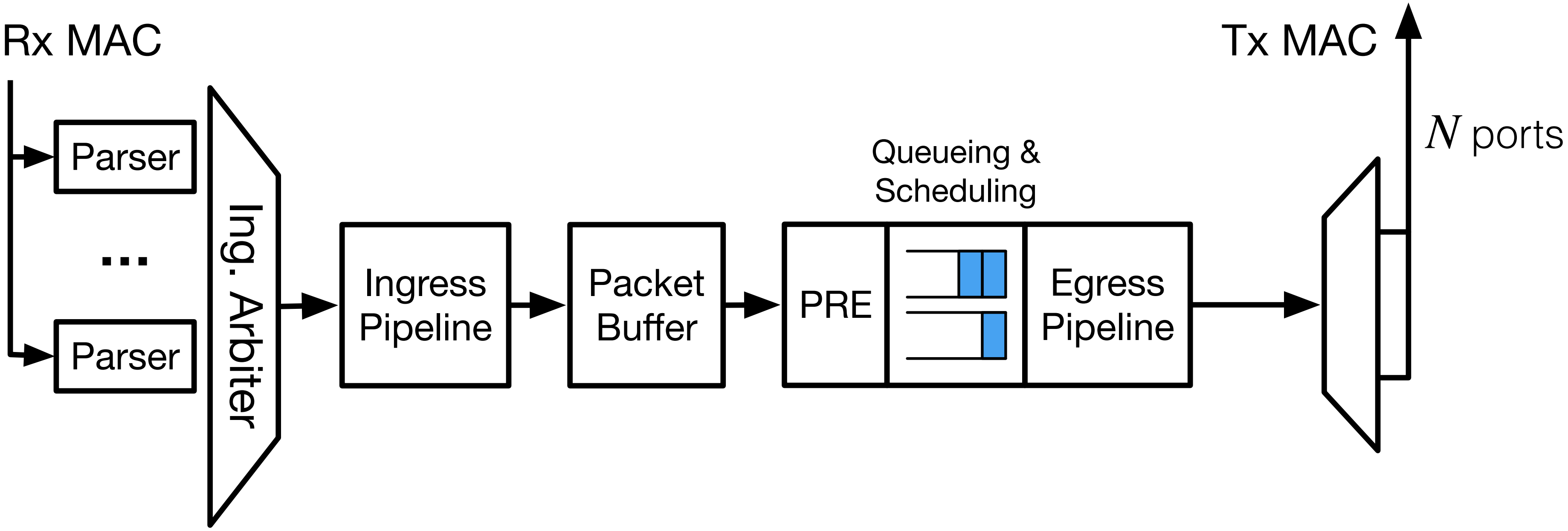
Extending IDLE characters to higher layers

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

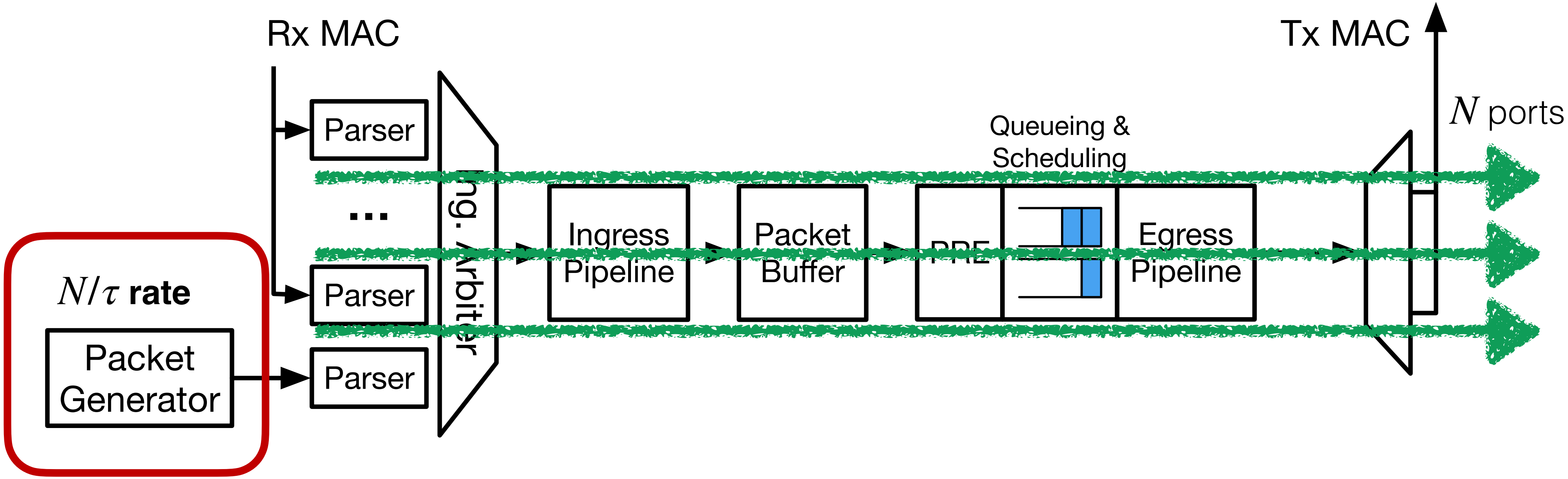
Outline

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

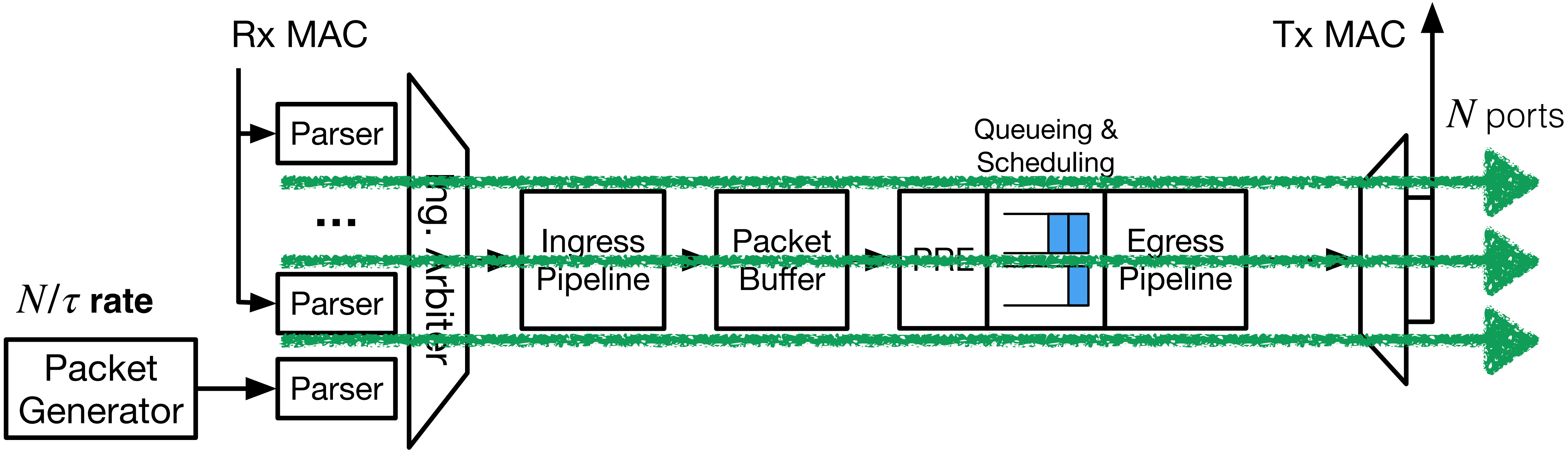
RMT switch model



Naive weaved stream generation

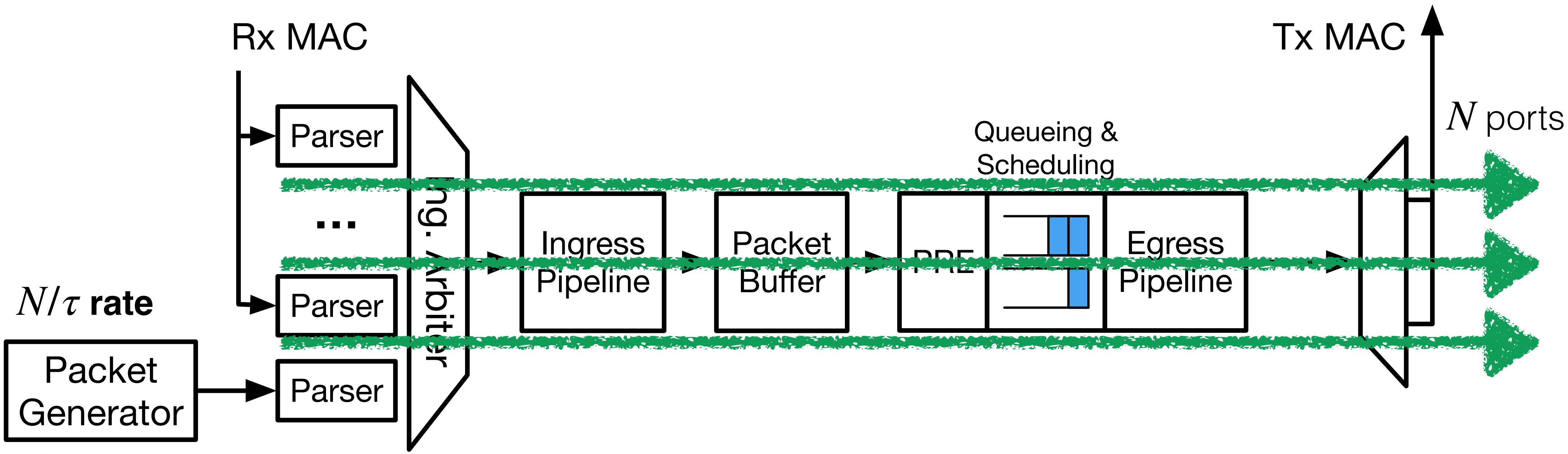


Naive weaved stream generation



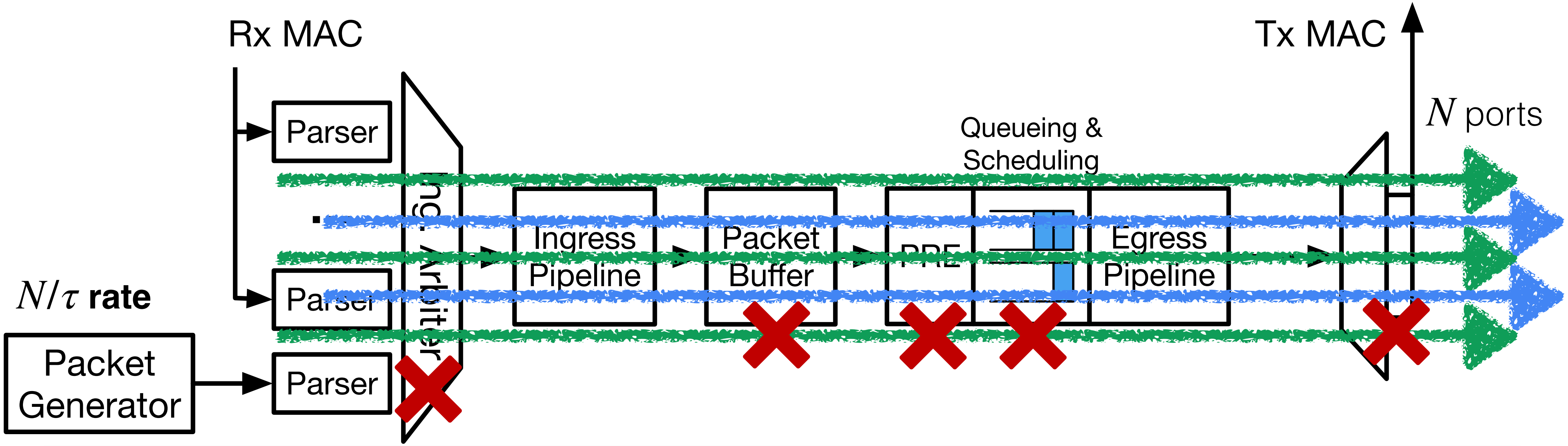
Predictability even there is no user traffic

Problems with blind injection



Scalability: overwhelm packet generator capacity to satisfy target rate

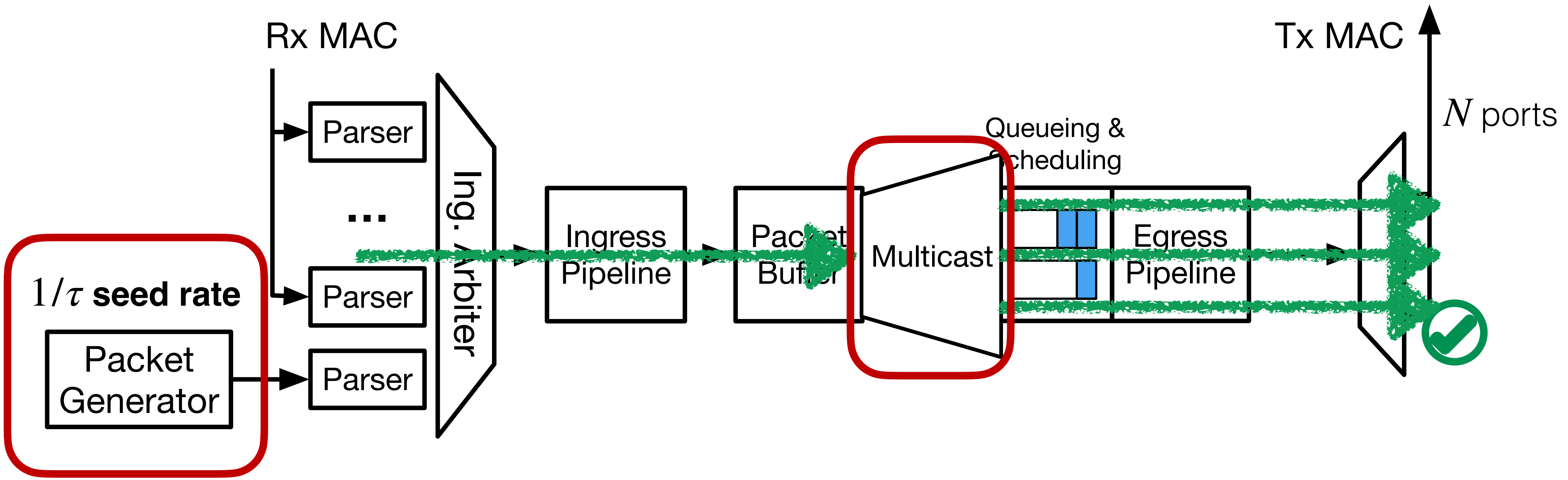
Problems with blind injection



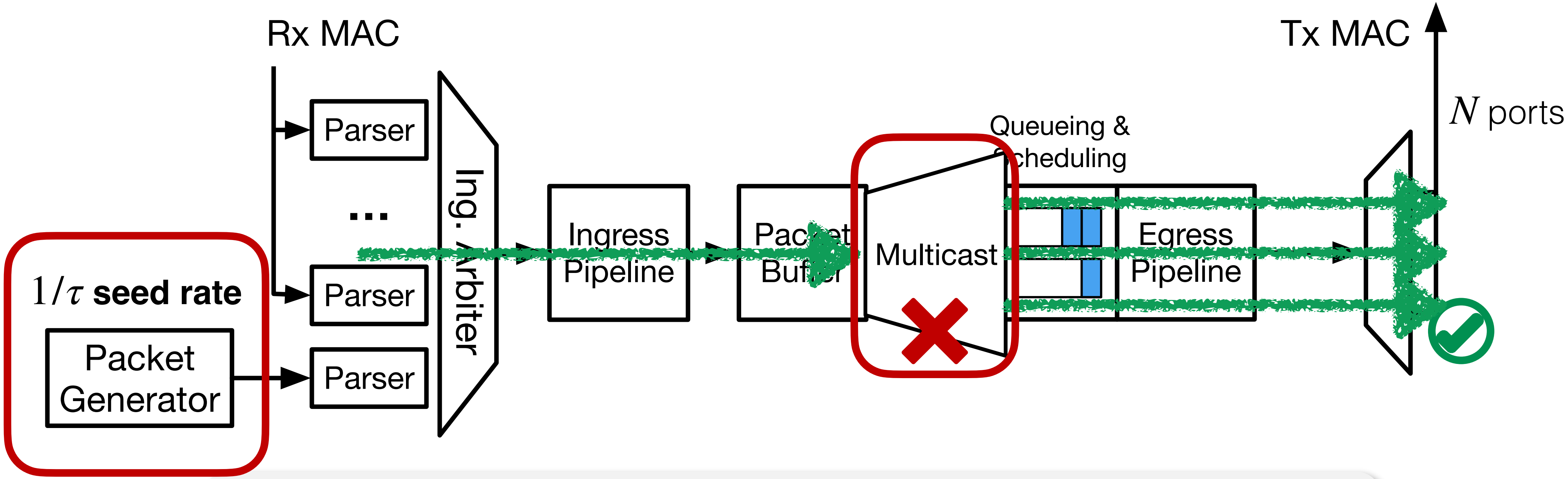
Scalability: overwhelm packet generator capacity to satisfy target rate

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

Amplify seed stream

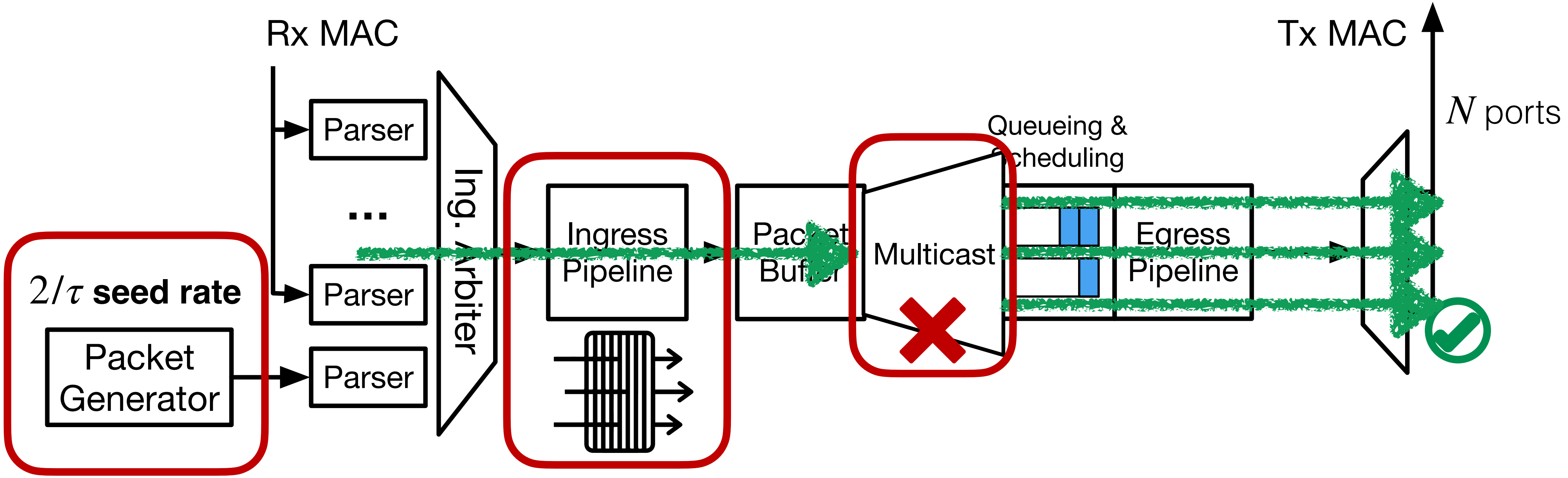


Amplify seed stream



Monopolize usage and waste PRE packet-level BW!

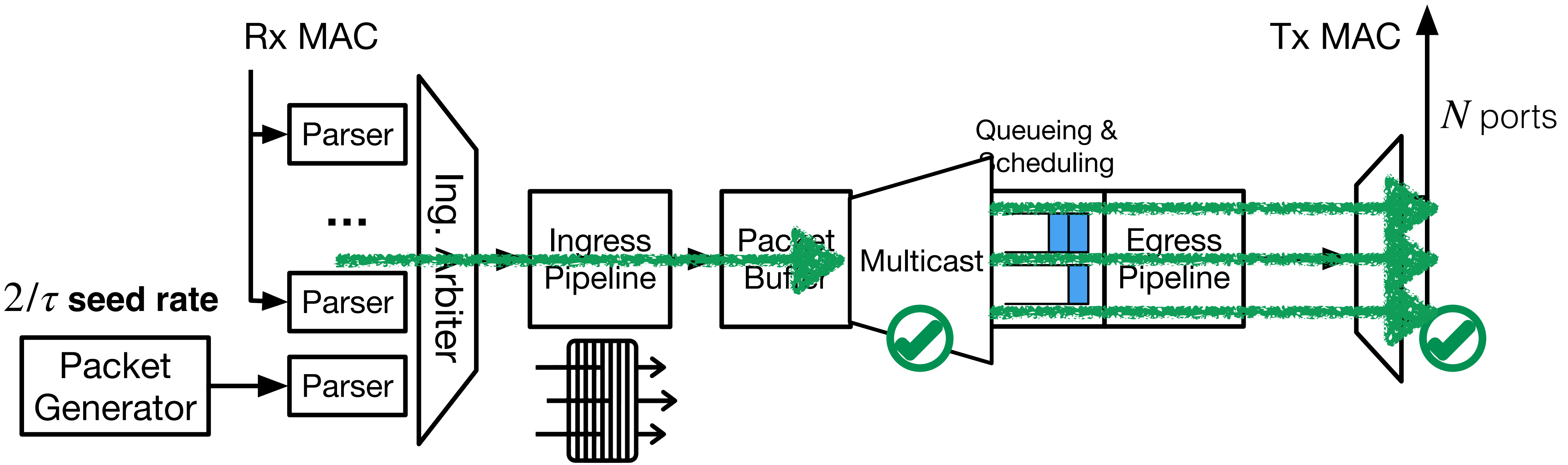
Amplify seed stream <u>on demand</u>



Selective filtering

- (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***

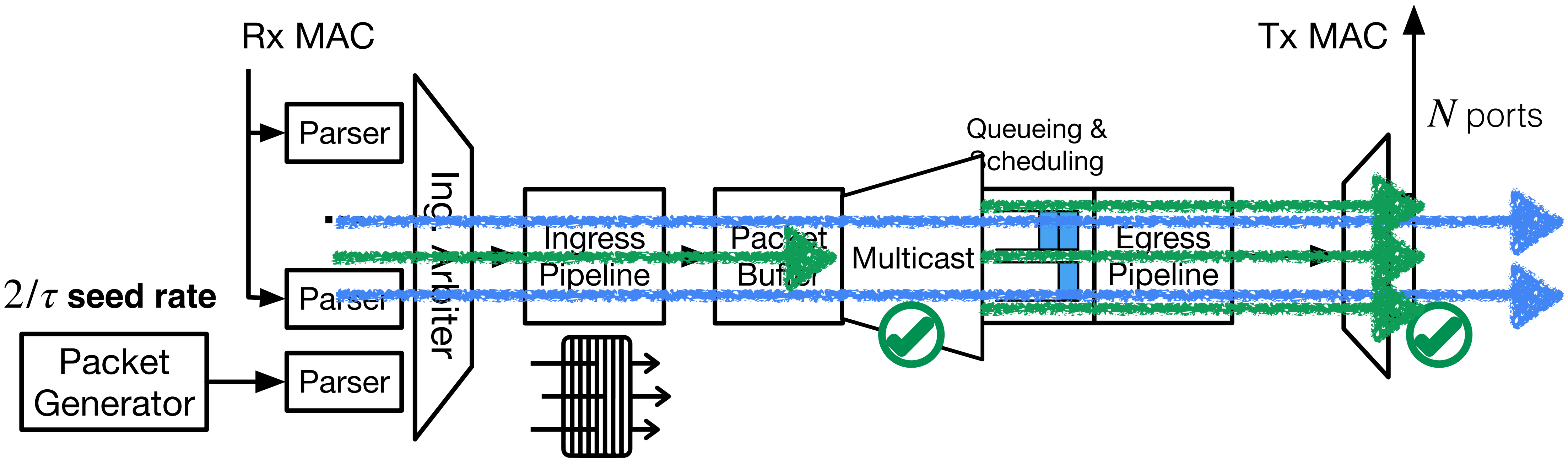
Amplify seed stream on demand



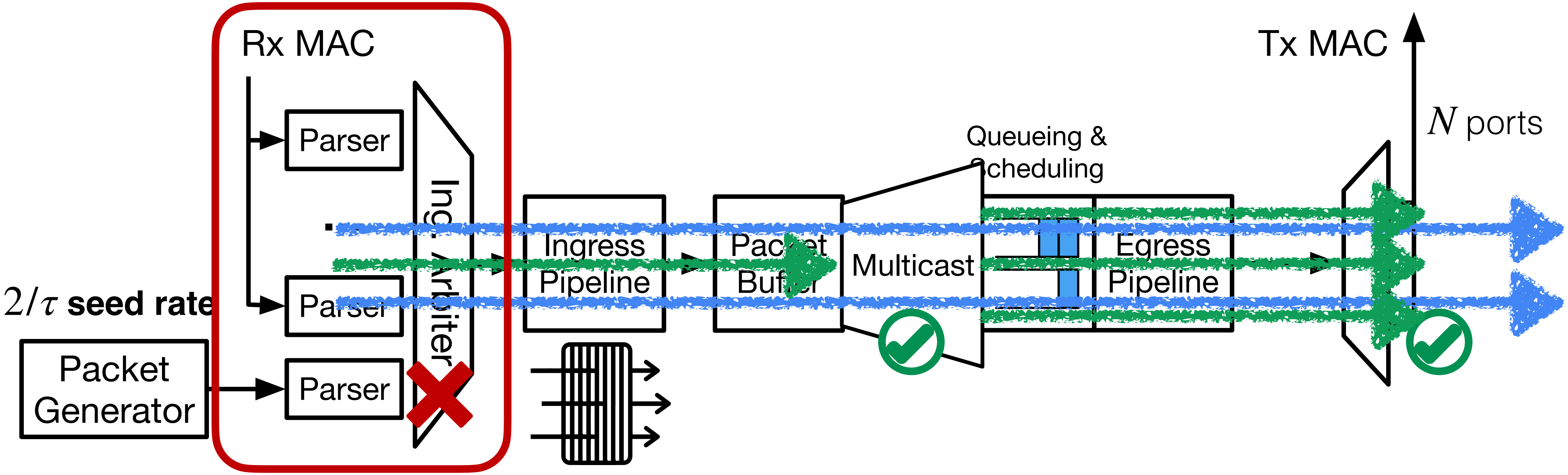
Selective filtering

- (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***

Cross-traffic contention

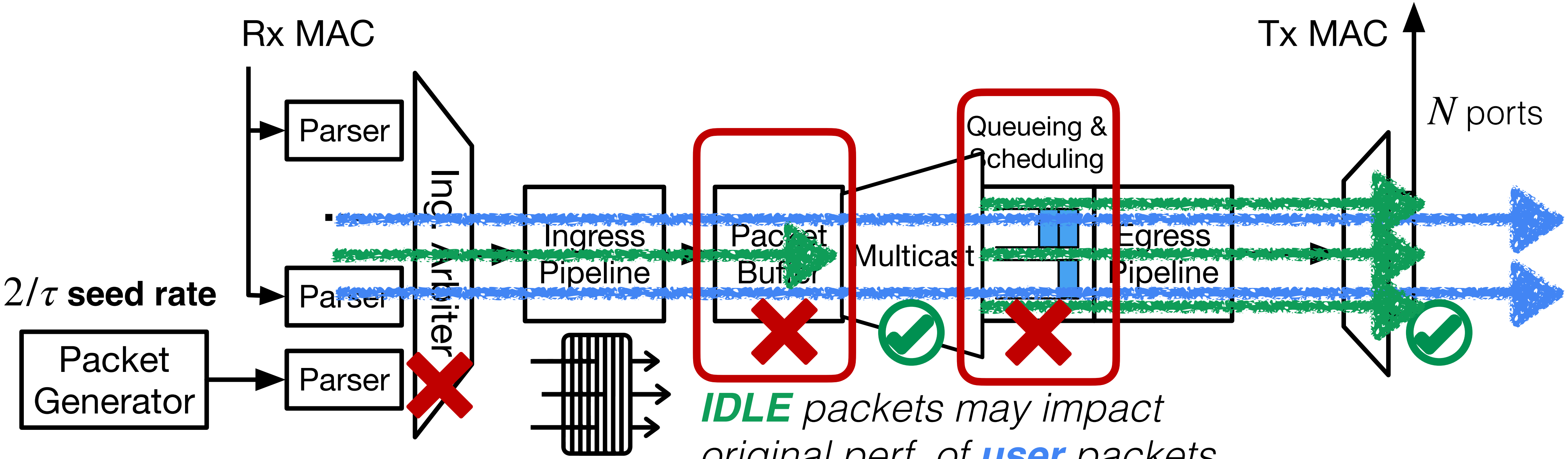


Cross-traffic contention



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

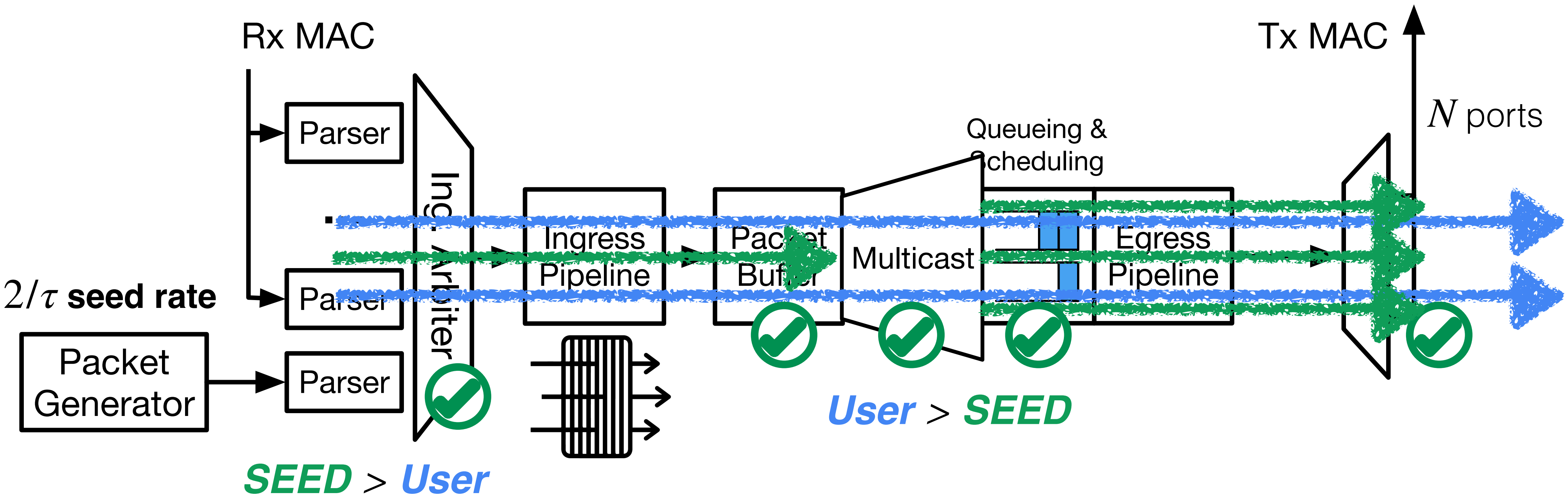
Cross-traffic contention



IDLE *packets may impact original perf. of* ***user*** *packets*

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

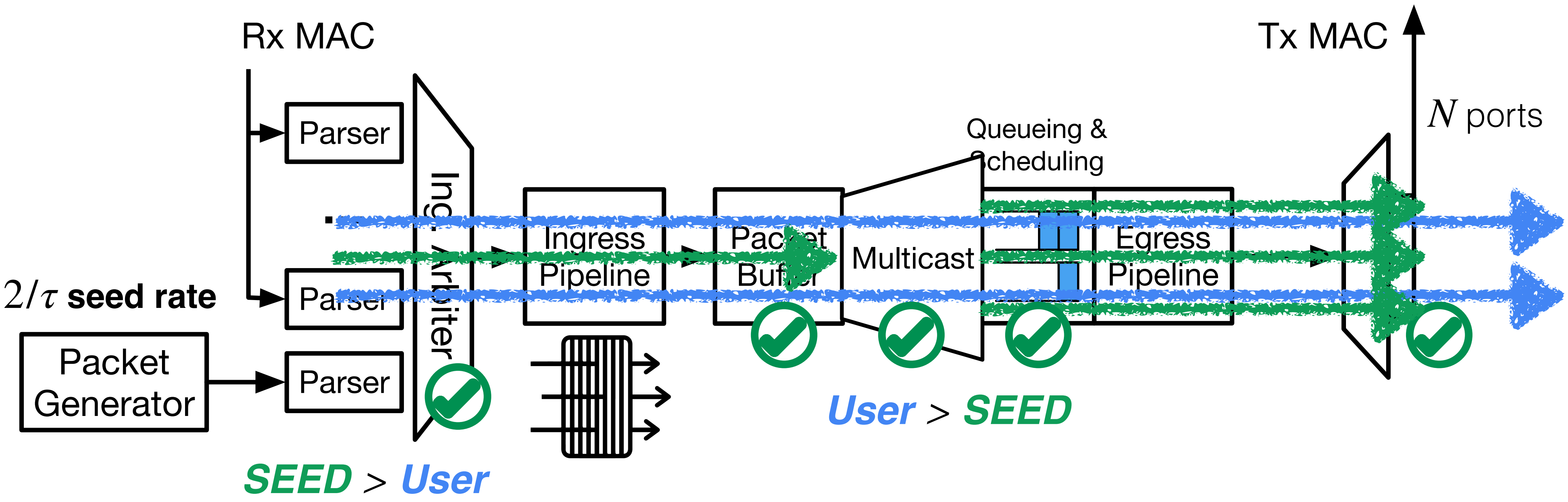
Preventing contention



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

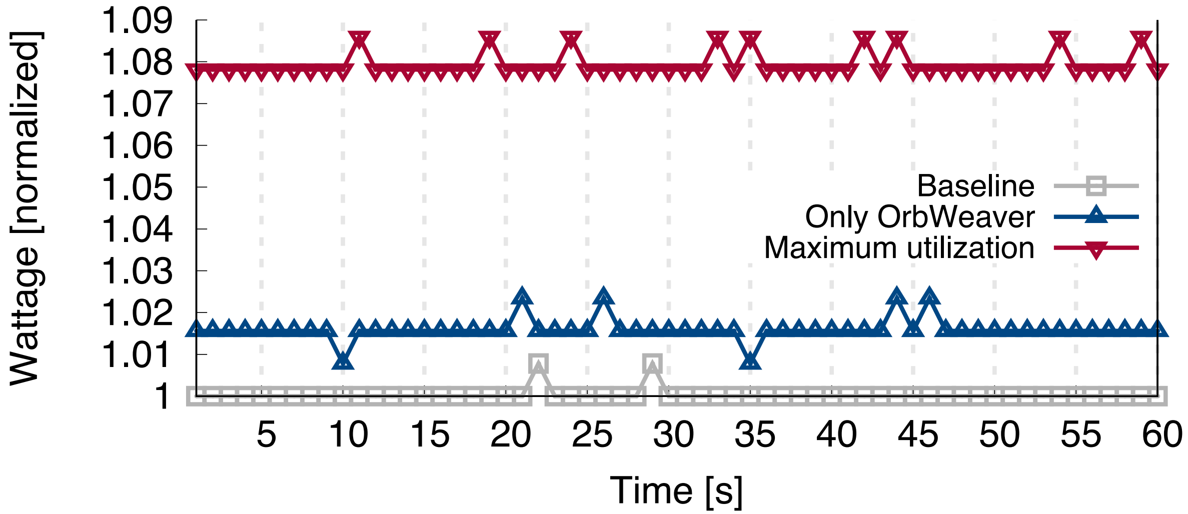


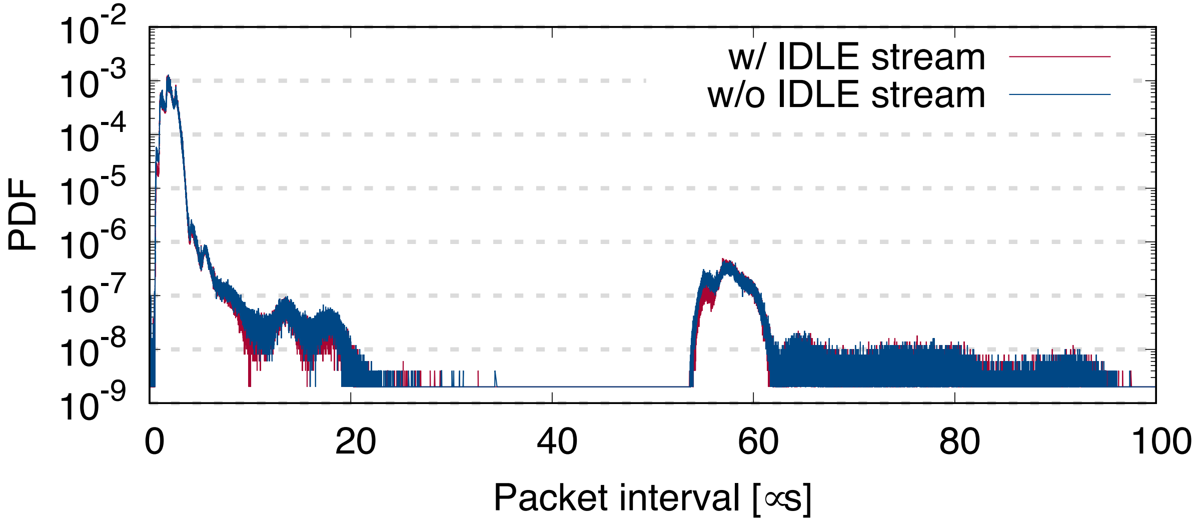
Rich configuration options for priorities and buffer management

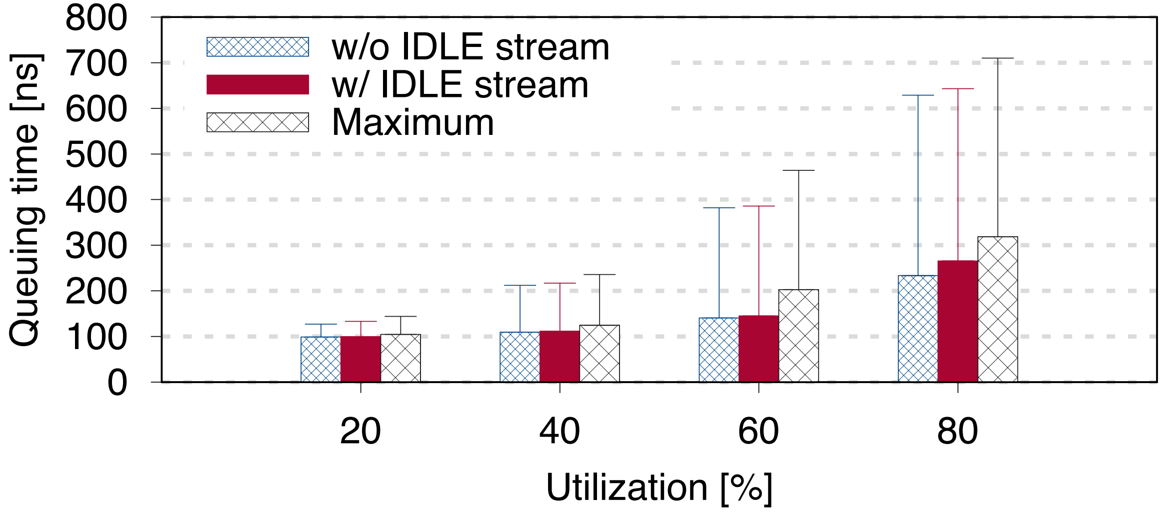
- *Zero impact of weaved stream predictability* ✓
- *Zero impact of* ***user traffic*** *throughput or buffer usage* ✓
- *Negligible impact of latency of* ***user packets*** ✓

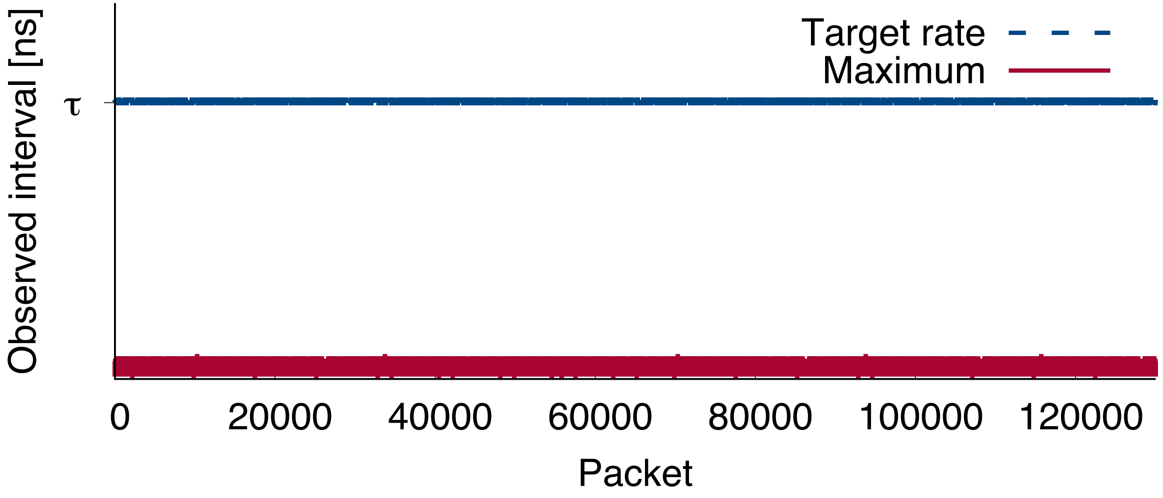
Implementation and evaluation

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



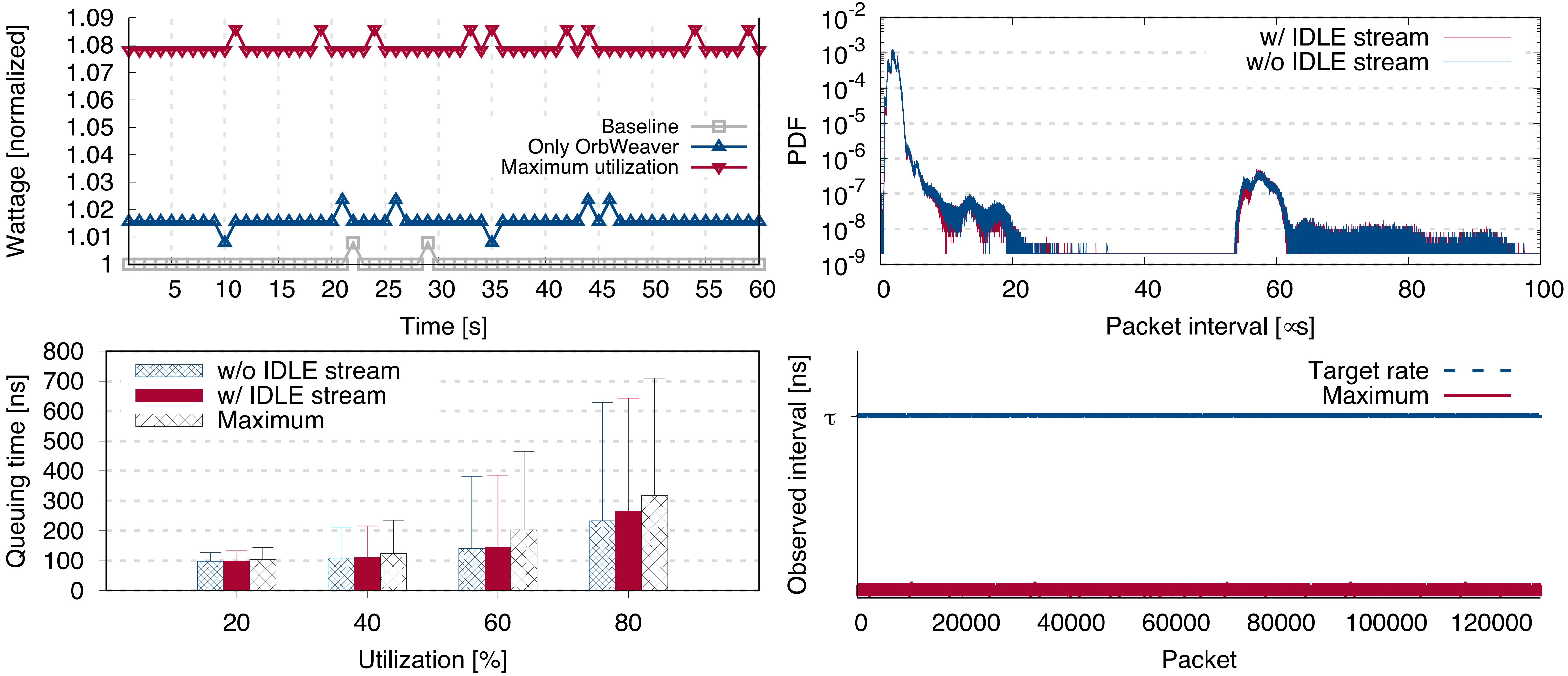






Takeaway: **Little-to-no impact** of power draw, latency, or throughput while guaranteeing **predictability** of the weaved stream!

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



OrbWeaver use cases

Free information dissemination [R2]

Fine-grained network state inference [R1]

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

Free information dissemination [R2]

Fine-grained network state inference [R1]

Performance aware routing

Flowlet load imbalance

Consistent replicas

Network queries

Latency localization

Header compression

Microburst detection

In-band telemetry

Event-based network control

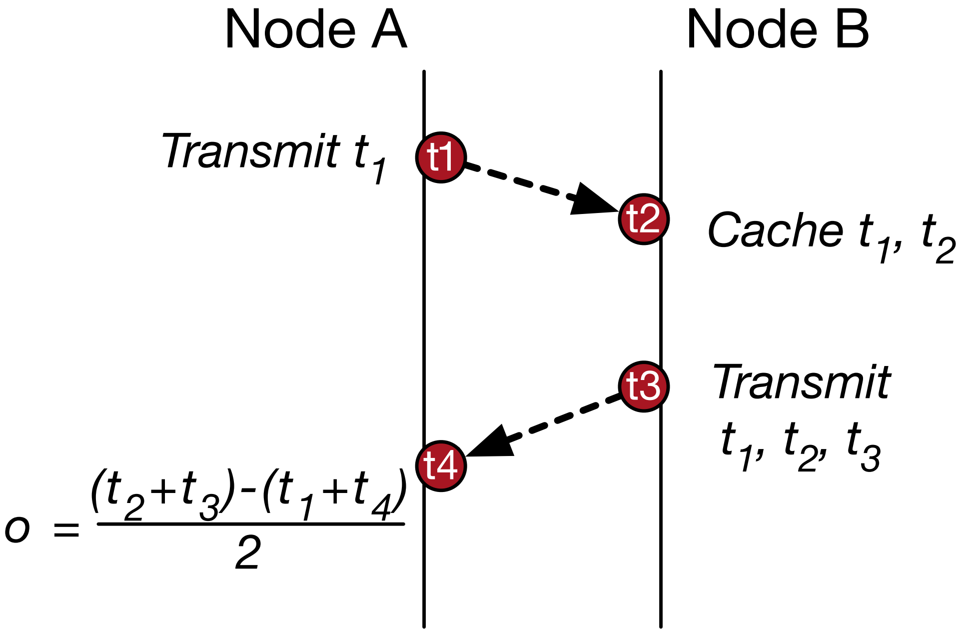
Failure detection

Network queries

Packet forensics

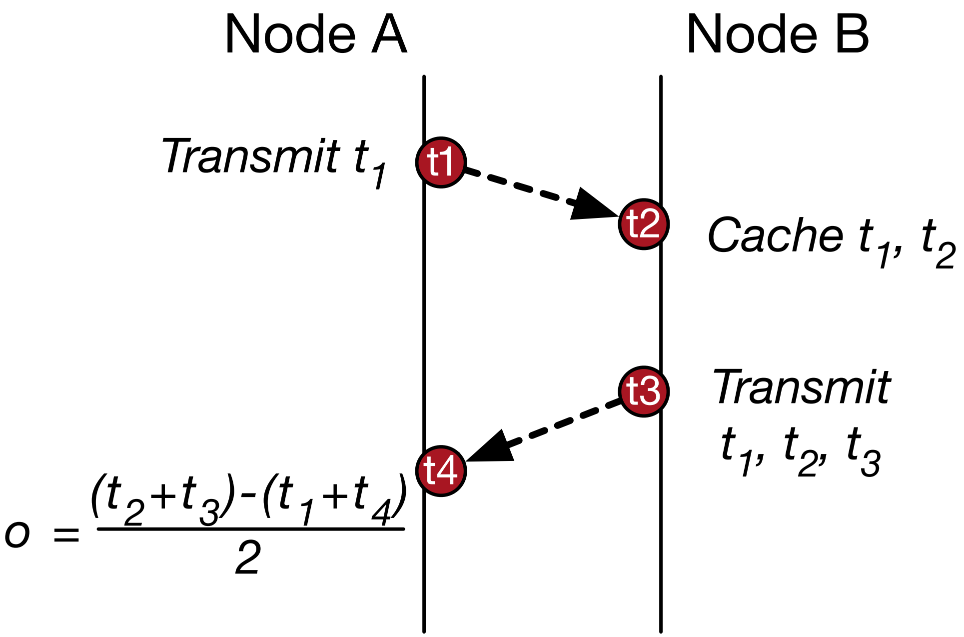
Clock synchronization

Example: time synchronization



Traditional two-way protocol

Example: time synchronization

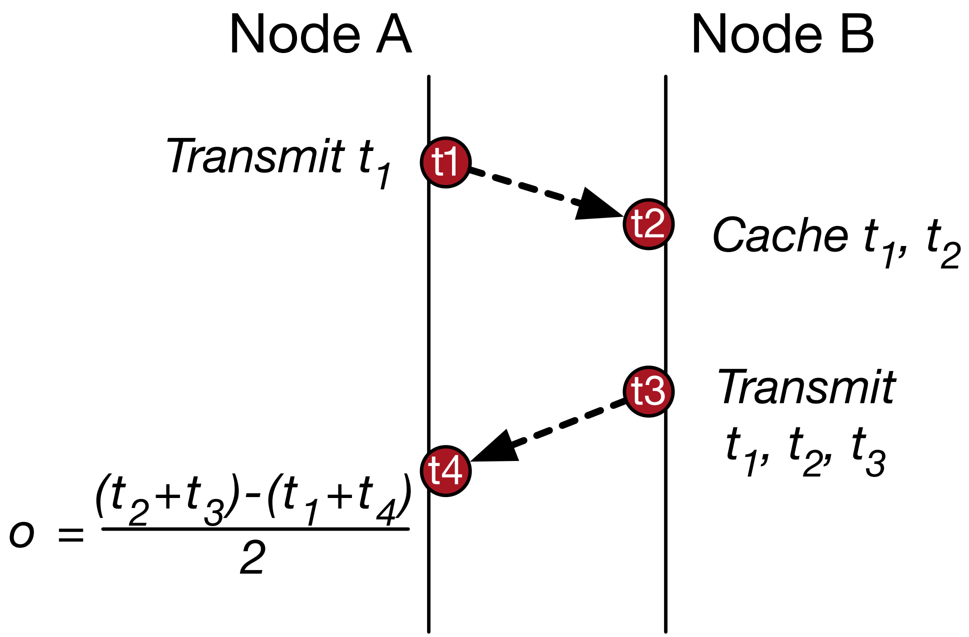


Traditional two-way protocol

Existing approaches for high precision

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

Example: time synchronization



Traditional two-way protocol

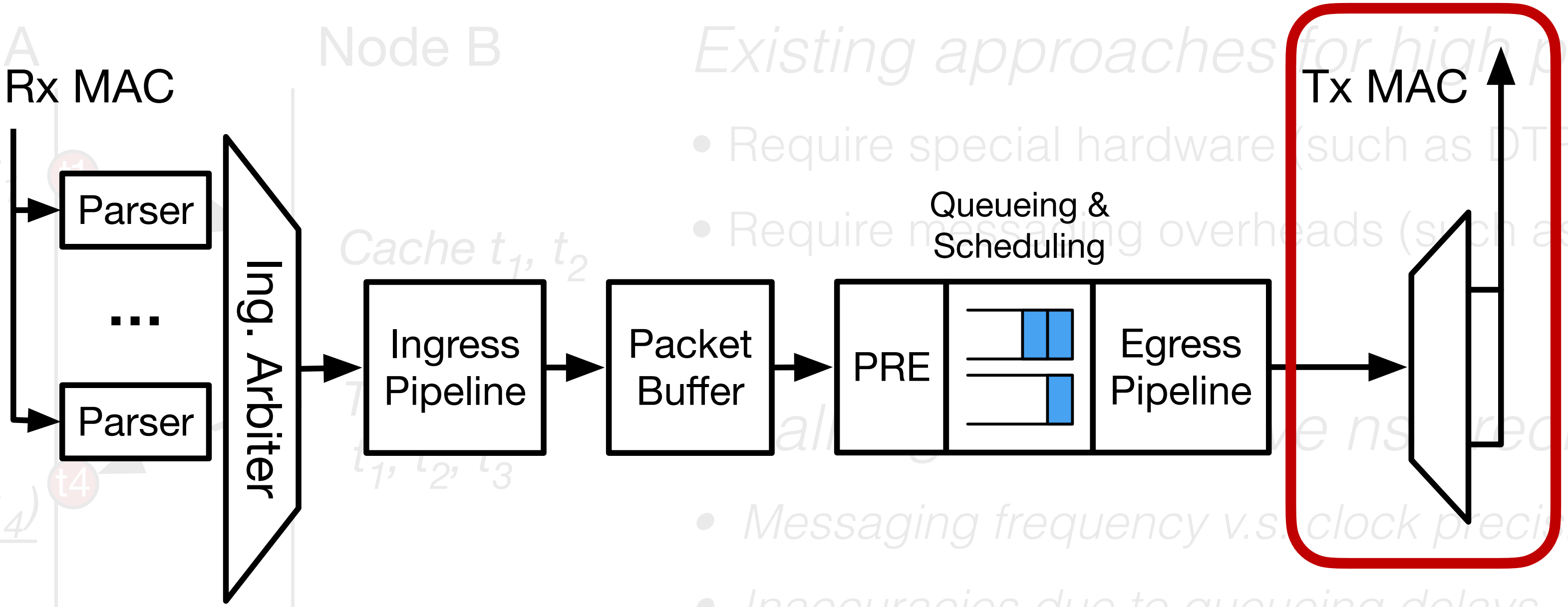
Existing approaches for high precision

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

Challenges to achieve ns precision

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

Example: time synchronization



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

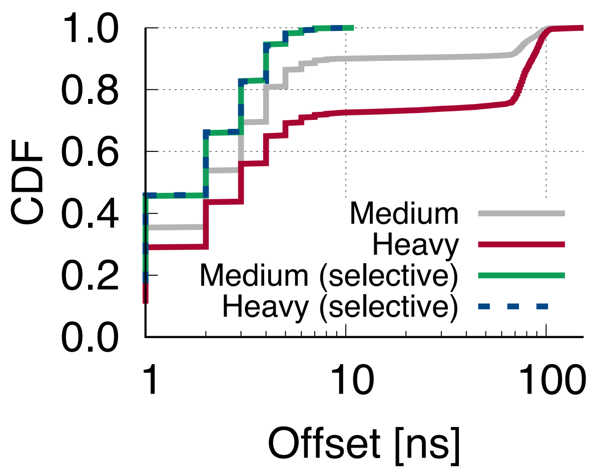
Key ideas:

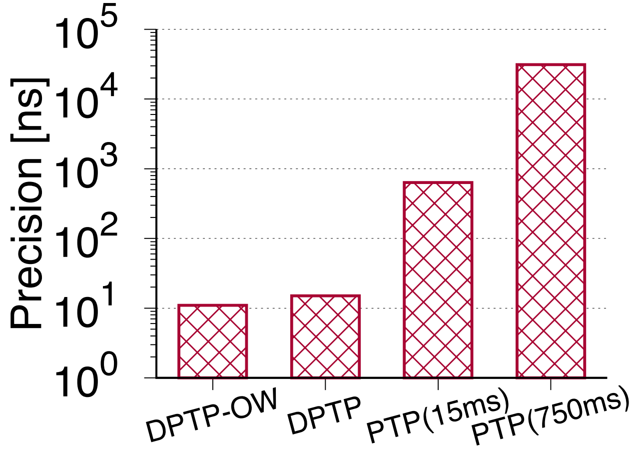
1. Embed timestamp information in **free IDLE packets** [R2]
2. Selective synchronization: **infer queue delay** from IDLE gaps and filter out **unreliable messages** [R1]

OrbWeaver Redesign

Key ideas:

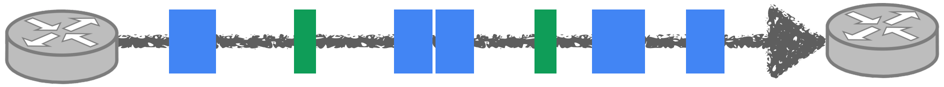
1. Embed timestamp information in **free IDLE packets** [R2]
2. Selective synchronization: **infer queue delay** from IDLE gaps and filter out **unreliable messages** [R1]





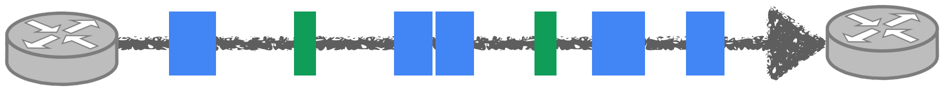
Achieve same or better performance with close-to-zero overheads

Summary



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

Summary

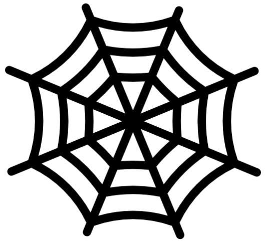


- **Weaved stream abstraction** to harvest IDLE cycles
  - Guarantee predictability with little-to-zero overhead
- Generic support of a wide range of data plane applications for free
  - ***Don't*** need to choose between coordination fidelity and bandwidth overhead

https://github.com/eniac/OrbWeaver

Thank you for your attention!

Outline



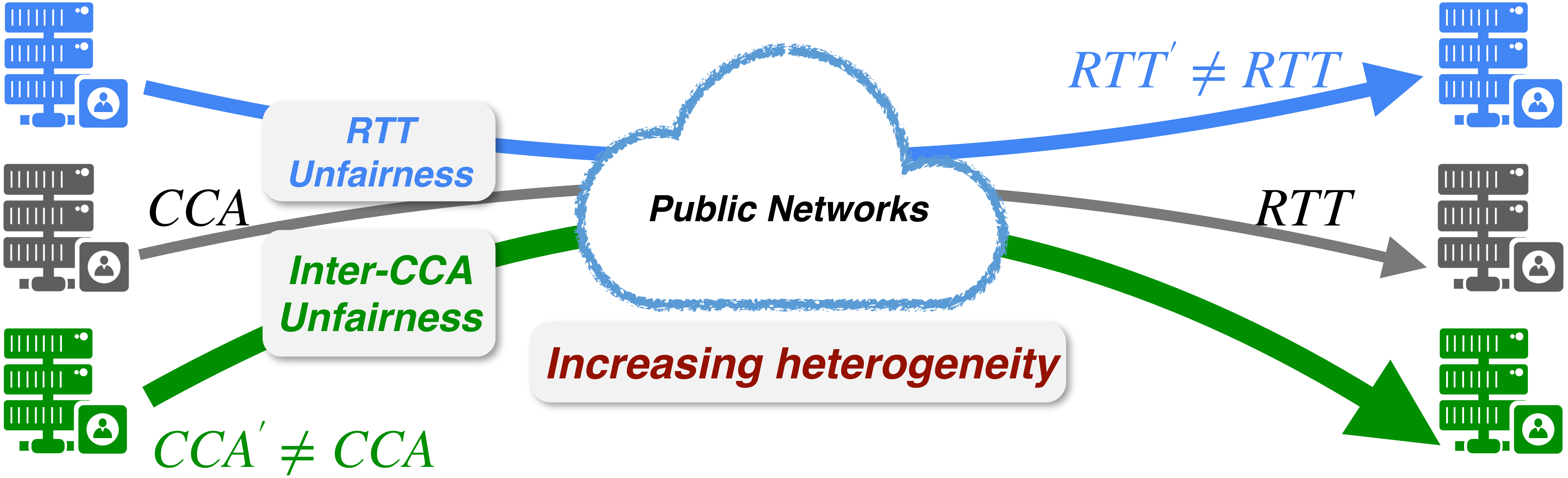
OrbWeaver:

Using IDLE Cycles in Programmable Networks for Opportunistic Coordination

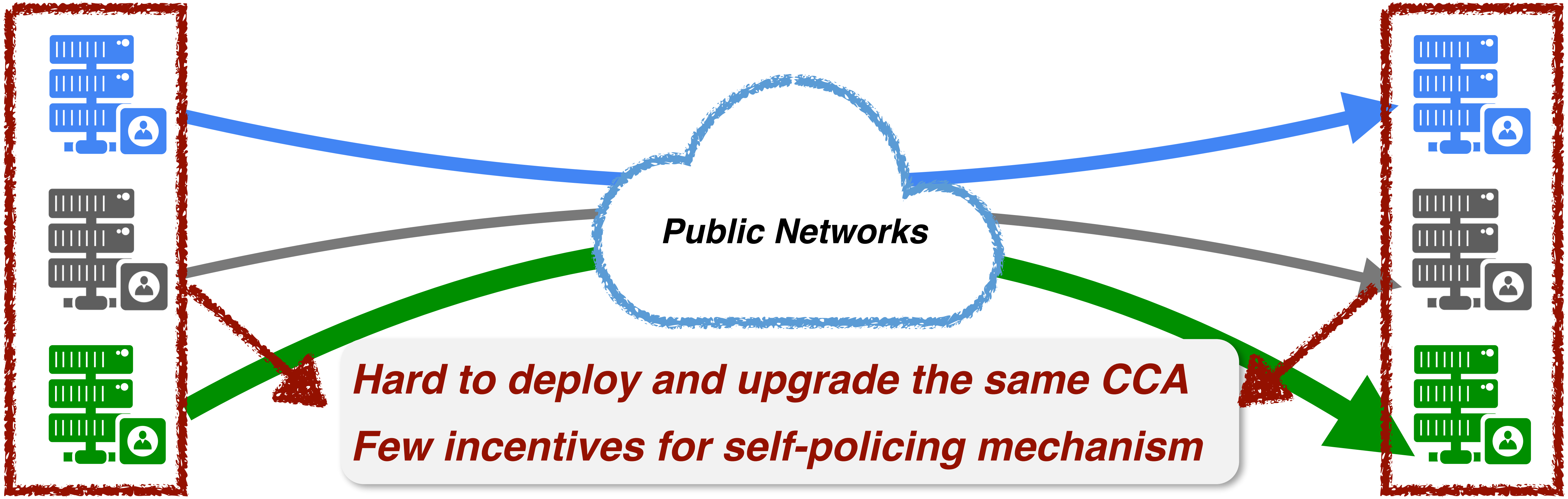
Cebinae:

Scalable In-network Fairness Augmentation

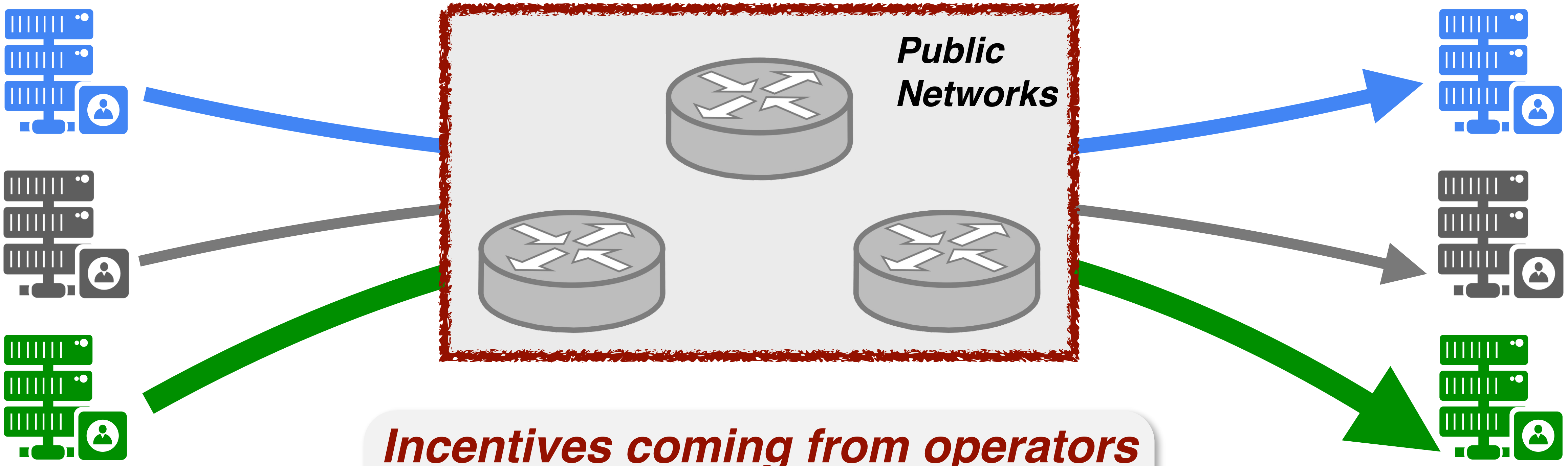
Public networks care about fairness



Fairness enforcement at the end hosts?



In-network fairness enforcement



Incentives coming 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…*

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*

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*

Cebinae: a simpler approach

- Relaxation of fairness **at every instance in time**
  - *Penalize/redistribute BW from flows exceeding fair share to others*
- **Binary classification** of flows
  - *Efficiently implement various subroutines (e.g., leaky-bucket filter)*

Cebinae: a simpler approach

- Relaxation of fairness **at every instance in time**
  - *Penalize/redistribute BW from flows exceeding fair share to others*
- **Binary classification** of flows
  - *Efficiently implement various subroutines (e.g., leaky-bucket filter)*

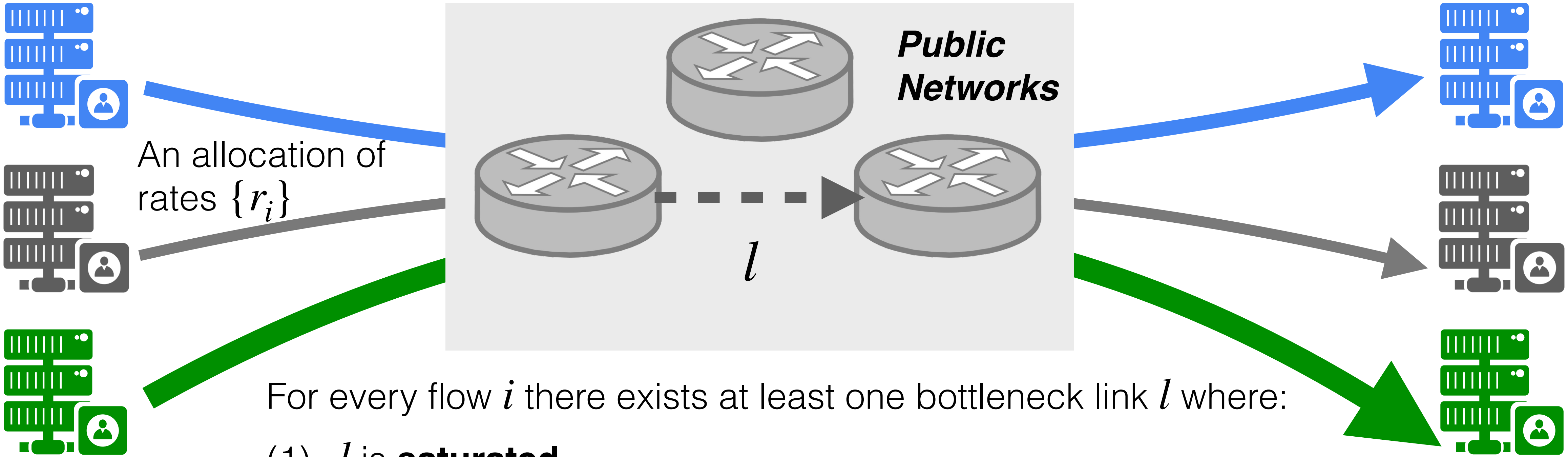
Cebinae router architecture for binary taxation

- **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

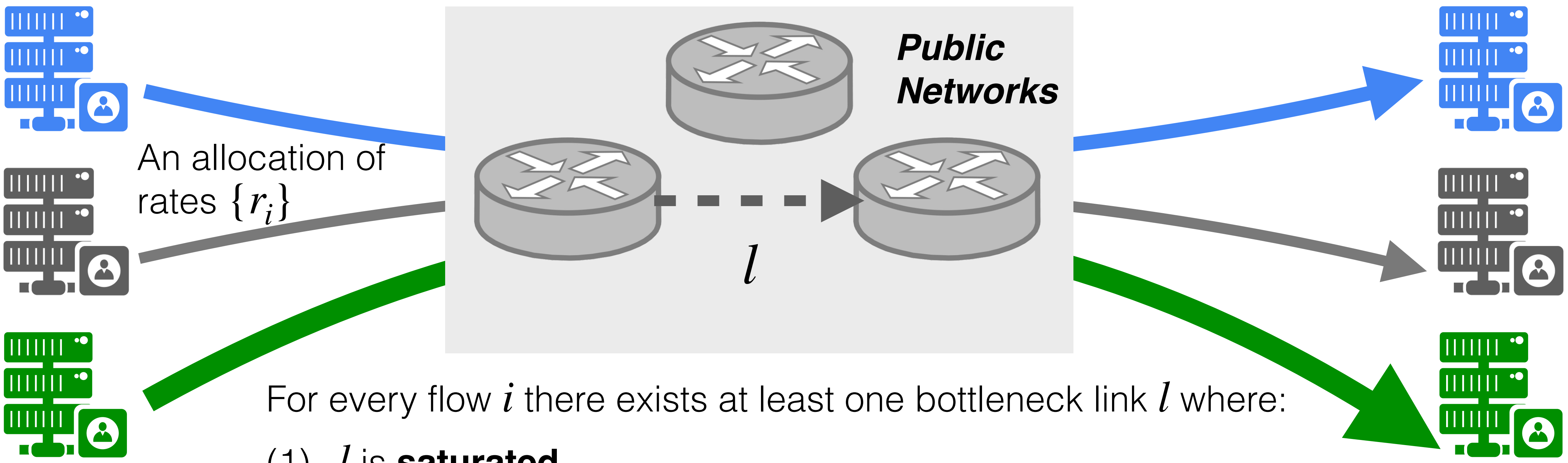


For every flow i there exists at least one bottleneck link l where:

(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 (⊤), not bottlenecked (⊥)

Naive enforcement

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)

*Drop packets of **all** i**s** per their current rate*

Else

NOP

Naive enforcement

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)

*Drop packets of **all** 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

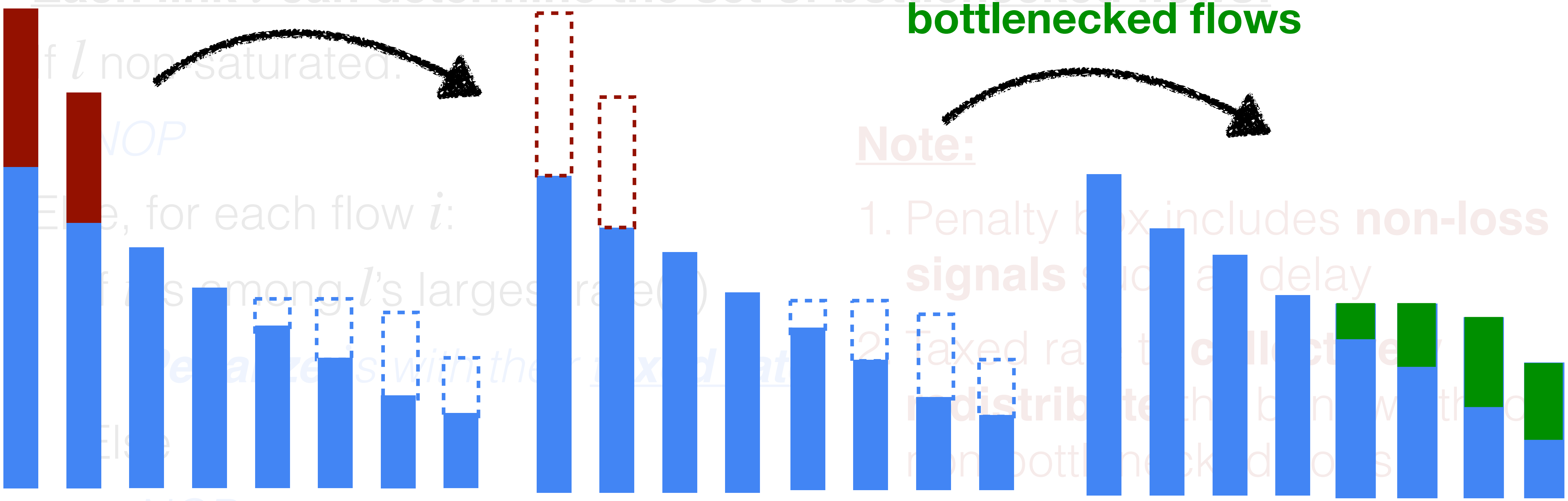
Note:

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

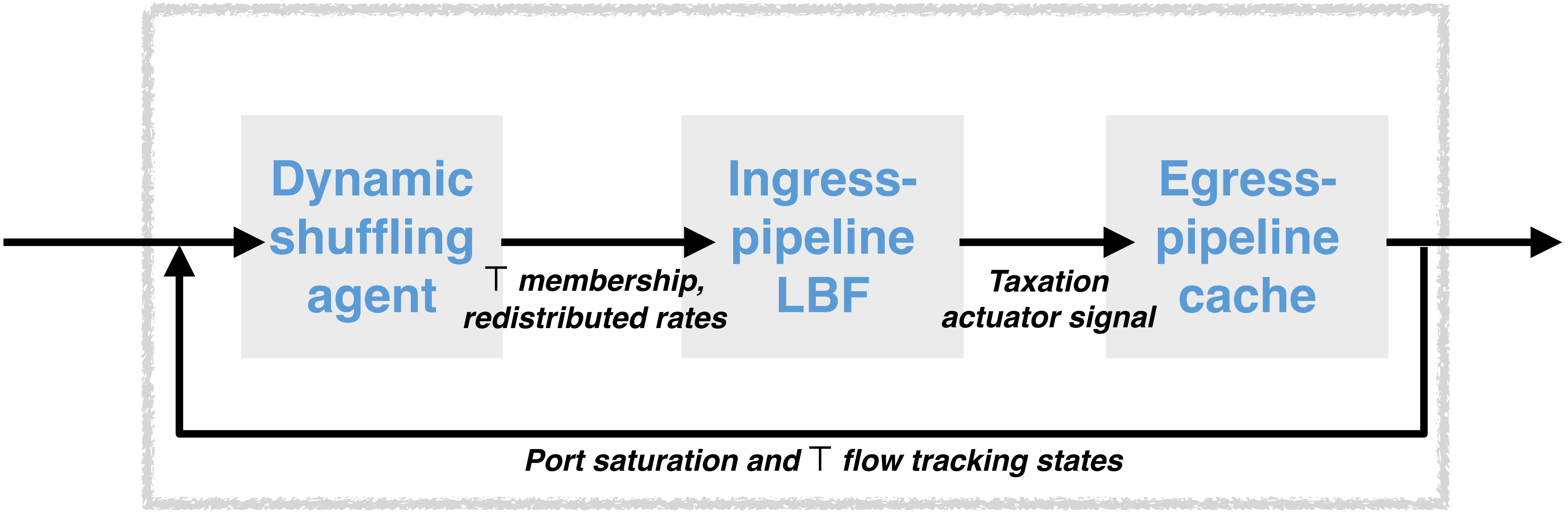
Cebinae taxation

Tax bottlenecked-flows exceeding fair bandwidth share

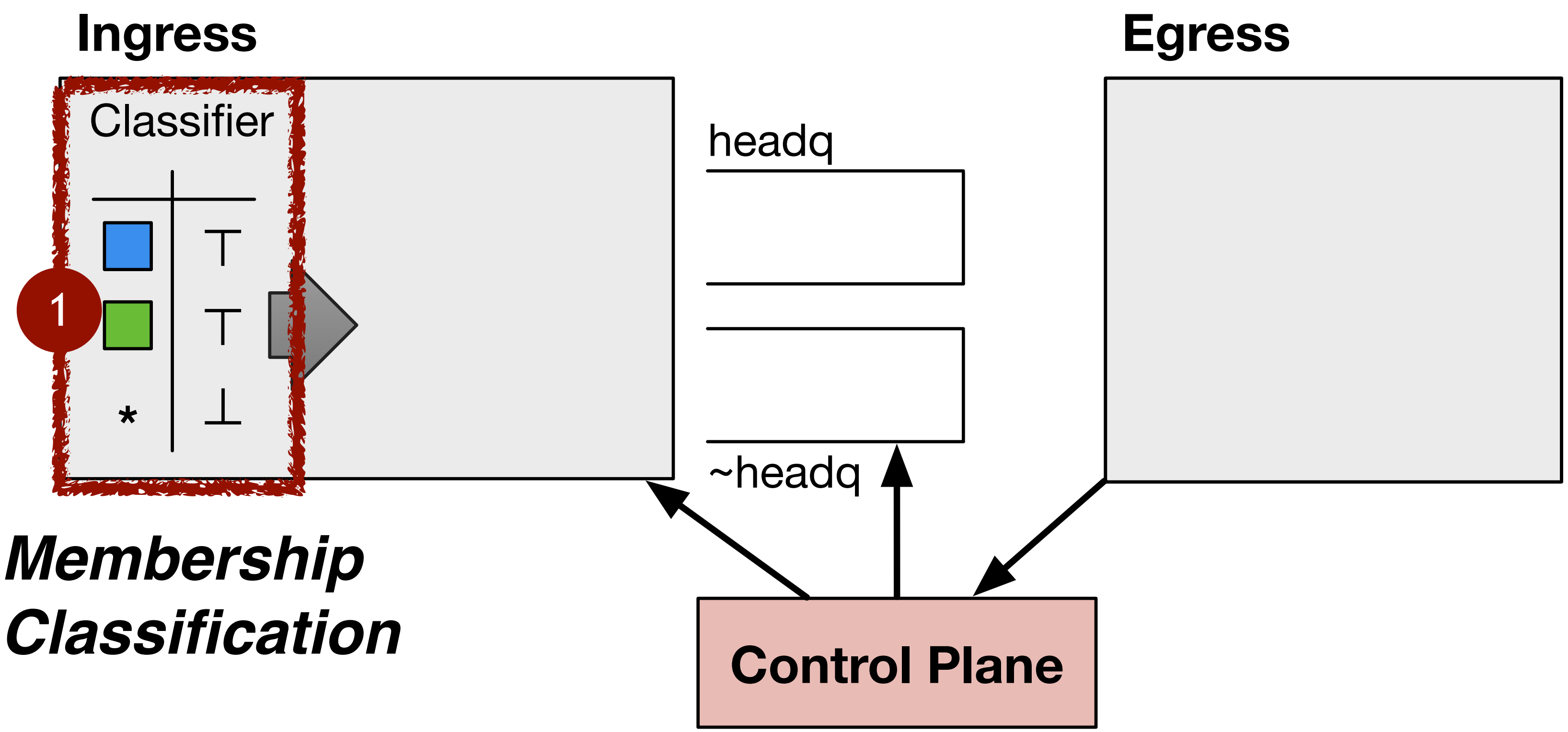
Redistribute to non-bottlenecked flows



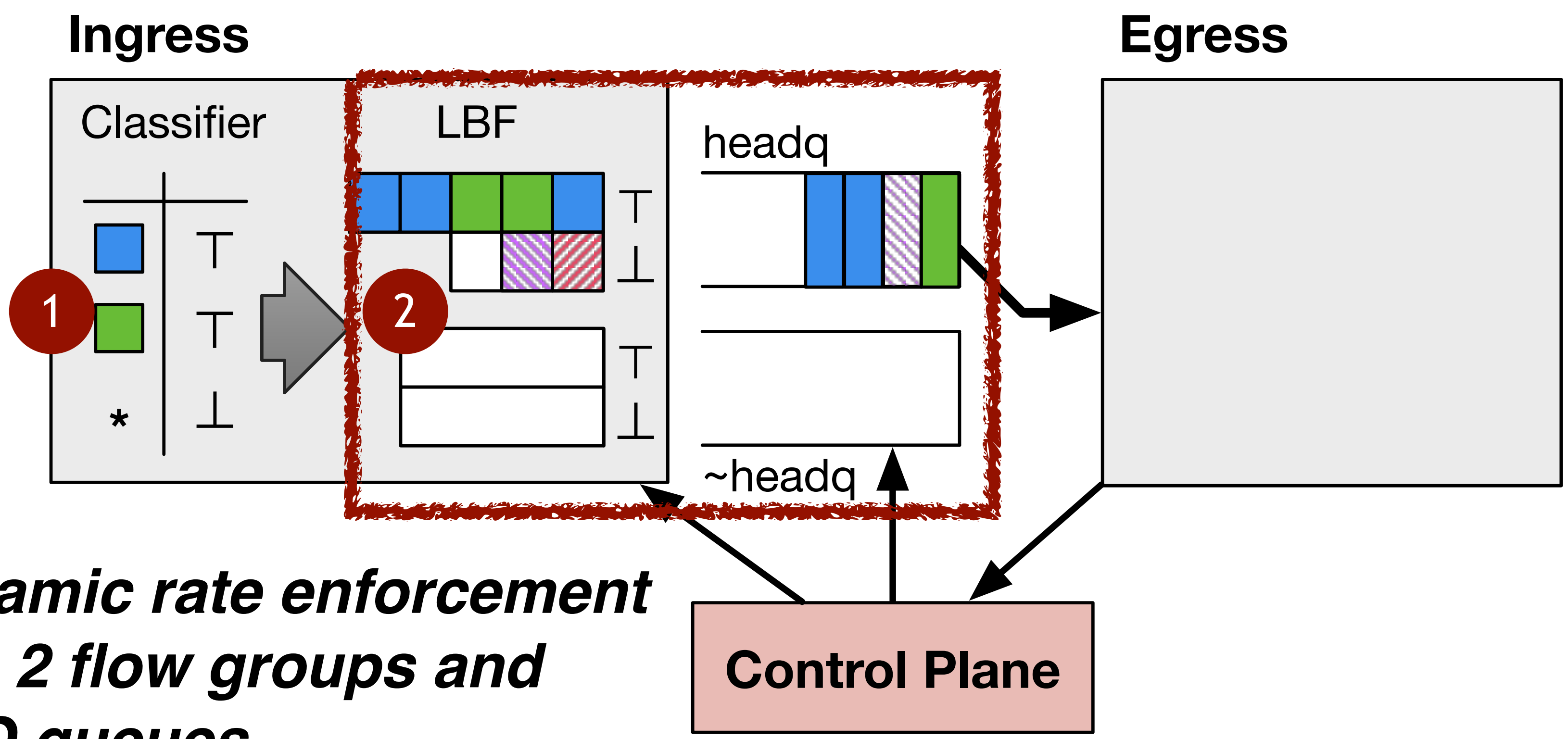
Instantiation: Cebinae router architecture



Normal operation

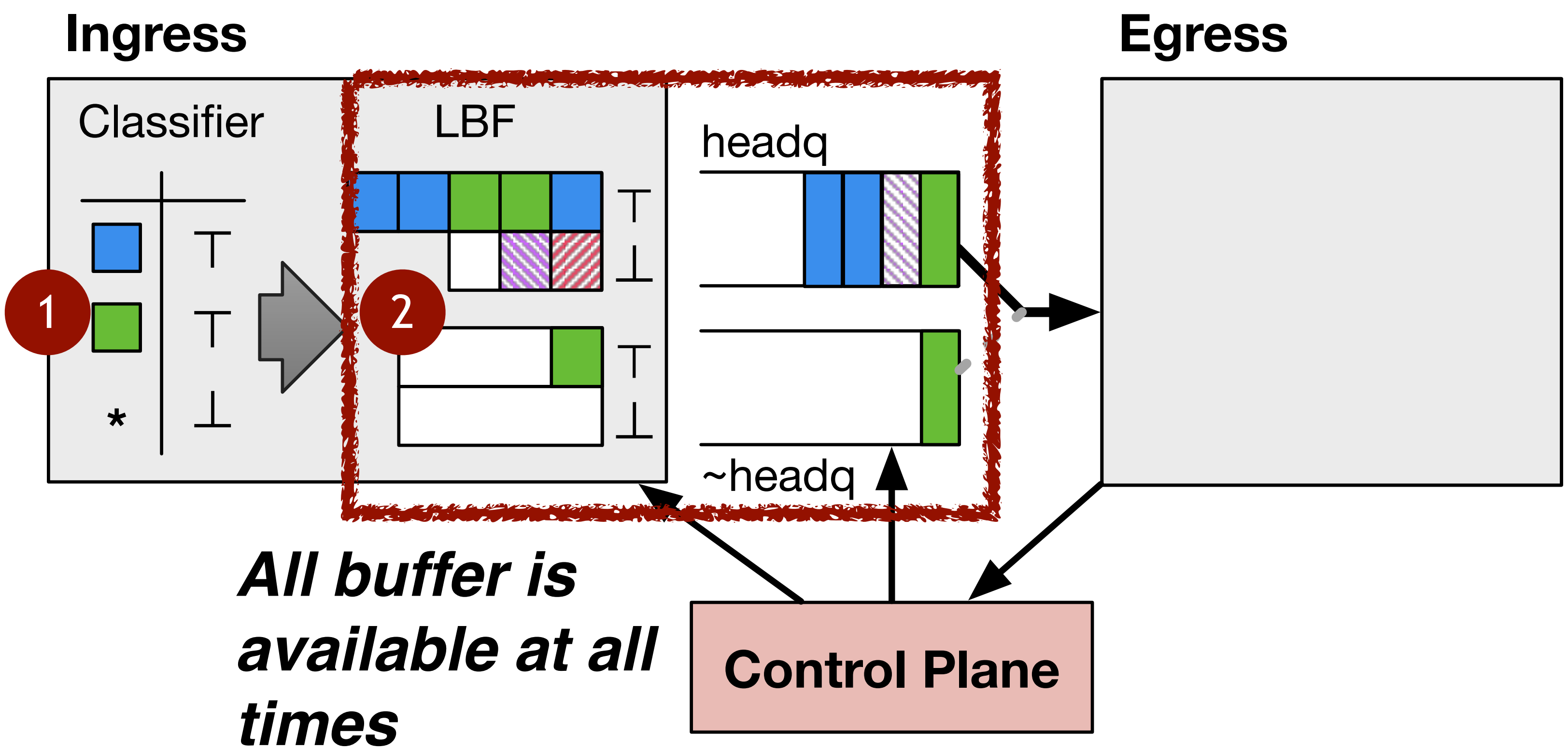


Normal operation



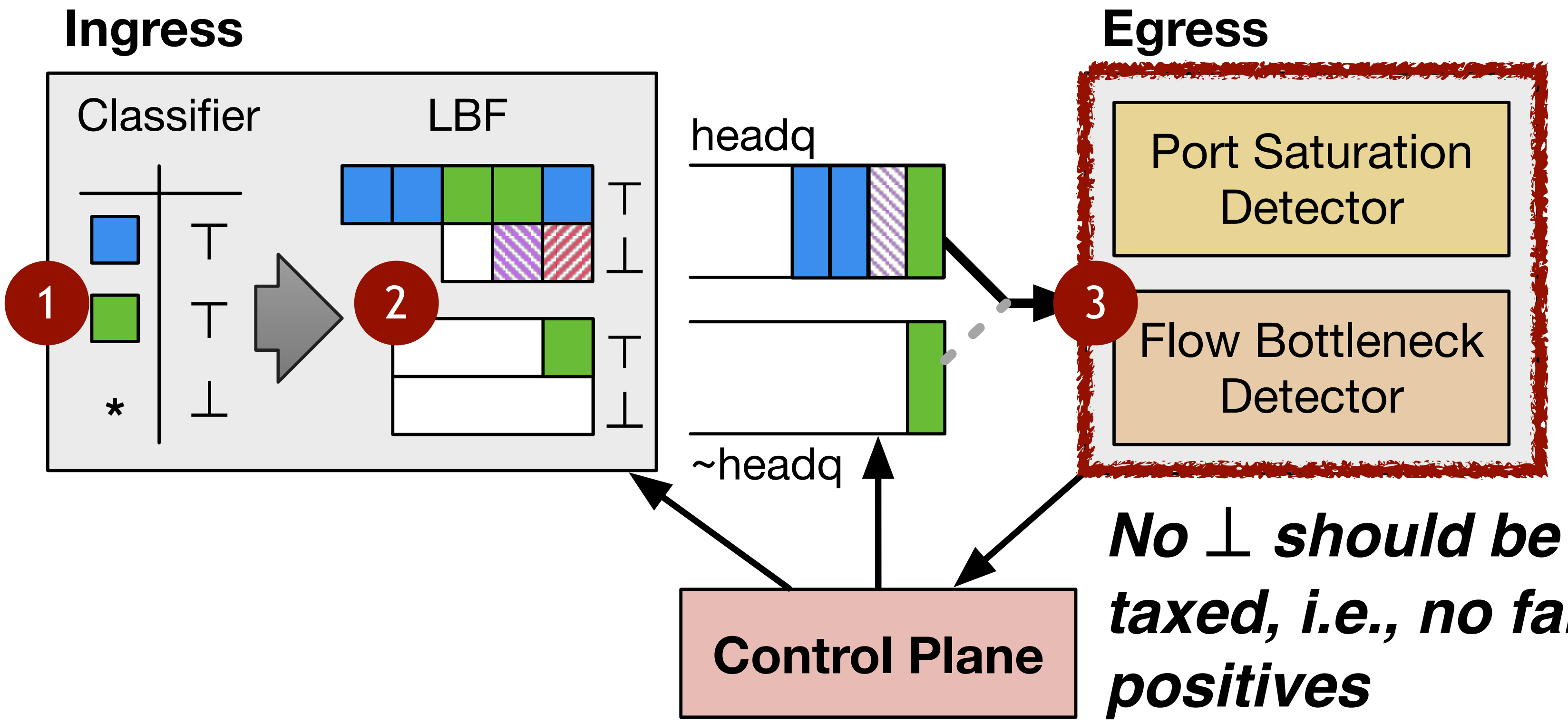
Dynamic rate enforcement with 2 flow groups and FIFO queues

Normal operation



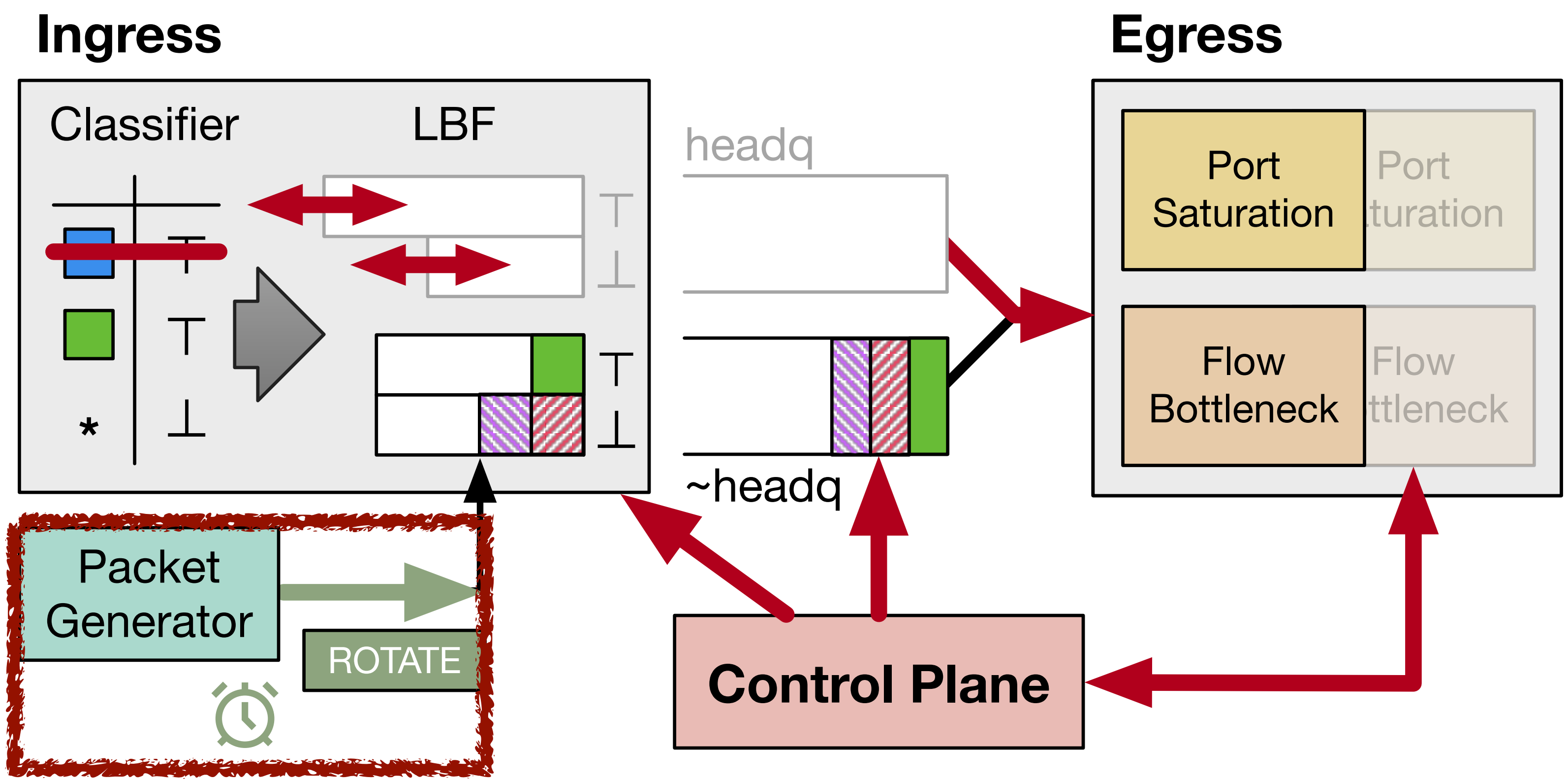
All buffer is available at all times

Normal operation

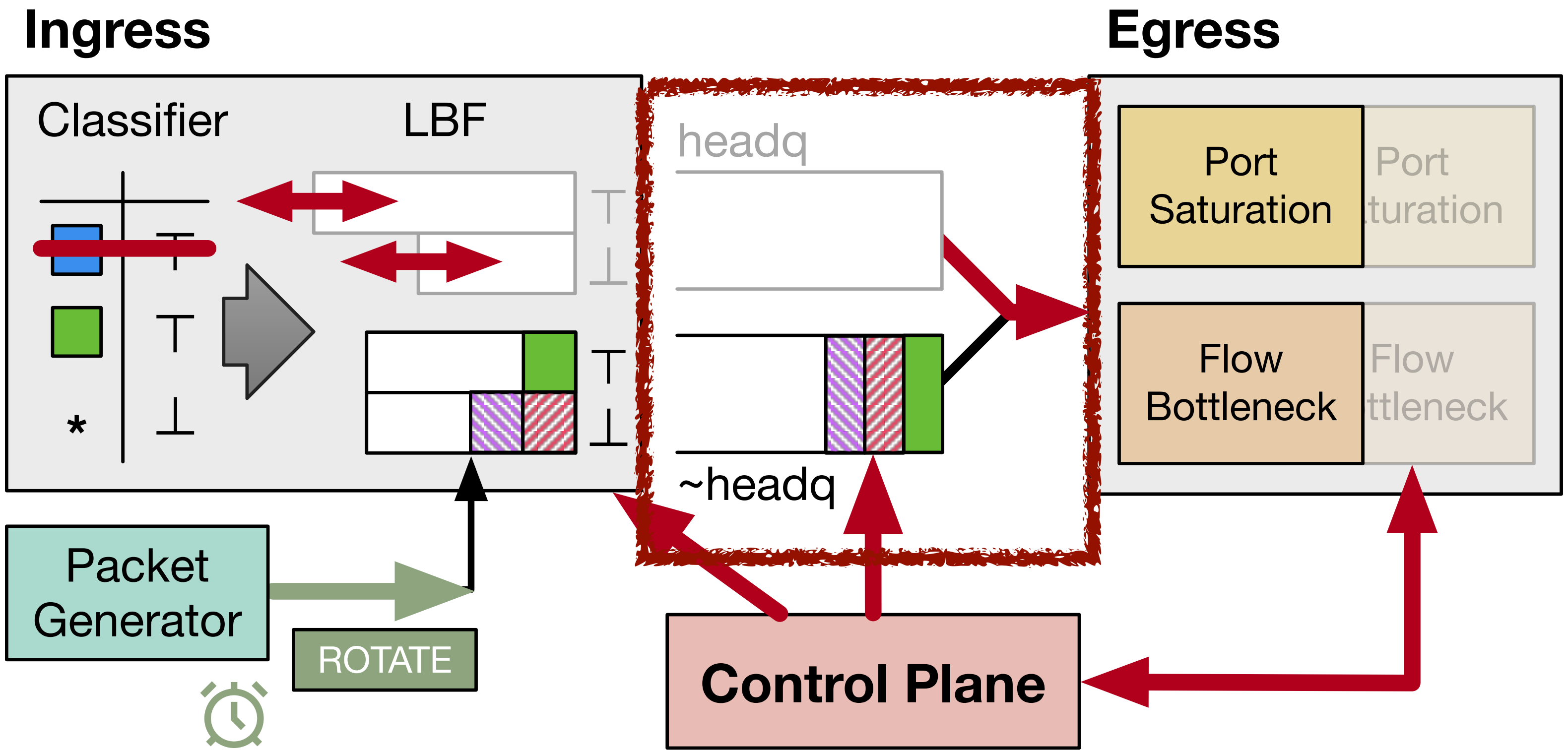


No ⊥ should be taxed, i.e., no false positives

Per-round reconfiguration

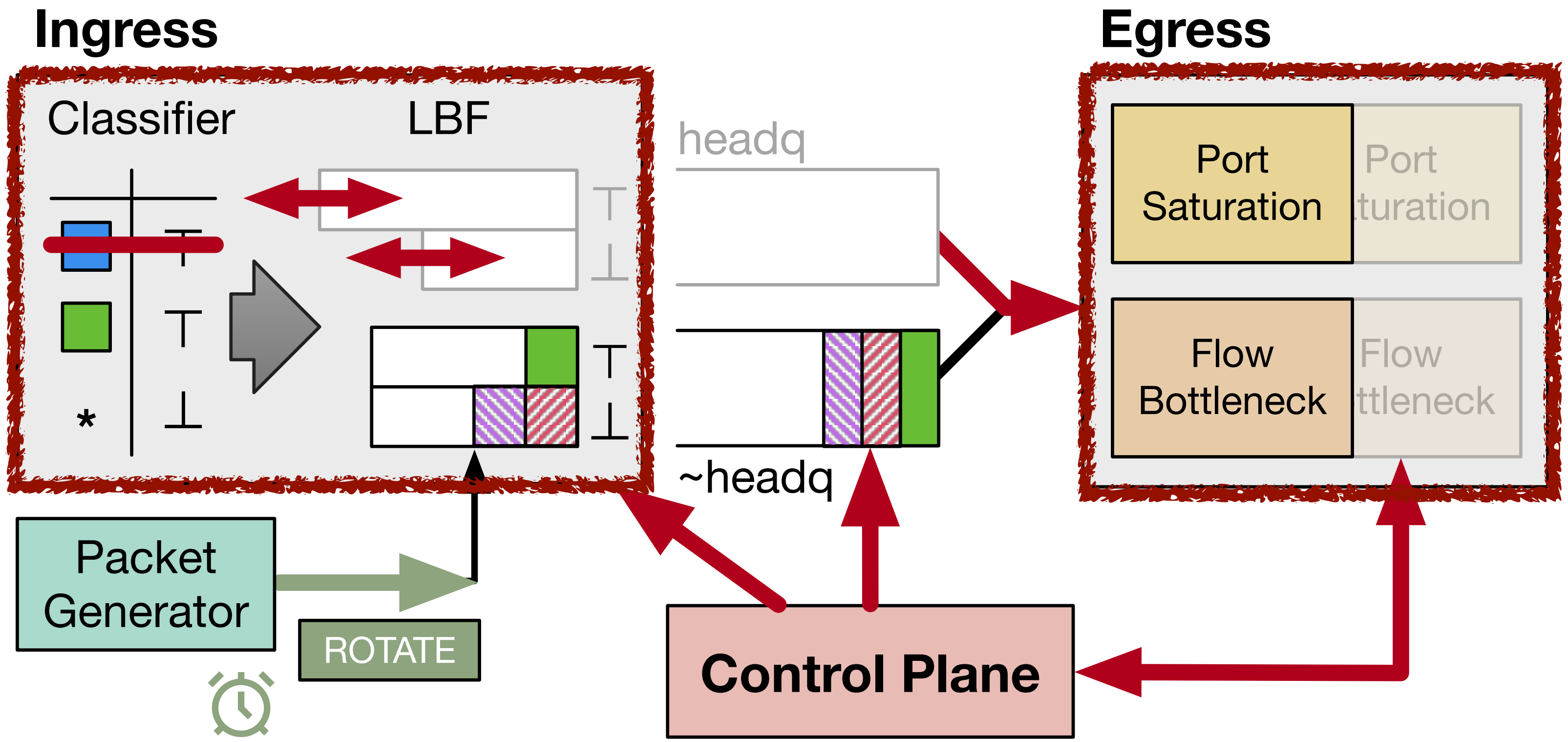


Per-round reconfiguration



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

Per-round reconfiguration



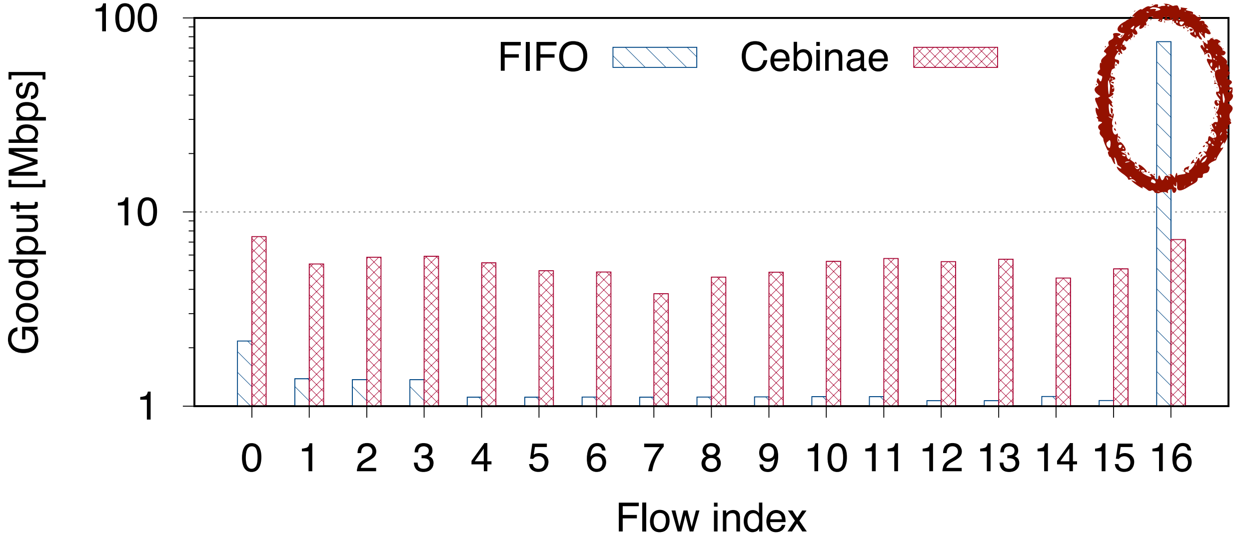
Atomic transactions: *LBF states and egress caches*

Implementation and evaluation

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

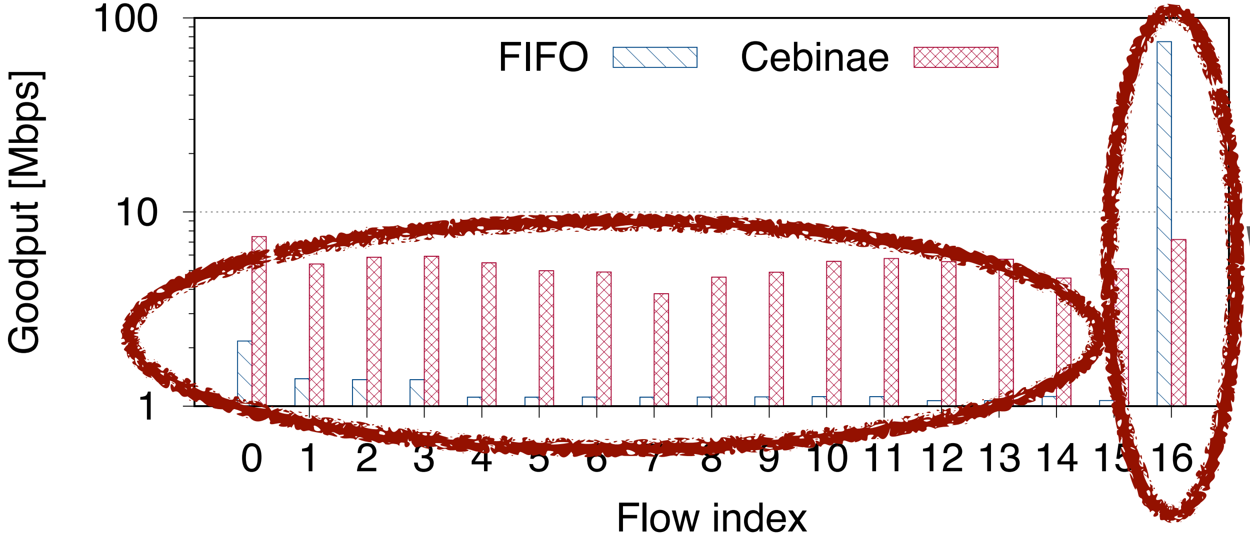
- Is Cebinae agnostic to CCAs?
- Can Cebinae mitigates unfairness (RTT, inter-CCA)?
- Can Cebinae move towards max-min fairness?
- Is Cebinae easy to configure?
- Does Cebinae resource usage scale?
- …

Cebinae mitigates unfairness



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

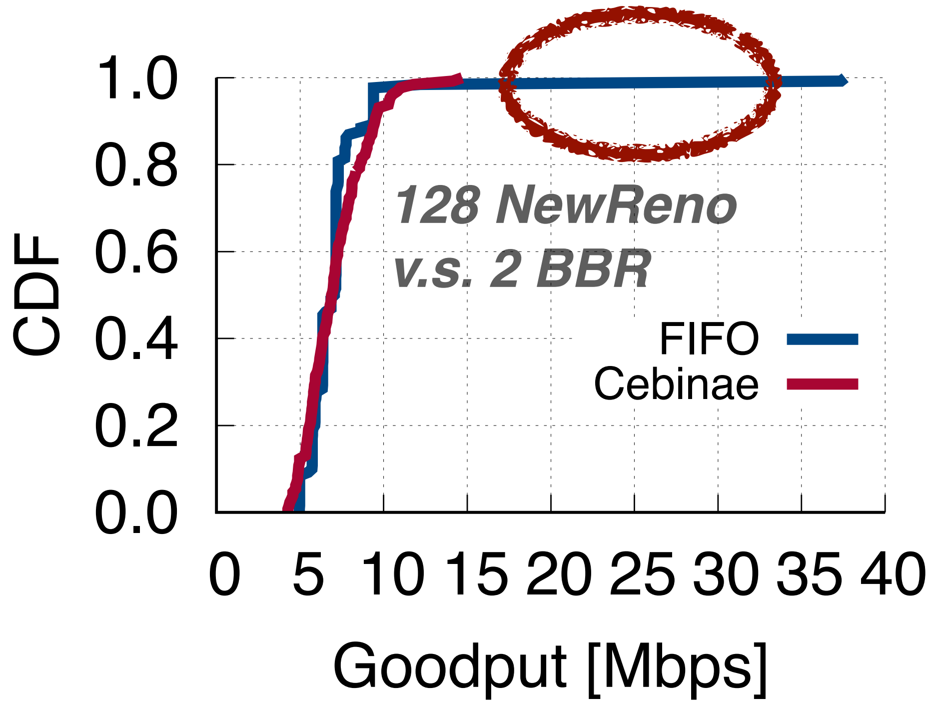
Cebinae mitigates unfairness



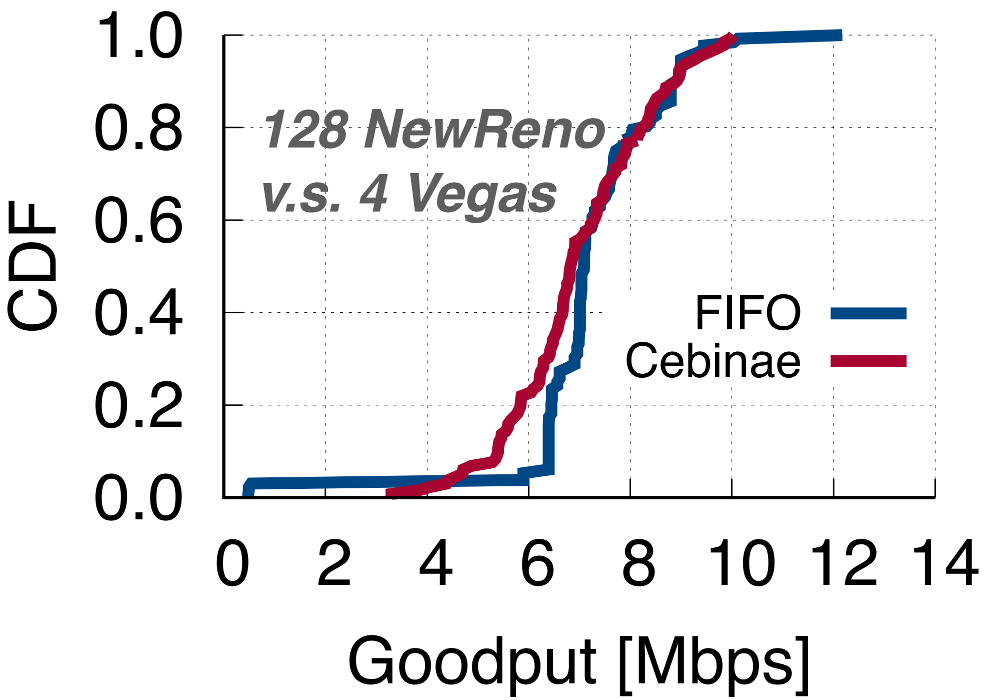
16 TCP Vegas (0–15)
v.s. 1 NewReno (16)

*Mitigates the **skewed and persistent unfairness** with little efficiency impact: **JFI from 0.093 to 0.984***

Cebinae mitigates unfairness

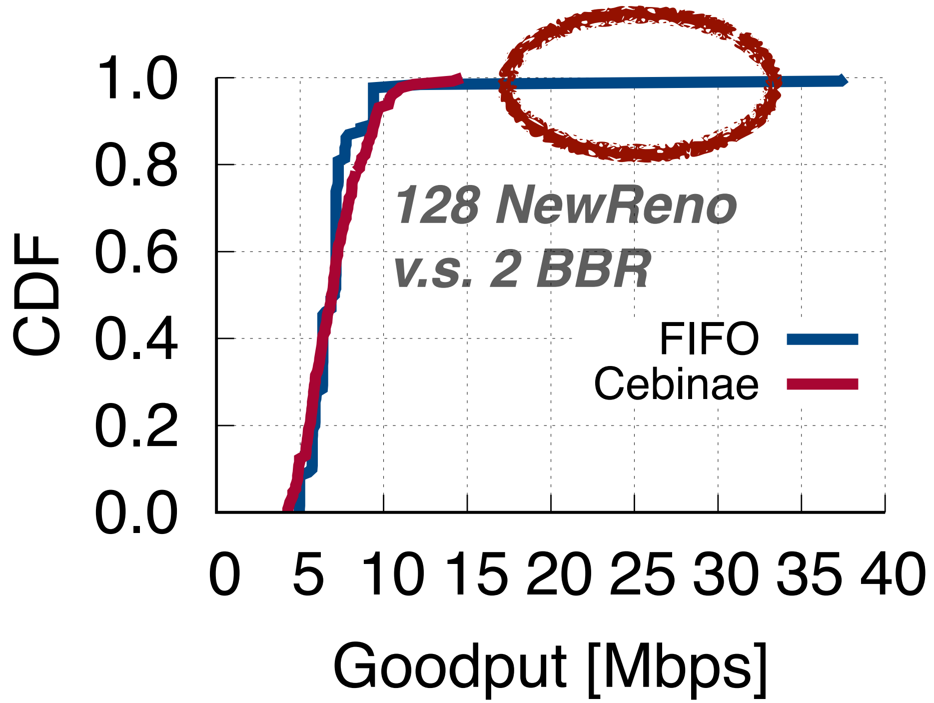


Preventing aggressiveness

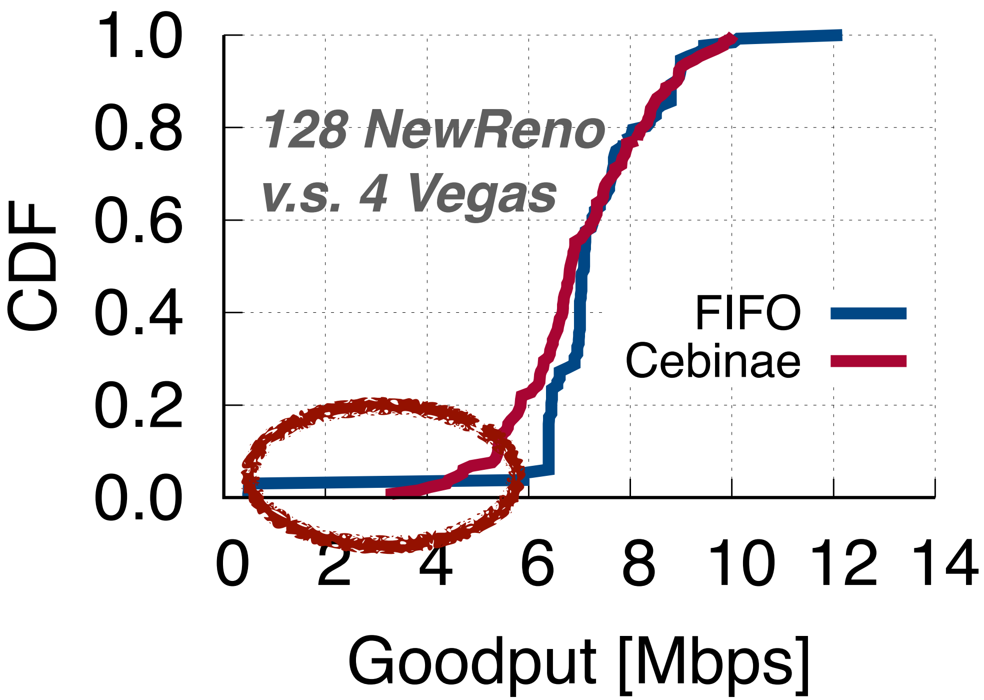


Mitigating starvation

Cebinae mitigates unfairness



Preventing aggressiveness



Mitigating starvation

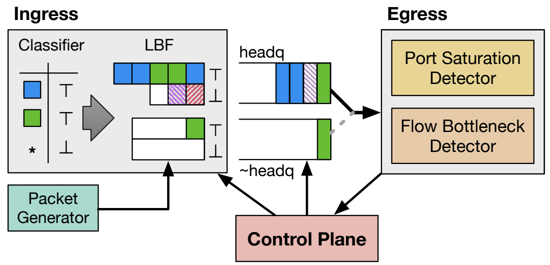
Cebinae mitigates unfairness

				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]			Goodput [Mbps]			JFI		
				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

Summary

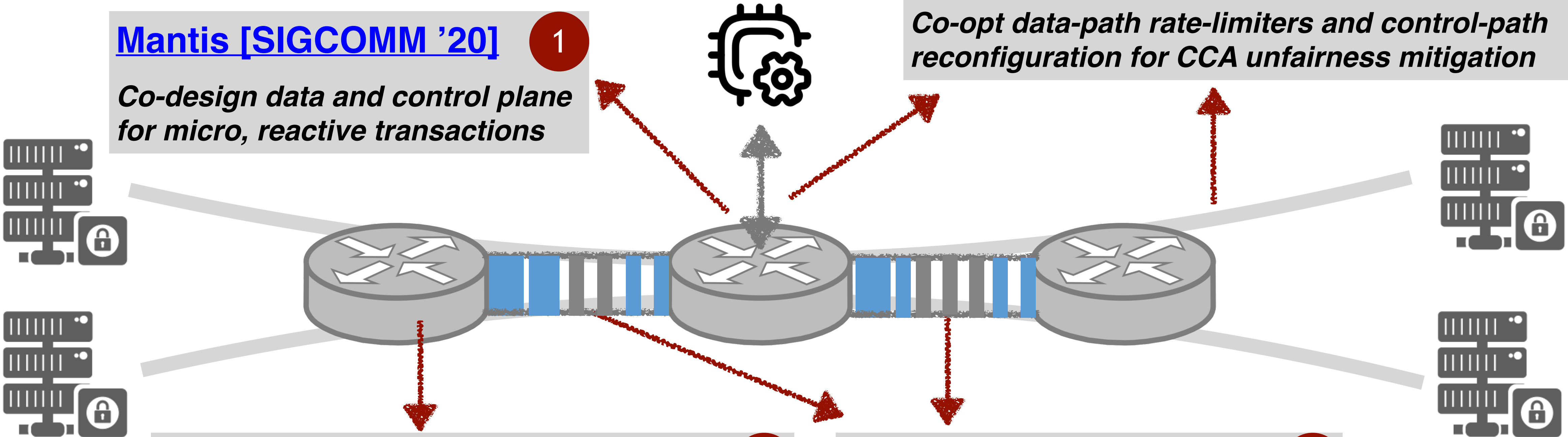


- **No modifications nor coordinations** to/with legacy host CCAs
  - *Real-time switch architecture serializing in-network compute modules*
- COTS hardware and **minimal resource requirements**
  - *Two queues/priorities are sufficient*
- Compatible with CCAs using **both loss and non-loss signals**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

https://github.com/eniac/Cebinae

Thank you for your attention!

More details



[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

[OrbWeaver [NSDI '22]] 3

Weave user and control packets for near-free communication channel

[PrintQueue [SIGCOMM '22]] 4

Correlate packets at small and large timescales for packet-level delay provenance