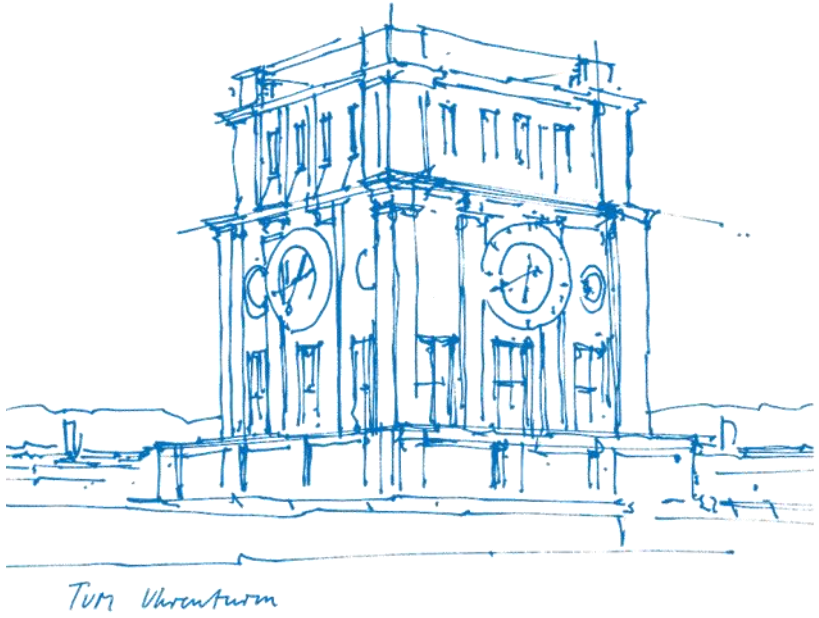
Assistant Professorship of Embedded Systems and Internet of Things
Department of Electrical and Computer Engineering
Technical University of Munich

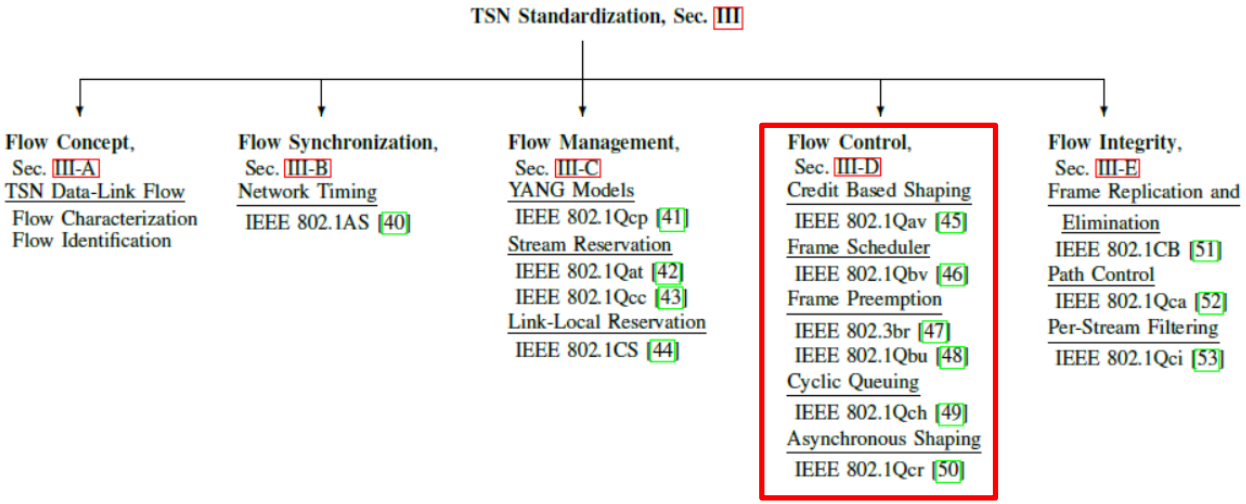
Quantitative Performance Comparison of Various Individual and Combined Traffic Shapers in Time-Sensitive Networking



Luxi Zhao
Paul Pop
Sebastian Steinhorst

Necessity and Contributions

- **Necessity**
  - Set of substandards (flow control):
    802.1Qbv – Time Aware Shaper (TAS);
    802.1Qav – Credit Based Shaper (CBS);
    802.1Qcr – Asynchronous Traffic Shaper (ATS);
    802.1Q – 2005 – Strict Priority (SP);
    Combinations …
  - Independent studies;
    No quantitative comparison;
    Proper shapers selection – tricky



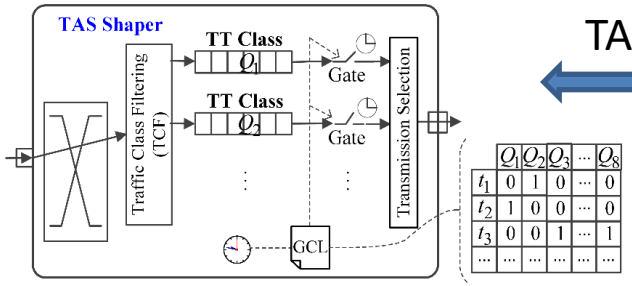
- **Contributions**
  - Tutorial of NC-based analysis for TSN;
  - Two new combined architectures (TAS+ATS+CBS, TAS+ATS+SP); extend NC approach;
  - Plenty of quantitative comparison → surprising but interesting results;
  - Provide a basis, select the suitable TSN traffic shapers.

Architecture – Individual Traffic Shapers

Evaluation Parameters

- Schedulability – End-to-end latency bound
- Buffer size without frame loss – Backlog bound
- Stable Communication – Jitter bound

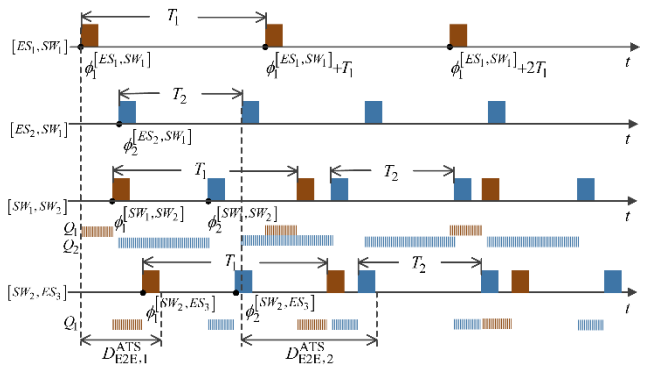
1. 802.1Qbv
2. Scheduling Synthesis
3. 2016, [1] S. S. Craciunas et al.; [2] P. Pop et al.



TAS

	Q_1	Q_2	Q_3	...	Q_8
t_1	0	1	0	...	0
t_2	1	0	0	...	0
t_3	0	0	1	...	1
...	...	...	...	...	...

- IEEE 802.1Qbv – Time Aware Shaper (TAS);
- Global network clock synchronization (IEEE 802.1ASrev);
- Time-Triggered communication – GCL synthesis – Schedulability guarantee;
- GCL synthesis – NP-complete problem [1], [2].



GCL – Gantt Chart

Individual Traffic Shapers

Architecture – Individual Traffic Shapers

Evaluation Parameters

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- Stable Communication – Jitter bound

1. 802.1Qbv
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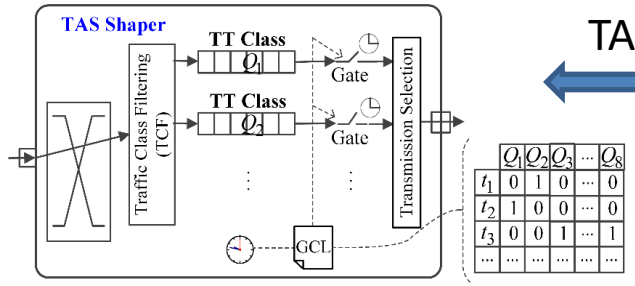
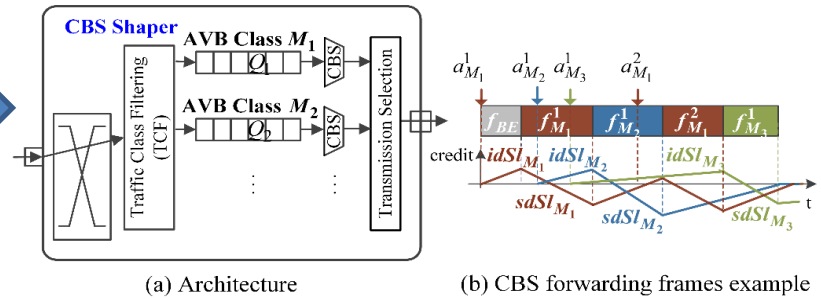


TAS

CBS

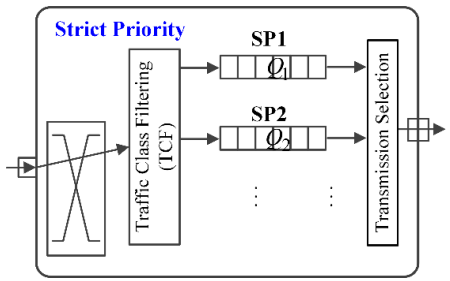


(a) Architecture (b) CBS forwarding frames example

1. 802.1Qav
2. Network Calculus
3. 2014, [3] J. A. R. De Azua et al.

- IEEE 802.1Q – Credit Based Shaper (CBS);
- Allocate the bandwidth reservation for different classes (priority)
- CBS algorithm – credit value (idleSlope / sendSlope) – non-work conserving;
- Schedulability guarantee – Network Calculus [3];

1. 802.1Q - 2005
2. Network Calculus
3. 2003, [4] J. Schmitt et. al.



SP

- IEEE 802.1Q - 2005 – Strict Priority (SP);
- Low priority traffic can transmit only when the high priority queue is empty;
- Schedulability guarantee – Network Calculus [4];

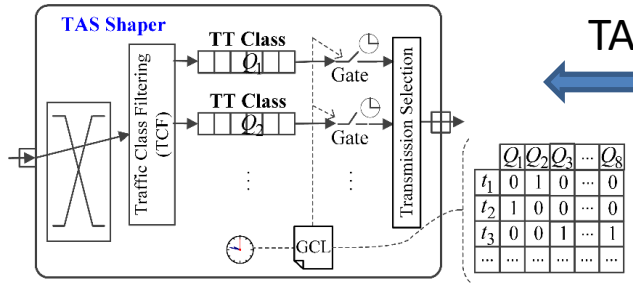
Individual Traffic Shapers

Architecture – Individual Traffic Shapers

Evaluation Parameters

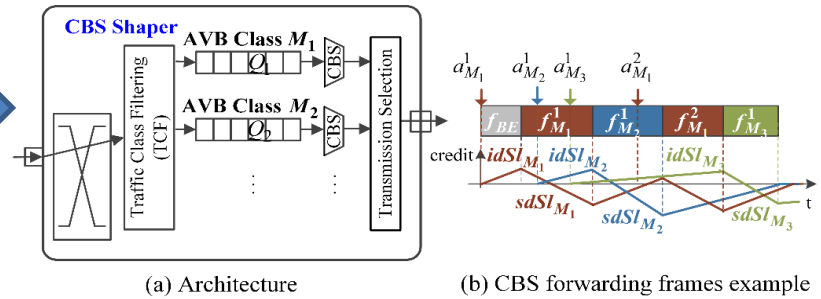
- Schedulability – End-to-end latency bound
- Buffer size without frame loss – Backlog bound
- Stable Communication – Jitter bound

1. 802.1Qbv
2. Scheduling Synthesis
3. 2016, [1] S. S. Craciunas et al.; [2] P. Pop et al.



TAS

CBS



(a) Architecture (b) CBS forwarding frames example

1. 802.1Qav
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3. 2014, [3] J. A. R. De Azua et al.

1. 802.1Q - 2005
2. Network Calculus
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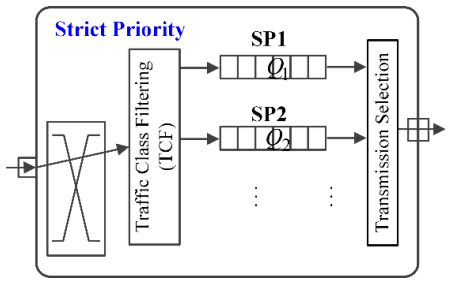
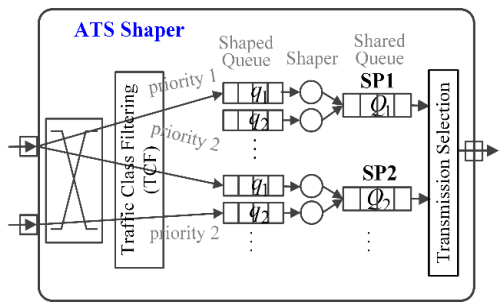


SP

ATS (+SP)



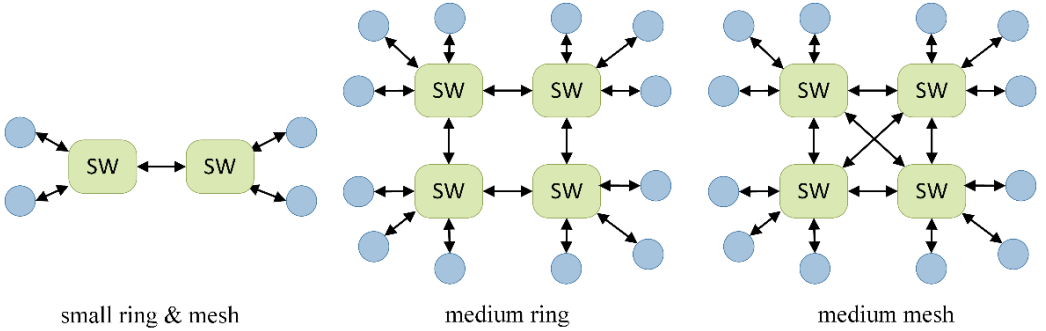
1. 802.1Qcr
2. Closed-form Formula
3. 2016, [5] J. Specht et al.
   2018, [6] J. Y. Le Boudec

- IEEE 802.1Qcr – Asynchronous Traffic Shaper (ATS);
- Asynchronous transmission, local clock;
- Two hierarchies of queues – shaped queue & shared queue;
- ATS – interleaved regulator – avoid burstiness cascades;
- Schedulability guarantee – Closed-form Formula [5], Network Calculus [6].

Individual Traffic Shapers

Evaluation – Individual Traffic Shapers

- Synthetic test cases – SRM, MR, MM, ST, MT
  - Each topology – 100 TCes;
  - Frame size – minimum (64 bytes) ~ maximum (1522 bytes);
  - Period (periodic) / Min time interval (sporadic) – T={1000, 2000, 5000, 10000} (μm);
  - 1 priority;
  - GCLs for TAS, Route – existing work [2];
  - Physical link rate 100 Mb/s.



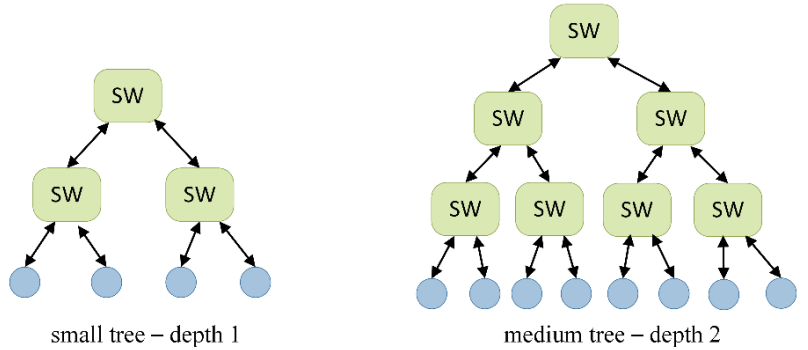
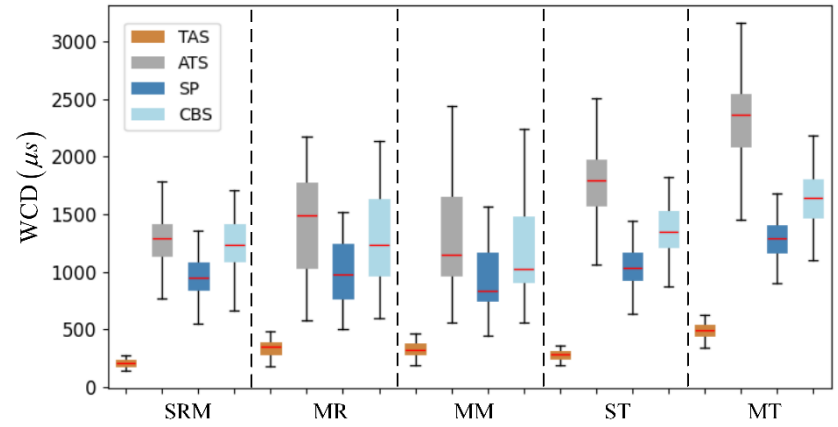


TABLE II
STATISTICAL HOPS AND TRAFFIC LOAD FOR 100 TEST CASES

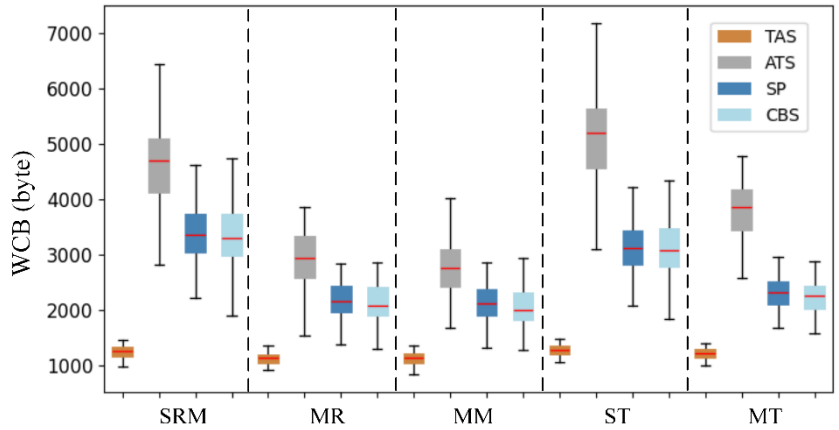
	SRM	MR	MM	ST	MT
Average Hops	2.7	4.2	3.8	3.5	5.5
Average Traffic Load	28.9%	20.5%	17.4%	29.0%	19.7%
Max Traffic Load	47%	40%	38%	47%	30%
Min Traffic Load	13%	8%	6%	13%	10%

Evaluation – Individual Traffic Shapers (1)

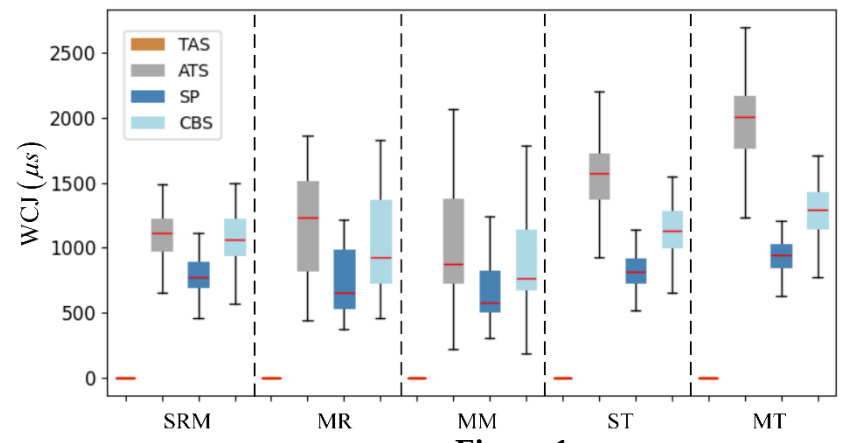
- Results
  - Each TC,
    1) End-to-end latency upper bounds – flow;
    2) Backlog upper bounds – egress port;
    3) Jitter bounds – flow.
  - Figure: each TC – metric – average value;
    100 TC – 100 dots - box plot.
- Comments
  - Different topologies – similar trends while comparing different traffic shapers;
  - TAS performs the best – latency, backlog, jitter;
  - …



End-to-end latency



Backlog



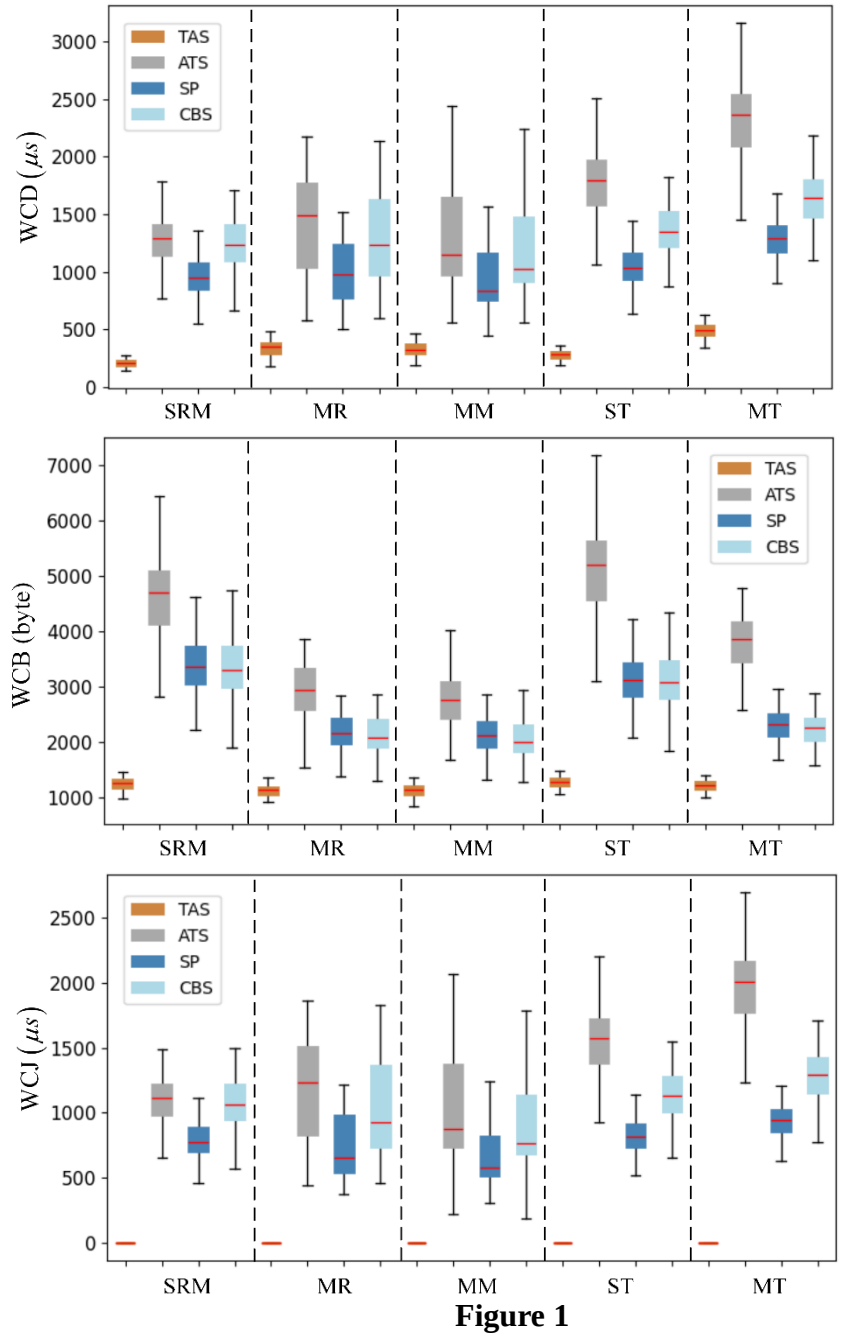
Jitter

Figure 1

Evaluation – Individual Traffic Shapers (1)

- Results
  - Table: X_i metric value for flow f_i;
    $\bar{X} = aver(X_i) = aver\left(\left(X_i^{Y_1} - X_i^{Y_2}\right)/X_i^{Y_2}\right)$

		(CBS – SP) /SP	(ATS – SP) /SP	(ATS – CBS) /CBS
Average WCD	SRM	30.7%	34.1%	2.8%
	MR	28.2%	43.9%	12.5%
	MM	26.2%	35.7%	7.7%
	ST	31.2%	72.3%	31.4%
	MT	27.3%	79.1%	40.8%
Average WCB	SRM	-1.3%	38.0%	39.9%
	MR	-2.5%	34.7%	38.1%
	MM	-3.2%	31.0%	35.4%
	ST	-0.8%	65.0%	66.5%
	MT	-3.3%	64.4%	70.0%
Average WCJ	SRM	37.1%	41.4%	3.4%
	MR	38.0%	60.7%	16.6%
	MM	30.3%	43.0%	10.4%
	ST	39.5%	91.9%	37.7%
	MT	37.3%	108.3%	51.9%



End-to-end latency

Backlog

Jitter

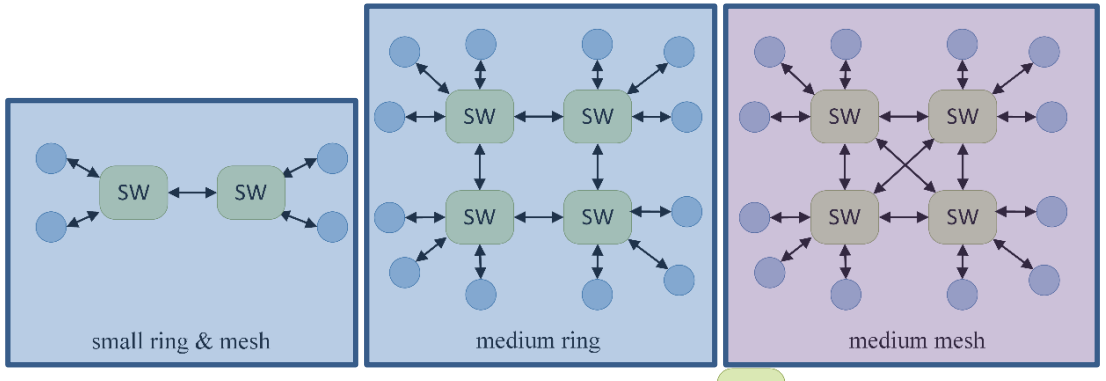
Figure 1

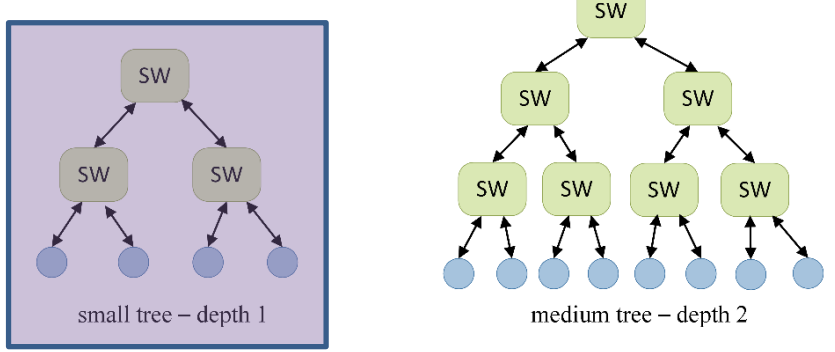
Evaluation – Individual Traffic Shapers (1)

- Comments
  - ATS positive effect ↓ ← concentration of flows ↑
    ← number of hops ↑
  - For example
    1. Flows concentration: MR > MM →
       ATS positive effect: MR < MM
    2. Number of hops: ST > SRM →
       ATS positive effect: ST < SRM

		(ATS – SP) /SP
Average WCD	SRM	34.1%
	MR	43.9%
	MM	35.7%
	ST	72.3%
	MT	79.1%
Average WCB	SRM	38.0%
	MR	34.7%
	MM	31.0%
	ST	65.0%
	MT	64.4%
Average WCJ	SRM	41.4%
	MR	60.7%
	MM	43.0%
	ST	91.9%
	MT	108.3%

Table 1





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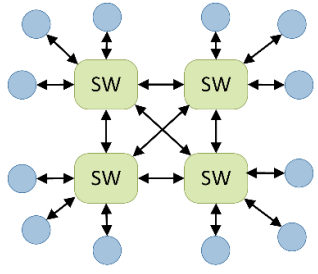
Max Traffic Load	47%	40%	38%	47%	30%
Min Traffic Load	13%	8%	6%	13%	10%

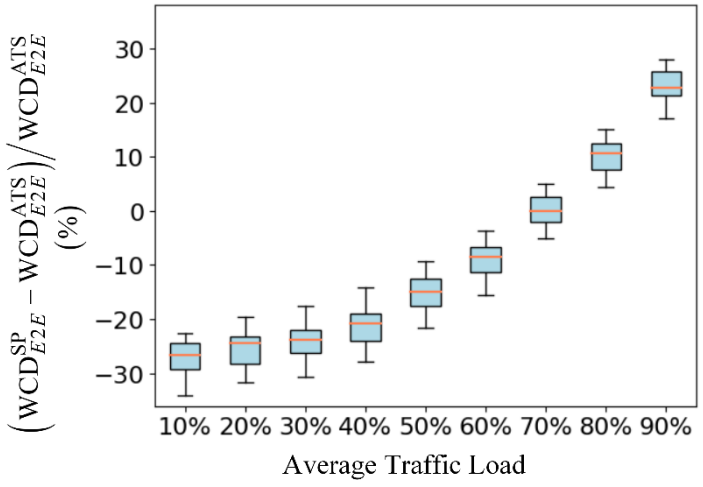
Evaluation – Individual Traffic Shapers (2)

- Synthetic test cases – MM
  - Average traffic load: 10% ~ 90%
  - Each traffic load – 20 TCes
  - **Case 1 – 1 priority; Case 2 – 2 priorities + BE**
- Results
  - $X = aver(X_i) = aver\left(\left(X_i^{SP} - X_i^{ATS}\right)/X_i^{ATS}\right)$
- Comments
  - End-to-end latency bounds:
  - **Case 1 – 1 priority**
    – Average traffic load ↑ → comparison percentage X ↑ → ATS positive effect ↑;
    – Average traffic load < 70% – SP performs better than ATS;
  - **Case 2 – 2 priorities + BE**
    High priority:
    – ≈ Top 40% traffic load with single priority;
    – ATS no positive effect on high-priority traffic.
    Low-priority:
    – ATS positive effect on low-priority traffic ← average overall traffic load > 30%.

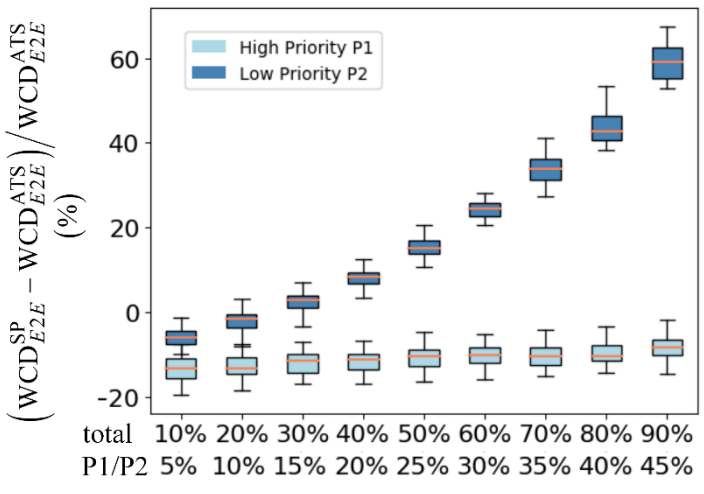


medium mesh

ATS vs. without ATS (i.e., SP)



(a)



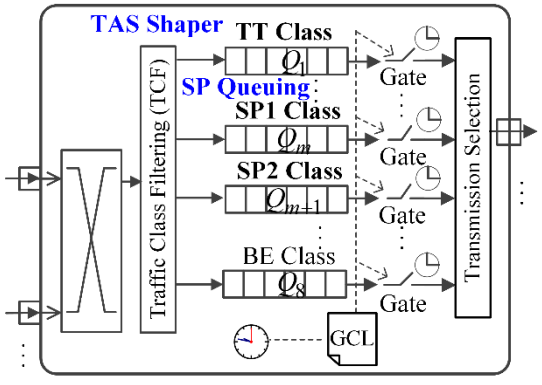
(b)

Figure 2

L. Zhao, et al., "Quantitative Performance Comparison of Various Traffic Shapers in Time-Sensitive Networking", arXiv:2103.13424, 2021

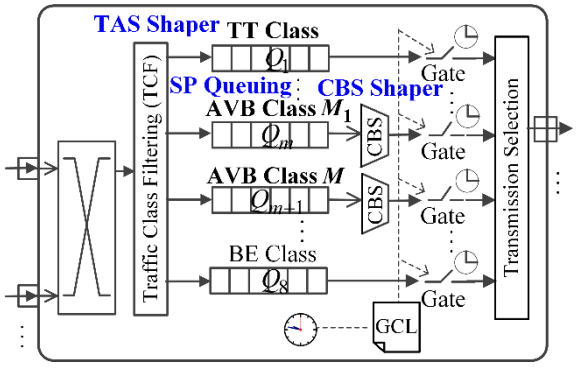
Architecture – Combined Traffic Shapers

1. 802.1Qbv+802.1Q - 2005
2. Network Calculus
3. 2017, [7] L. Zhao et. al.



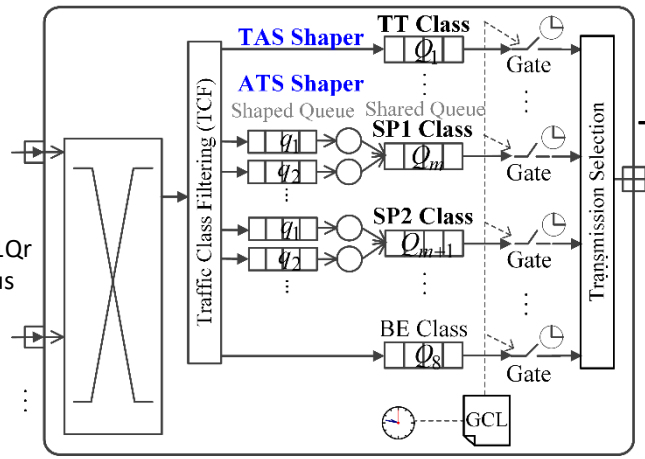
TAS+SP

TAS+CBS



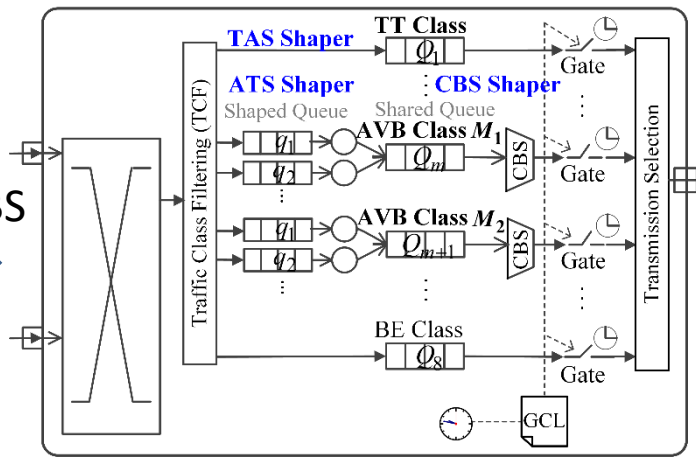
1. 802.1Qbv+802.1Qav
2. Network Calculus
3. 2016, [8], [9] L. Zhao et. al.

NEW
1. 802.1Qbv+802.1Qr
2. Network Calculus



NEW
TAS+**ATS**(+SP)

NEW
TAS+**ATS**+CBS



NEW
1. 802.1Qbv+802.1Qcr
+802.1Qav

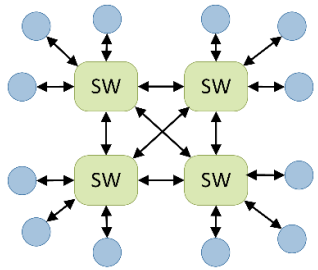
- TAS outperforms than all the others (latency, backlog, jitter); Scalability problem.
- Promising combination model: TAS+X

- New: TAS+ATS(+SP); TAS+ATS+CBS
- TAS+SP vs. TAS+ATS(+SP)
  TAS+CBS vs. TAS+ATS+CBS

Combined Traffic Shapers

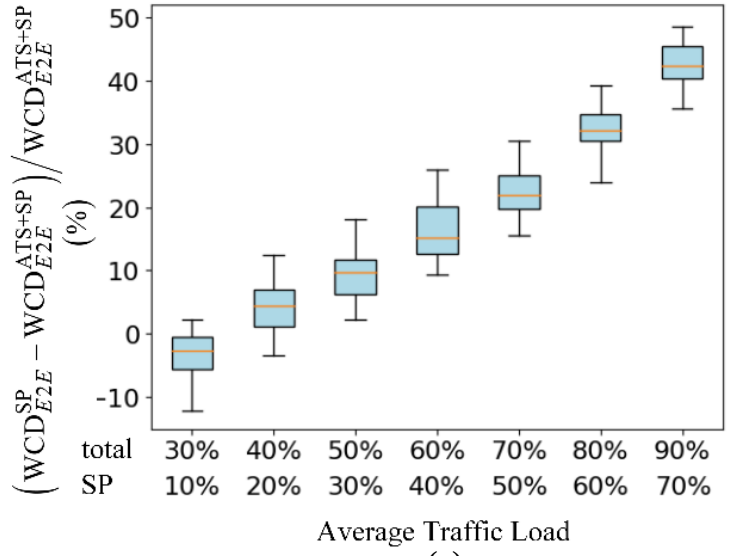
Evaluation – Combined Traffic Shapers (1)

- Synthetic test cases – MM
  - Case 1 – TT traffic load: 20%;
    – SP average traffic load: 10% ~ 70%
  - Each traffic load – 20 TCes
- Results
  - $X = aver(X_i) = aver\left(\left(X_i^{SP} - X_i^{ATS+SP}\right)/X_i^{ATS+SP}\right)$
- Comments
  - With the influence of TT traffic (TAS)
  - End-to-end latency bounds:
    – Average traffic load ↑ – ATS positive effect ↑;
    – ATS positive effect ← average overall traffic load > 40%;
  - Backlog bounds:
    – ATS positive effect ← average overall traffic load > 30%;

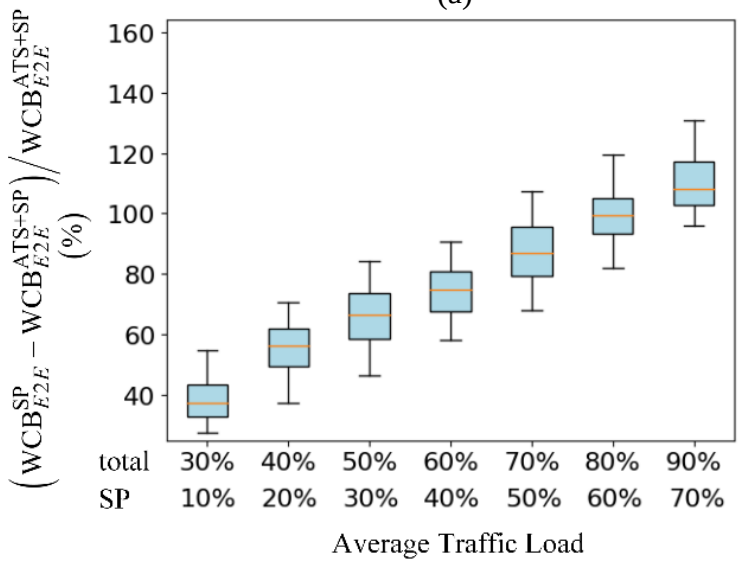


medium mesh

TAS+SP vs. TAS+ATS (+SP) – TT 20%



(a)

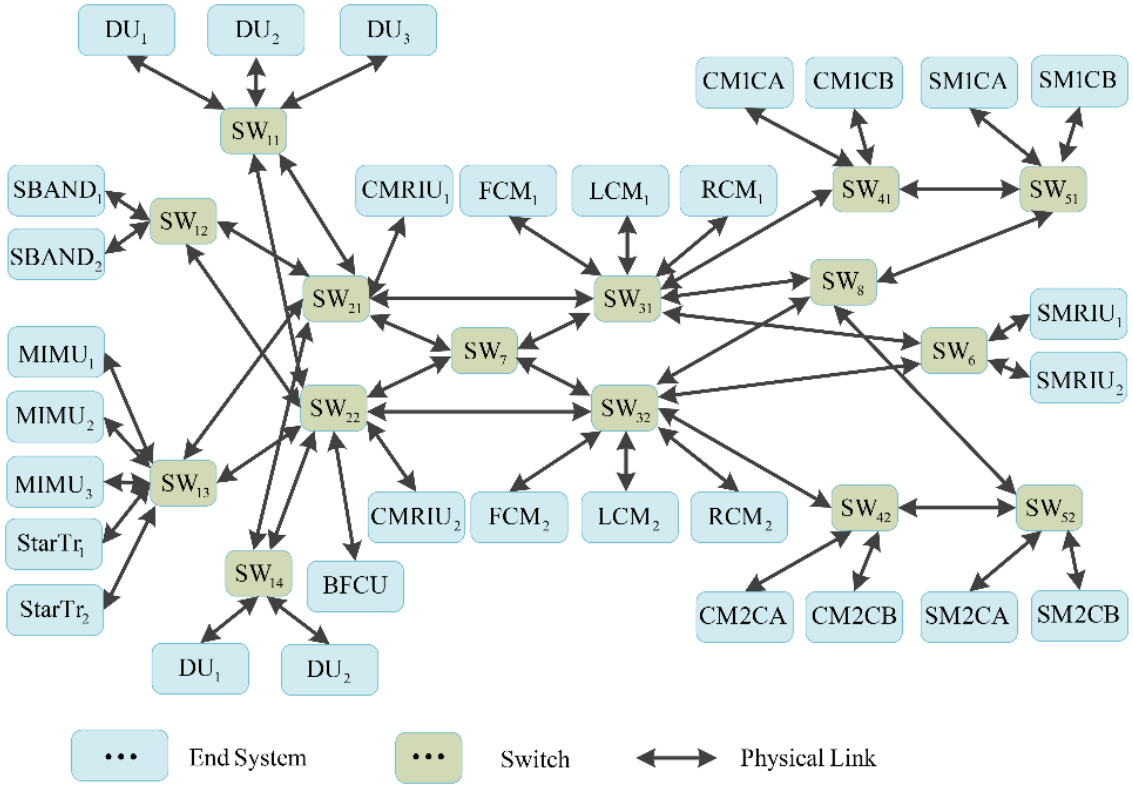


(b)

Figure 3

Evaluation – Combined Traffic Shapers (2)

- Realistic Test Cases – Orion CEV
  - 31 ESes, 15 SWs, 188 dataflow routes, 100 Mbps link rate;
  - 99 TT flows (TAS), 87 rate constraint flows with the same priority → SP flows / AVB flows (CBS);
  - TT traffic load in network
    → 1.5% on average & 5.5% in maximum.
    Overall traffic load in network
    → 3.5% on average & 10% in maximum.
  - IdleSlope for AVB is set to 75% (default);
- Results
  - $100 \times ln(X)$, $X = (WCD, WCB)$;
  - Sorted in increasing order by results (WCD, WCB).

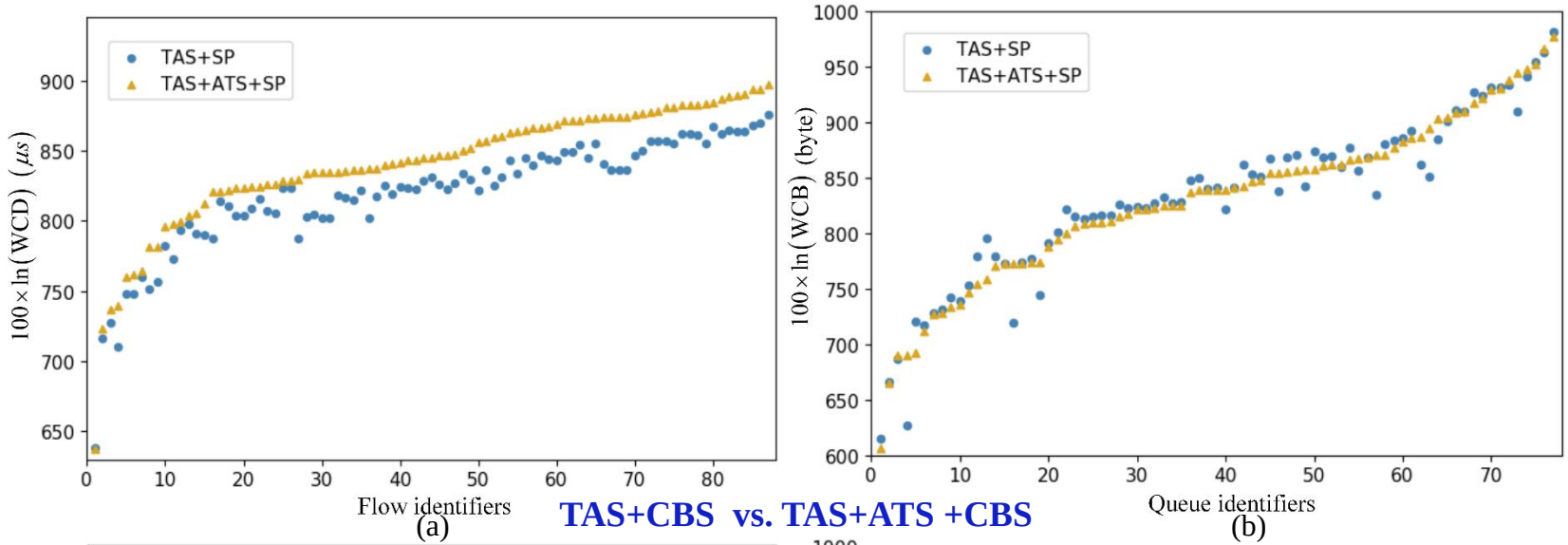


Orion CEV

Evaluation – Combined Traffic Shapers (2)

- Comments
  - End-to-end latency bounds:
    – ATS no positive effect.
  - Backlog bounds:
    – ATS positive effect.
  - ← Average overall traffic load (TT, SP/AVB) low;
  - → Consistent with results in Fig. 3.

TAS+SP vs. TAS+ATS +SP



TAS+CBS vs. TAS+ATS +CBS

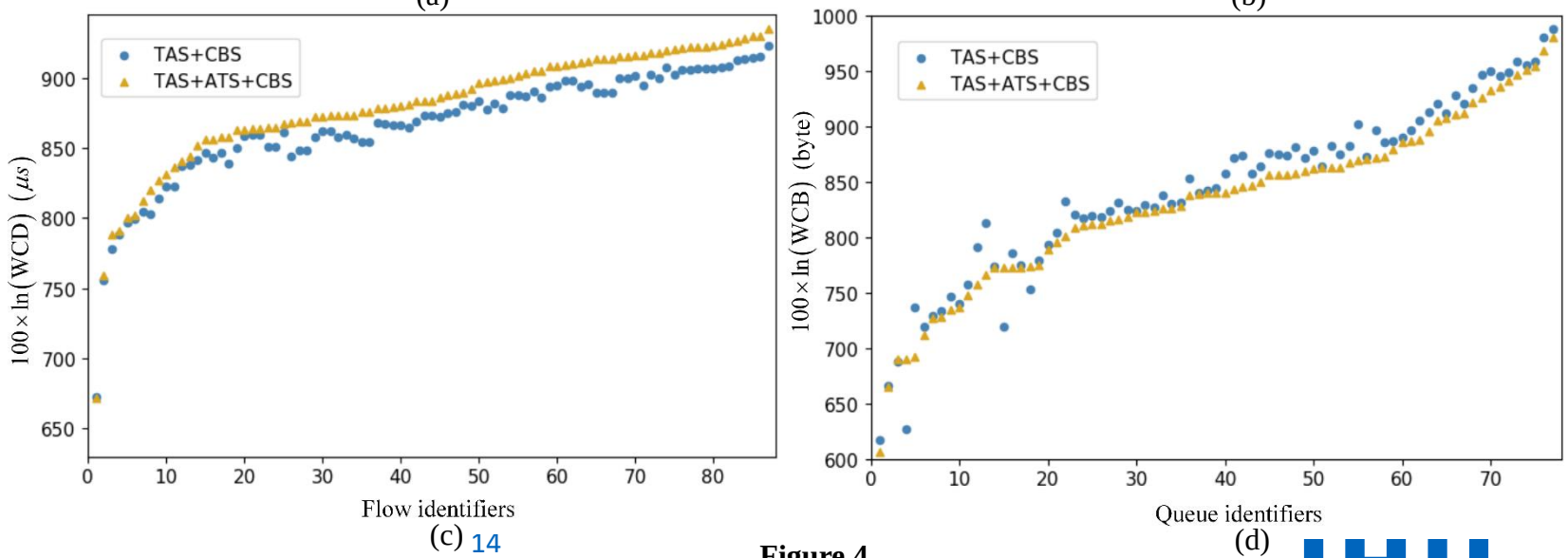


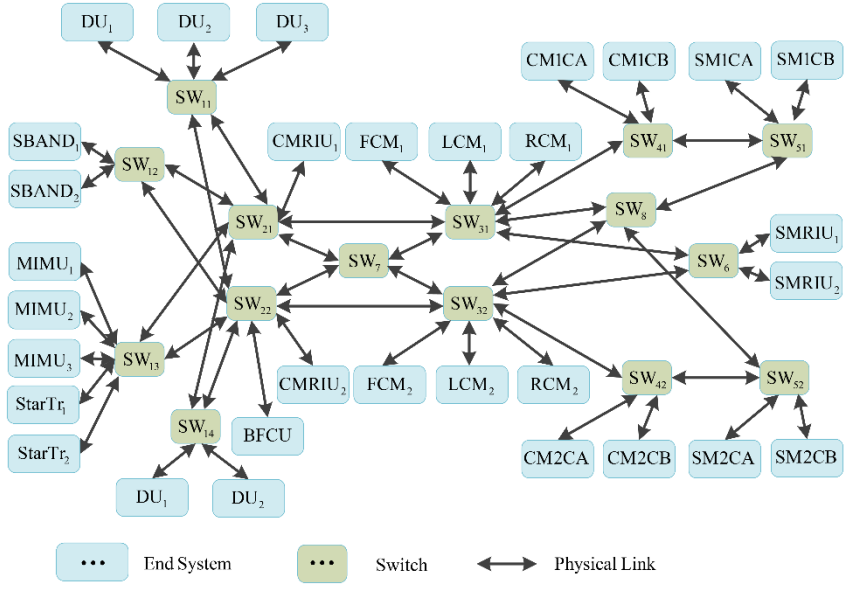
Figure 4

Evaluation – Combined Traffic Shapers (3)

- **Realistic Test Cases – Orion CEV**
  - Increase traffic load:
    TT traffic load in network
    → 15% on average & 54% in maximum.
    Overall traffic load in network
    → 25% on average & 69% in maximum.
  - 4 priorities, 25 flows of P1, 25 flows of P2, 24 flows of P3, 13 flows of P4;
  - IdleSlope ← actual bandwidth utilization,

$$idSl_i = operIdleSlope(P_i) \cdot \frac{OperCycleTime}{GateOpenTime}$$

- **Results**
  - $100 \times ln(X), X = (WCD, WCB)$;
  - Sorted in increasing order by results (WCD, WCB).



Orion CEV

Evaluation – Combined Traffic Shapers (3)

- Comments
  - End-to-end latency bounds:
    Backlog bounds:
    – ATS positive effect.
  - ATS positive effect
    TAS+ATS+CBS > TAS+ATS+SP
    ← service capability AVB < SP.
  - In combination of ATS
    → performance of SP & CBS get closer to each other.

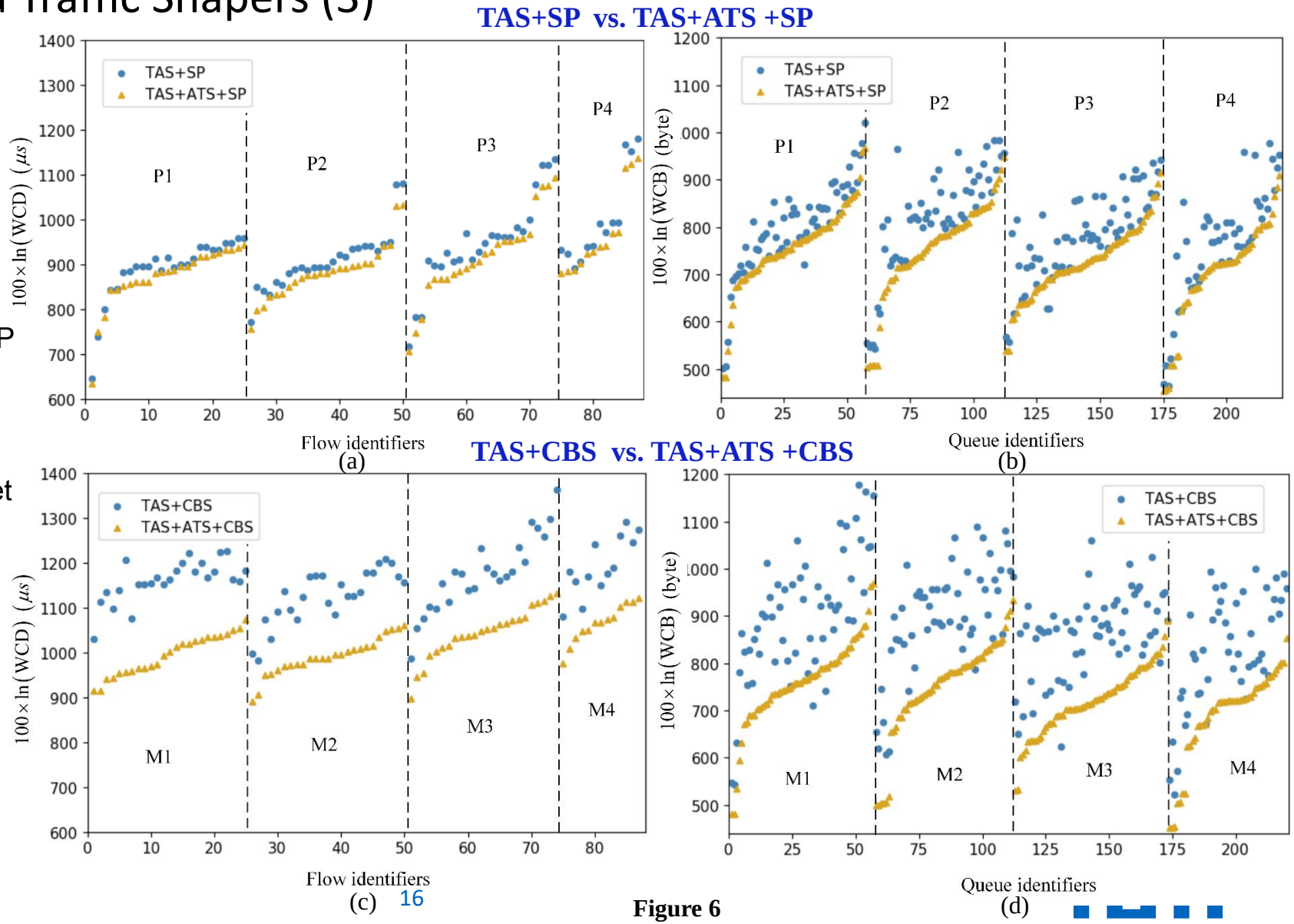


Figure 6

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Thank you!