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

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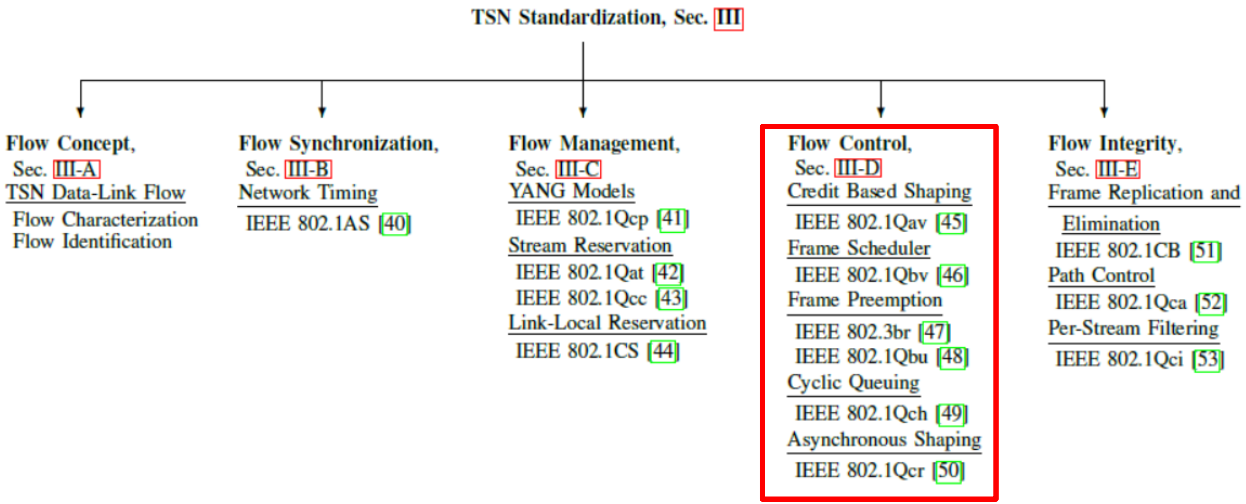
Necessity and Contributions

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.

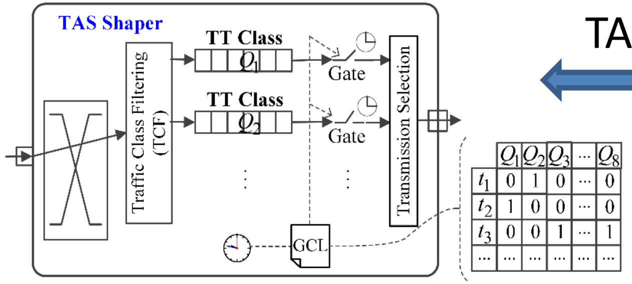


Architecture – Individual Traffic Shapers

Evaluation Parameters

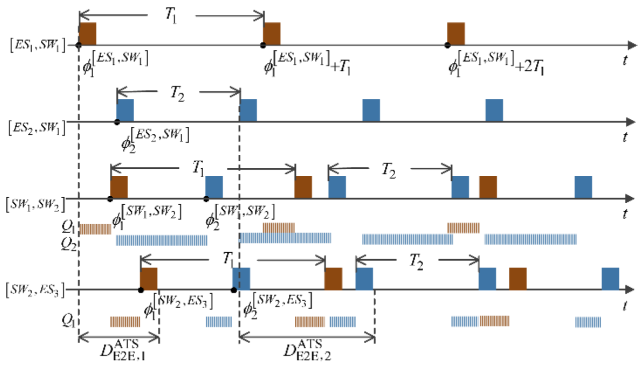
- Schedulability – End-to-end latency bound
- Buffer size without frame loss – Backlog bound
- Stable Communication – Jitter bound

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



TAS

- 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

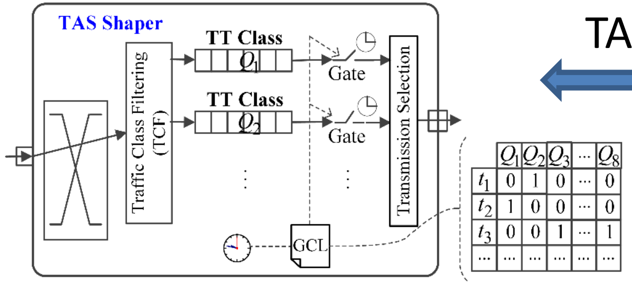
Individual Traffic Shapers

Architecture – Individual Traffic Shapers

Evaluation Parameters

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

TAS



1. 802.1Qbv
2. Scheduling Synthesis
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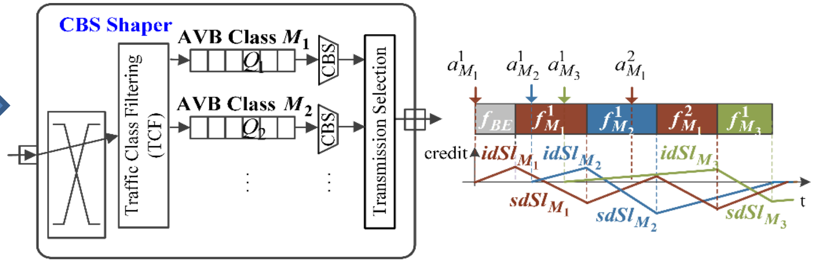
CBS

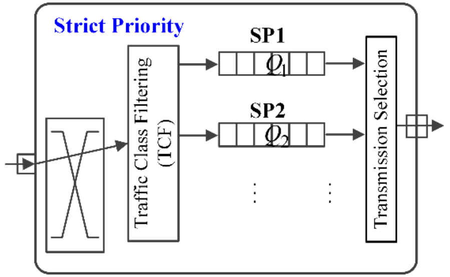


(a) Architecture (b) CBS forwarding frames example

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

- IEEE 802.1Qav – 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];

SP



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

- 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];

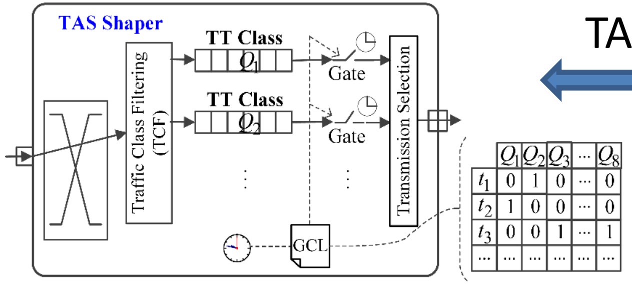
Individual Traffic Shapers

Architecture – Individual Traffic Shapers

Evaluation Parameters

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

TAS



1. 802.1Qbv
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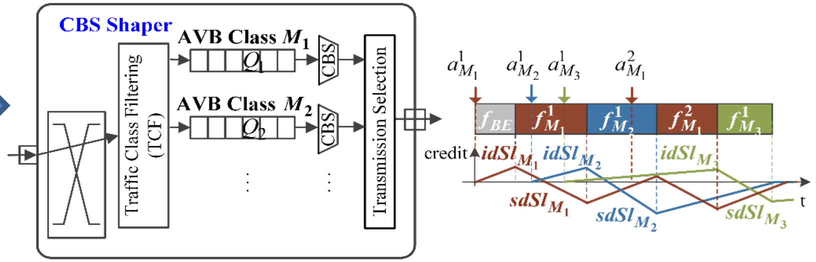
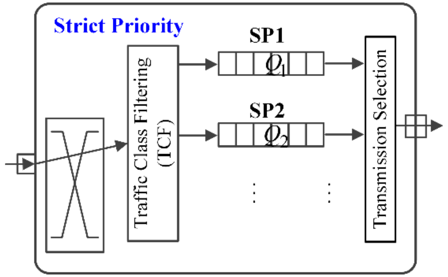
CBS



(a) Architecture (b) CBS forwarding frames example

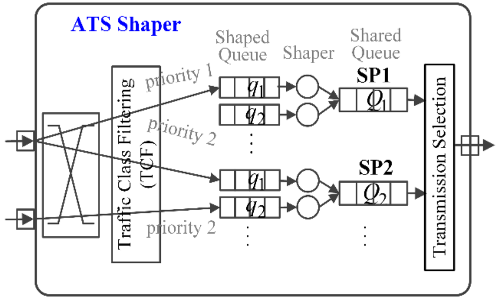
1. 802.1Qav
2. Network Calculus
3. 2014, [3] J. A. R. De Azua et al.

SP



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

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.

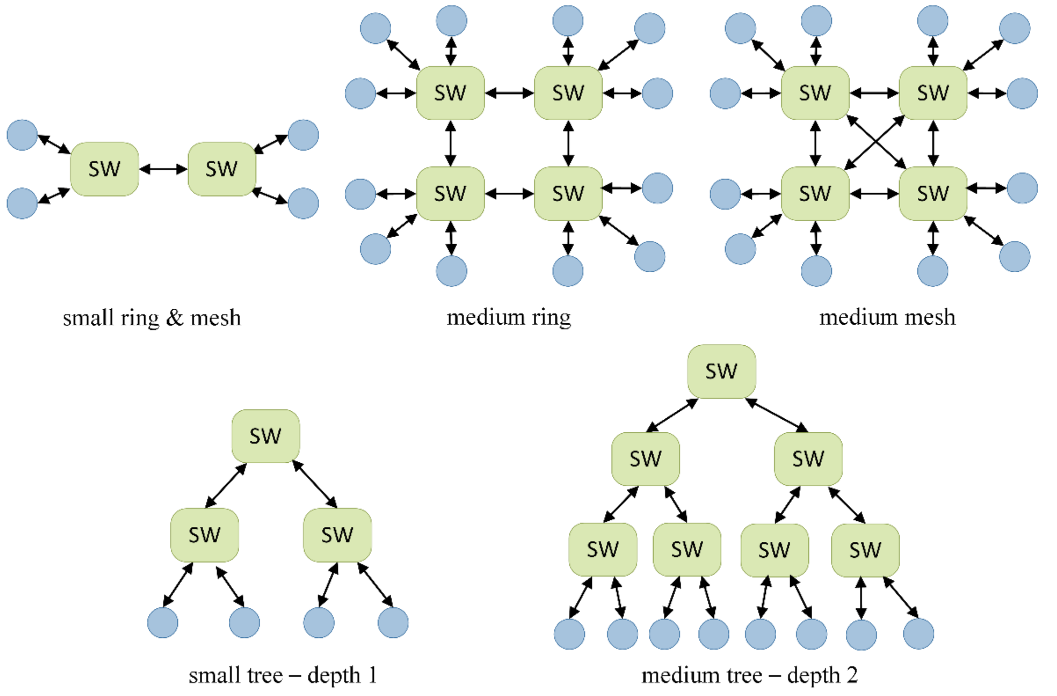
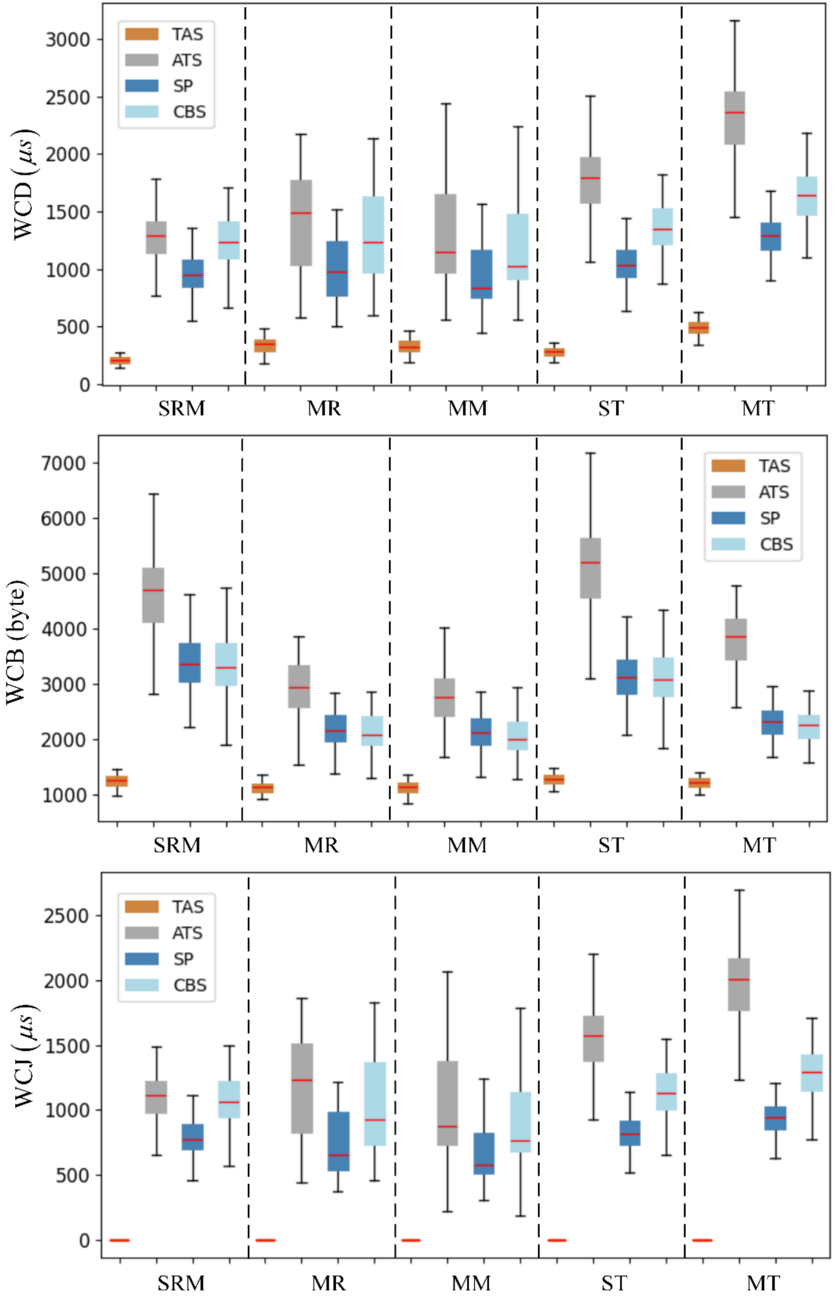


TABLE II
STATISTICAL HOPS AND TRAFFIC LOAD FOR 100 TEST CASES

	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

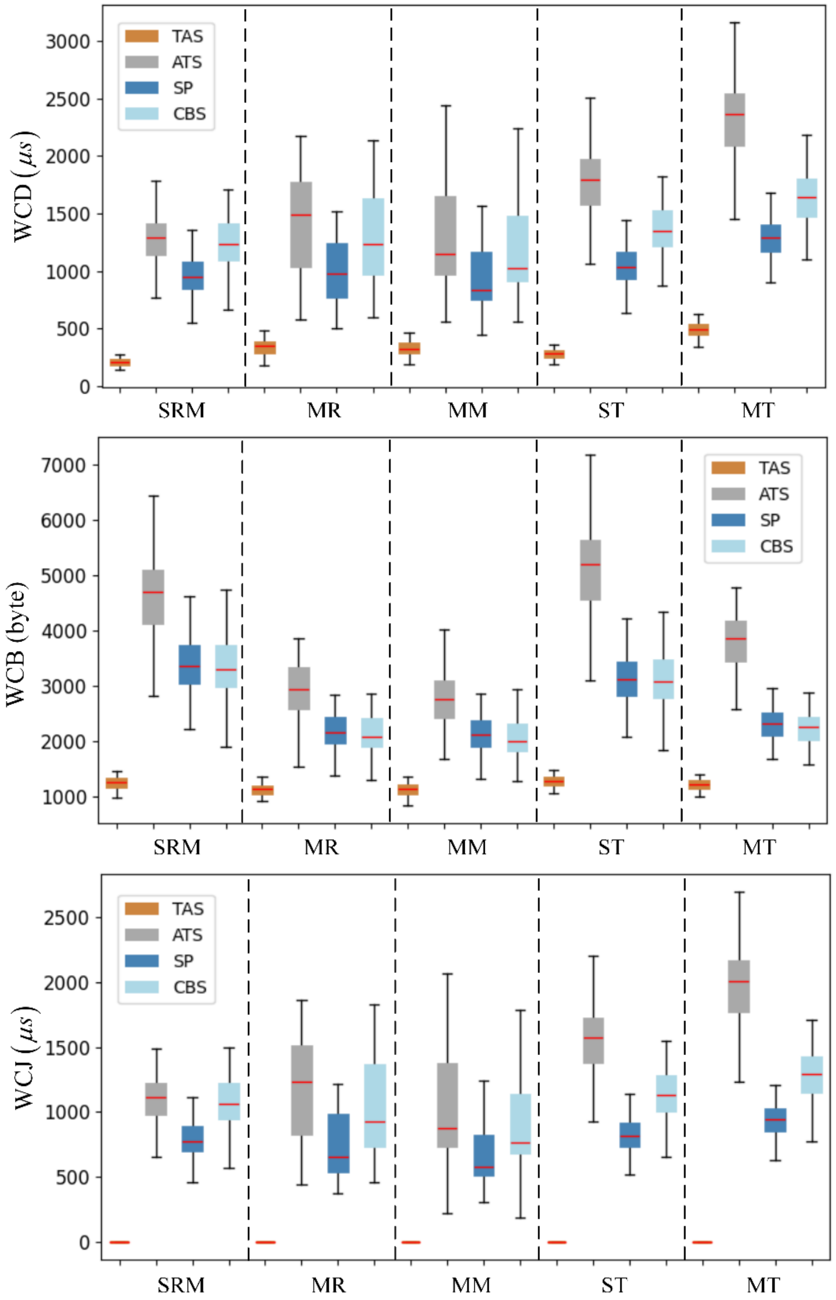
Jitter

Figure 1

Evaluation – Individual Traffic Shapers (1)

- **Results**
  - Table: X_i metric value for flow f_i;
    $\bar{X} = aver(X_i) = aver\left(\left(X_i^{Y_1} - X_i^{Y_2}\right)/X_i^{Y_2}\right)$
- **Comments**
  - latency & jitter – SP<CBS<ATS;
    backlog – CBS<SP<ATS;
  - Advantage of ATS ↓ ← concentration of flows ↑
    ← number of hops ↑
  - …

		(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

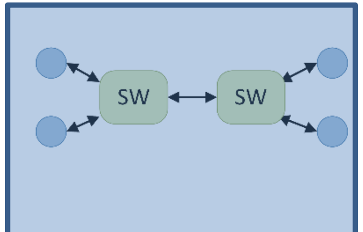
Jitter

Figure 1

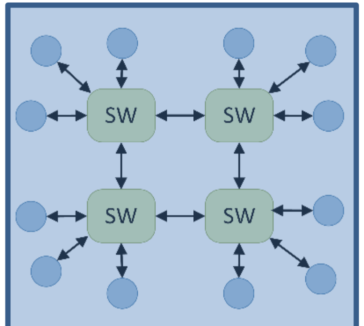
Evaluation – Individual Traffic Shapers (1)

Comments

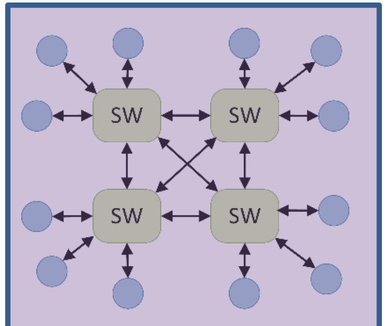
- ATS positive effect ↓ ← concentration of flows ↑
  ← number of hops ↑
- For example
  1. Flows concentration: MR > MM →
     ATS positive effect: MR < MM
  2. Number of hops: ST > SRM →
     ATS positive effect: ST < SRM



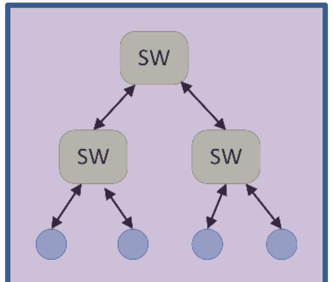
small ring & mesh



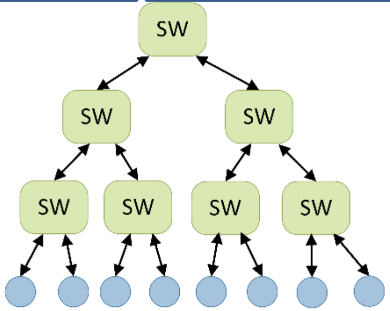
medium ring



medium mesh



small tree – depth 1



medium tree – depth 2

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

Table 1

TABLE II
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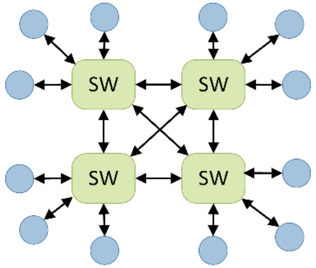
Evaluation – Individual Traffic Shapers (2)

- **Synthetic test cases – MM**
  - **Case 1 – 1 priority**
  - Average traffic load: 10% ~ 90%
  - Each traffic load – 20 Tces



medium mesh

- **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:
    – Average traffic load ↑ → comparison percentage X ↑ → ATS positive effect ↑;
    – Average traffic load < 70% – SP performs better than ATS;
  - Backlog bounds:
    – Average traffic load < 70% – unobvious change;
    – ATS performance is always inferior to SP.
  - …

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

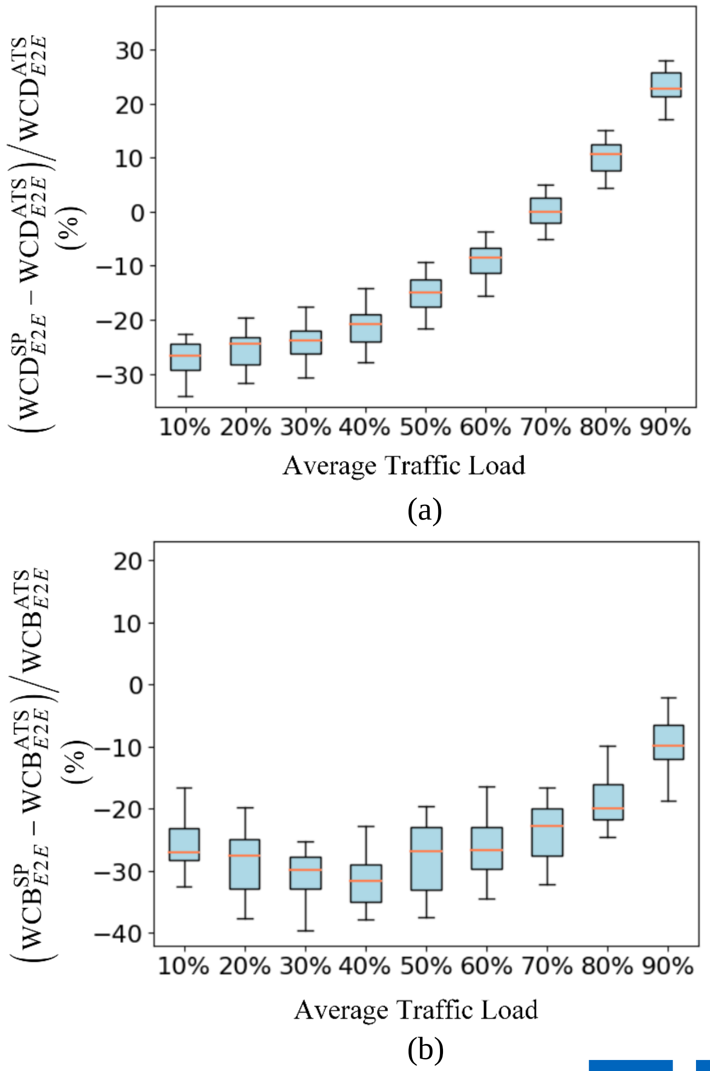
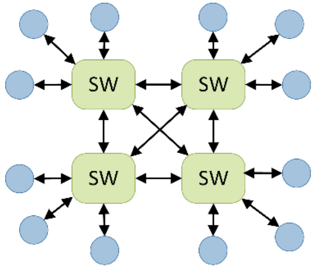


Figure 2

Evaluation – Individual Traffic Shapers (3)

- **Synthetic test cases – MM**
  - **Case 2 – 2 priorities + BE**
  - Average traffic load: 10% ~ 90%;
    High/low: 50% of overall traffic load
  - Each traffic load – 20 Tces



medium mesh

- **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:
    <u>High priority</u>:
    – ≈ Top 40% traffic load with single priority;
    – ATS no positive effect on high-priority traffic.
    <u>Low-priority</u>:
    – ATS positive effect on low-priority traffic ← average overall traffic load > 30%.
  - …

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

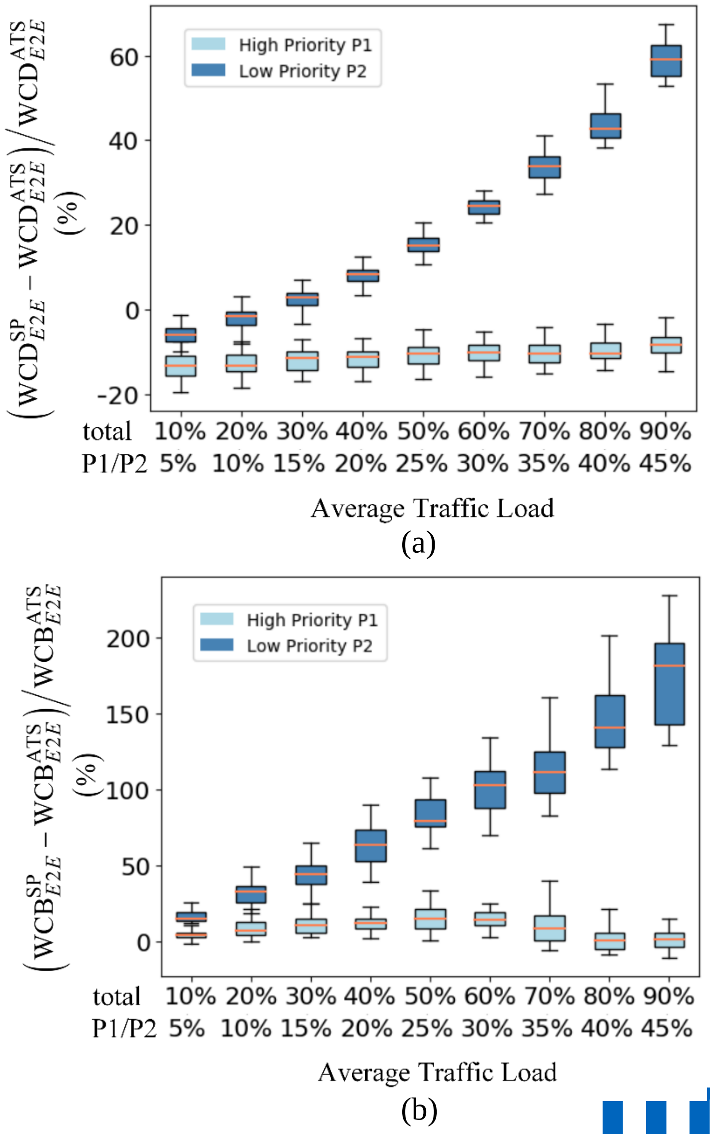
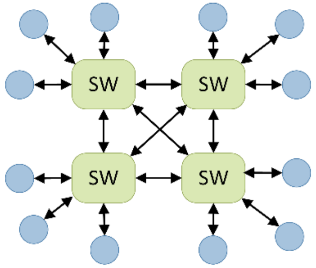


Figure 3

Evaluation – Individual Traffic Shapers (3)

- Synthetic test cases – MM
  - **Case 3 – 2 priorities + BE**
  - Average traffic load: 10% ~ 90%;
    High/low: 50% of overall traffic load
  - Each traffic load – 20 Tces
- Results
  - $X = aver(X_i) = aver\left(\left(X_i^{SP} - X_i^{ATS}\right)/X_i^{ATS}\right)$
- Comments
  - Backlog bounds:
    <u>High priority</u>:
    – ≈ Top 40% traffic load with single priority + BE;
    <u>Low-priority</u>:
    – ATS positive effect on low-priority traffic.



medium mesh

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

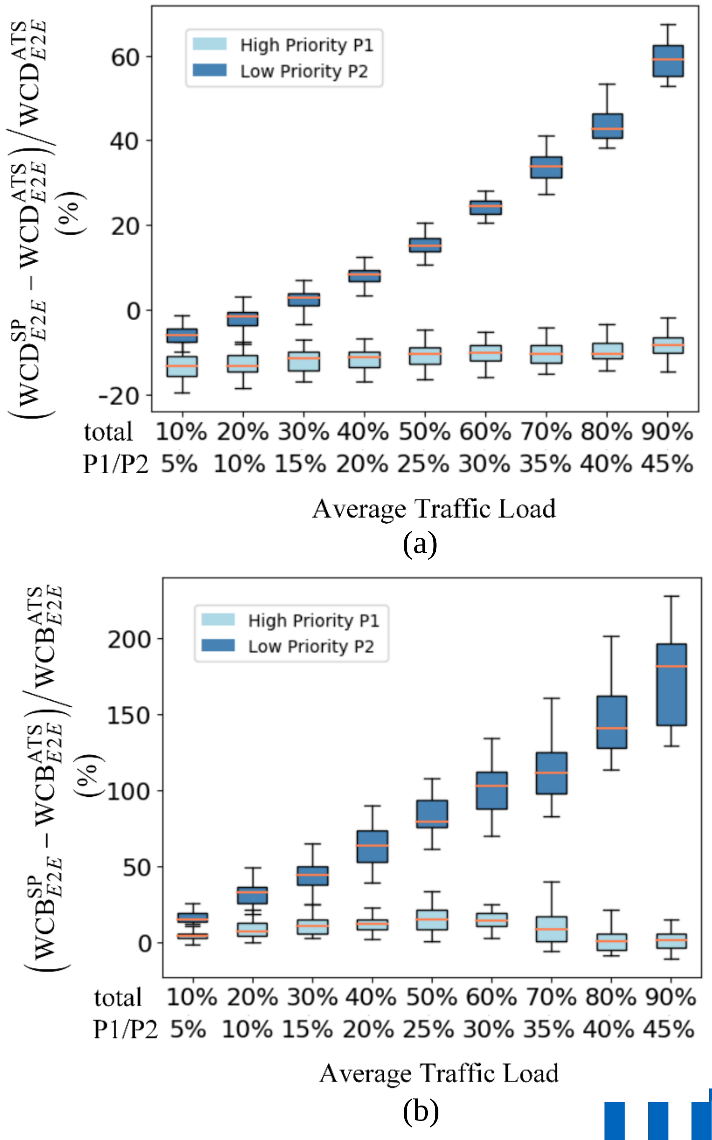
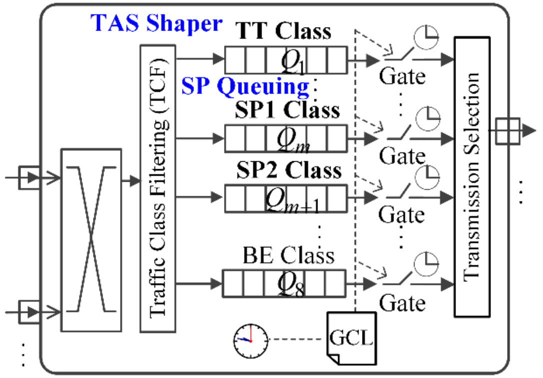


Figure 3

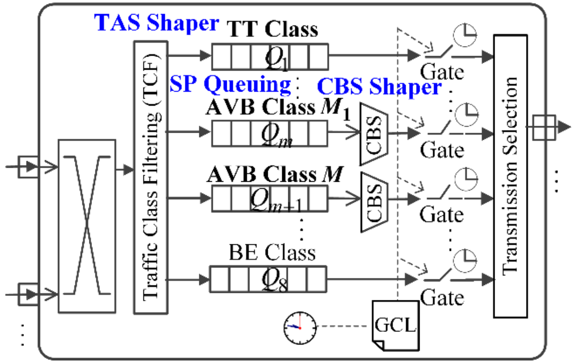
Architecture – Combined Traffic Shapers

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



TAS+SP

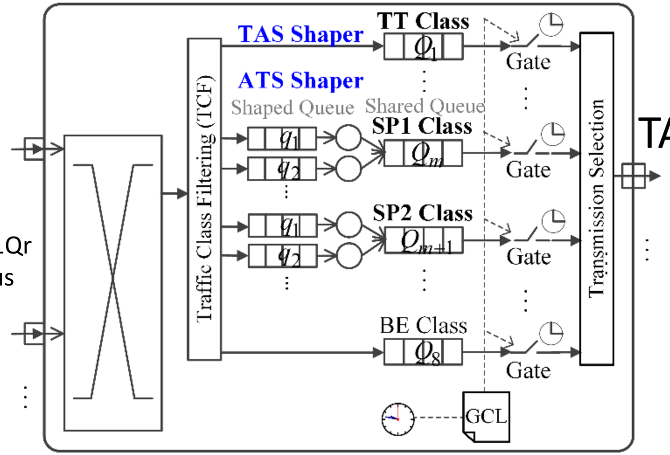
TAS+CBS



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

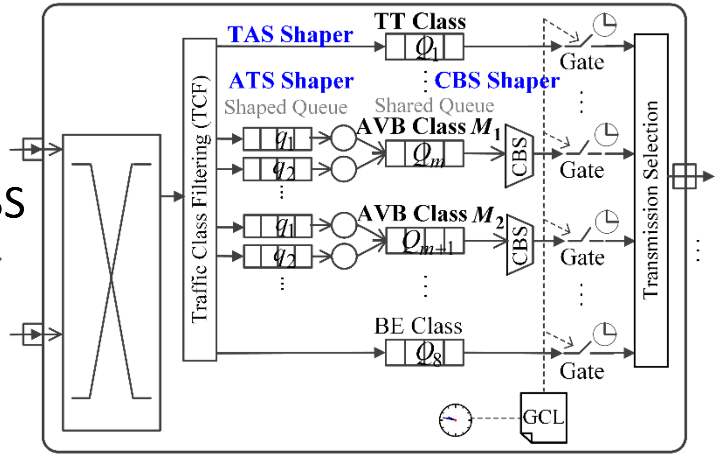


NEW

TAS+**ATS**(+SP)

NEW

TAS+**ATS**+CBS



NEW

1. 802.1Qbv+802.1Qcr +802.1Qav

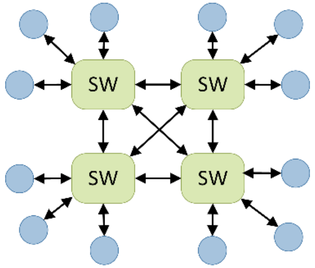
- TAS outperforms than all the others (latency, backlog, jitter); Scalability problem.
- Promising combination model: TAS+X

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

Combined Traffic Shapers

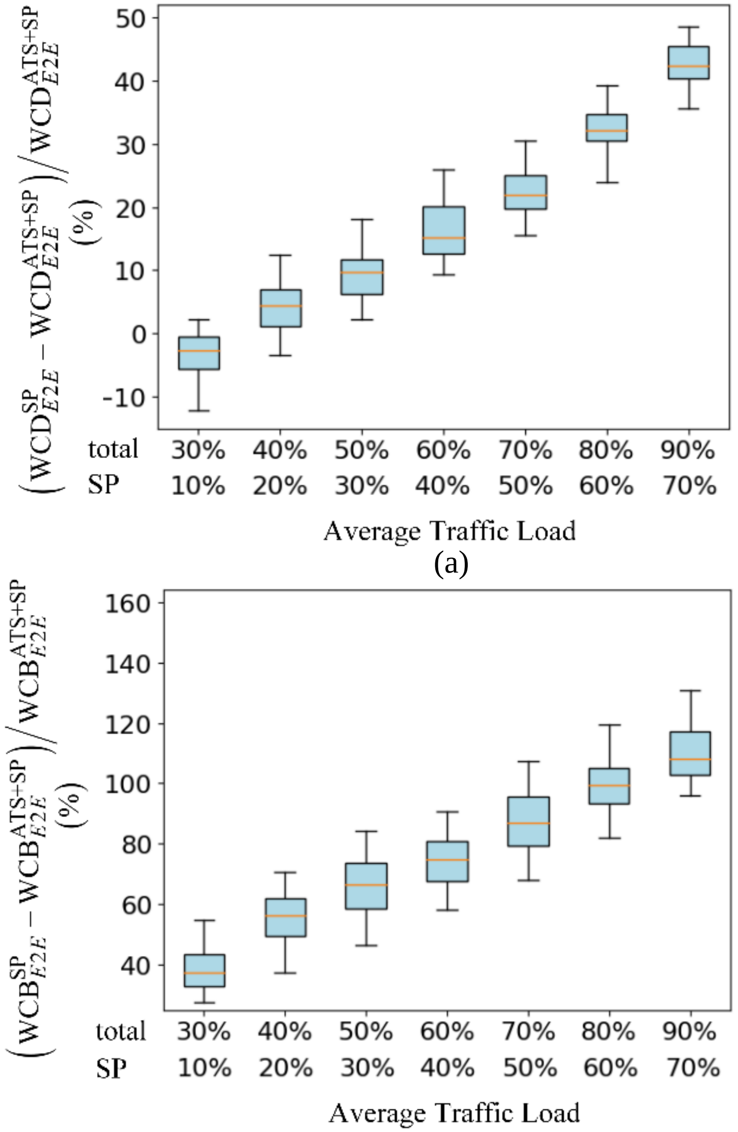
Evaluation – Combined Traffic Shapers (1)

- **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

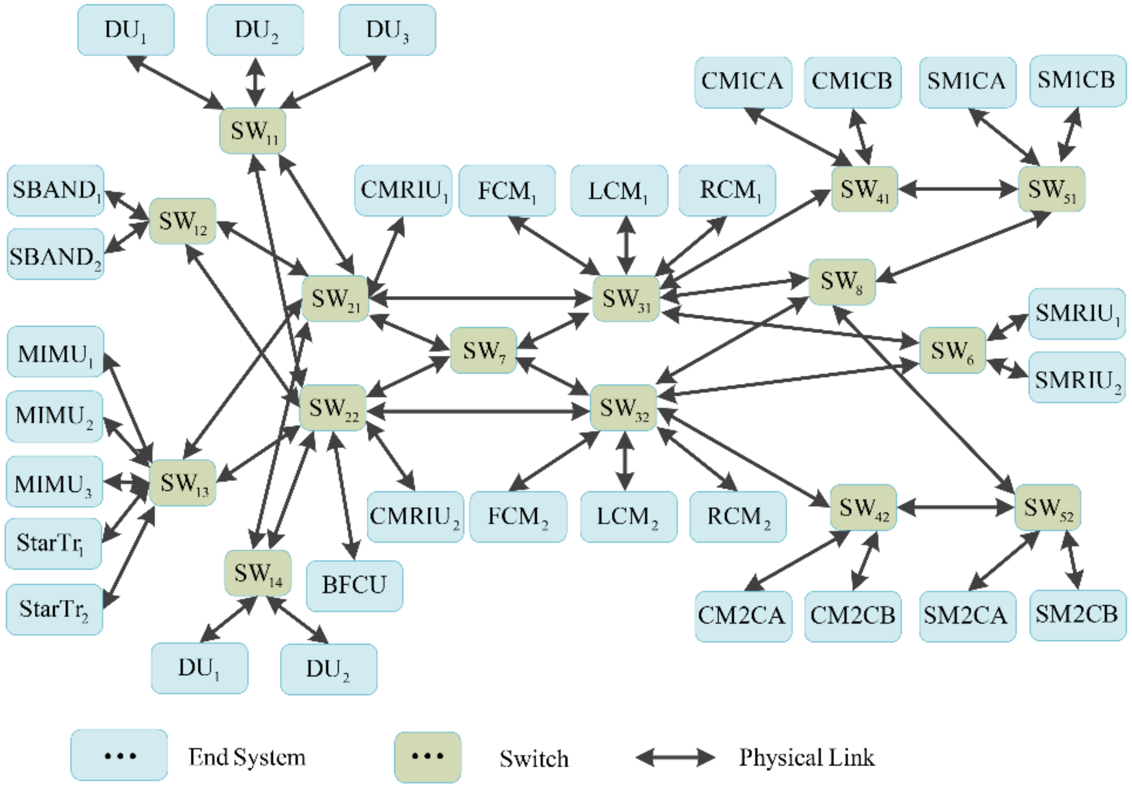
TAS+SP vs. TAS+ATS (+SP) – TT 20%



(b)
Figure 4

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. 4.

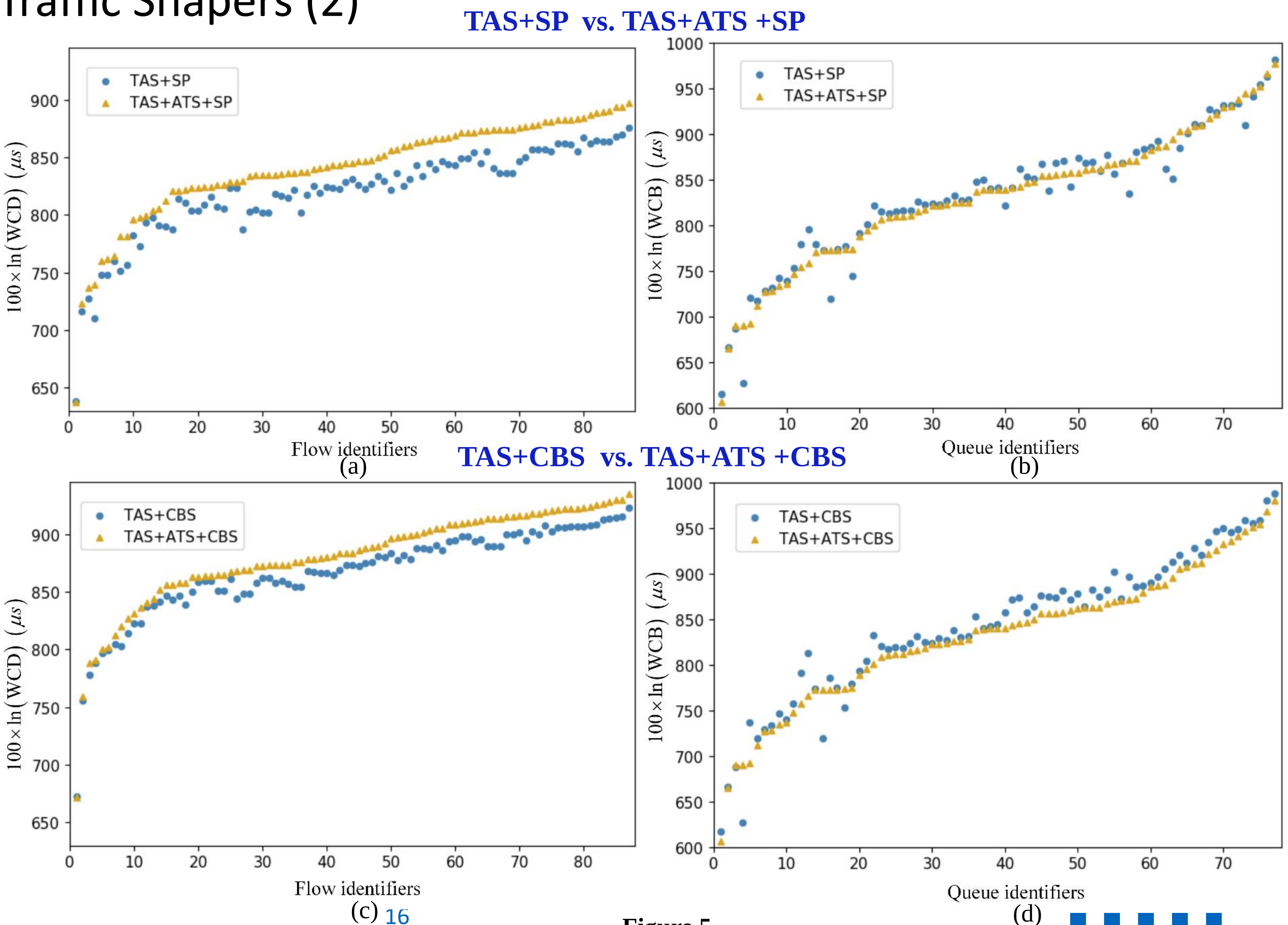
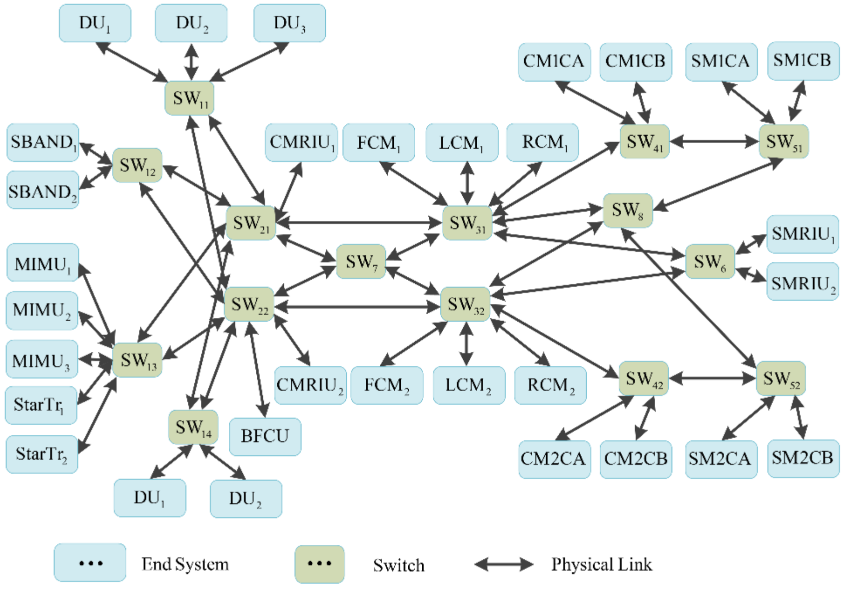


Figure 5

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,

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



Orion CEV

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

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.

TAS+SP vs. TAS+ATS +SP

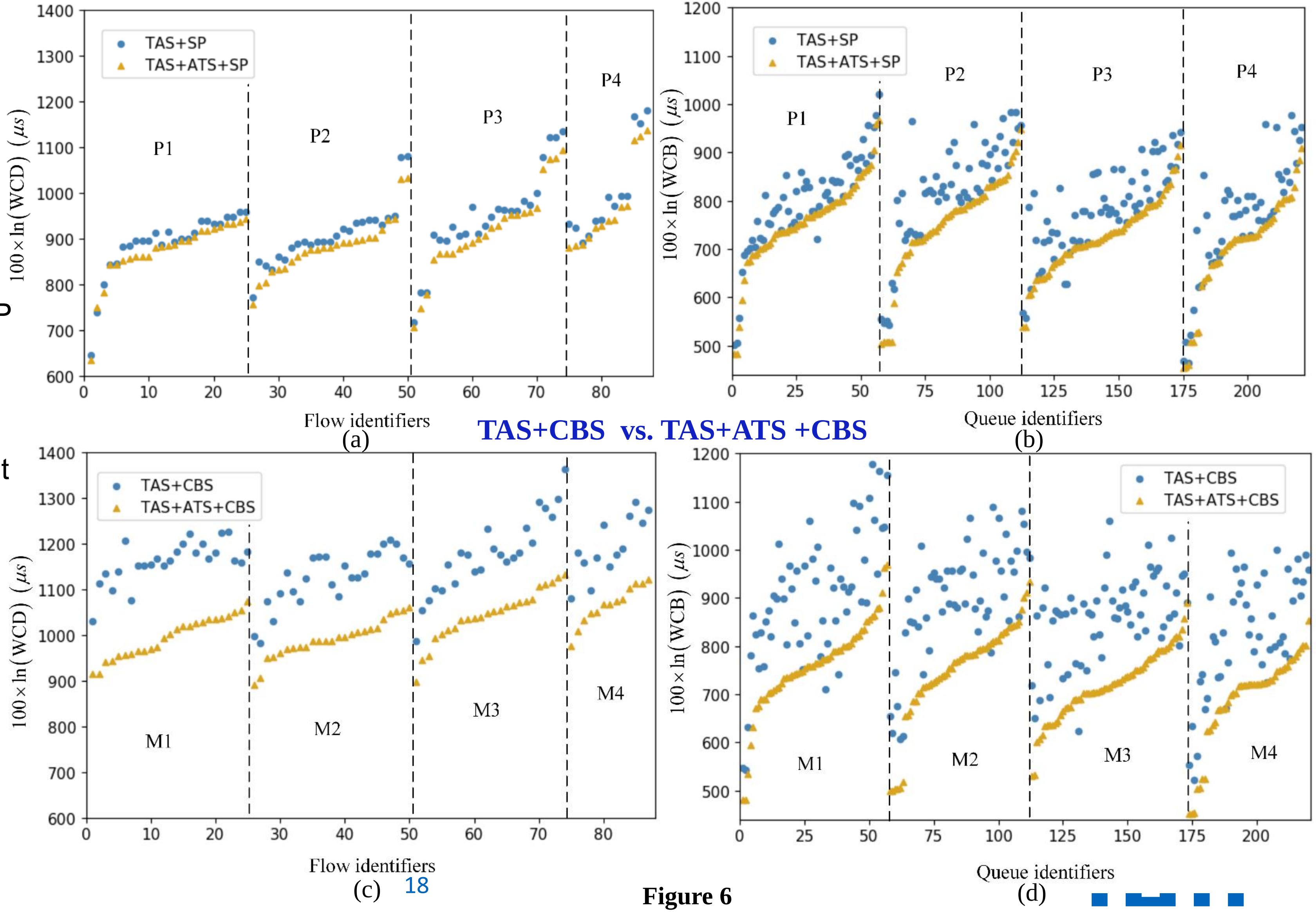


Figure 6

Conclusion

- SP vs. CBS
  - SP is more beneficial to the transmission delay of high-priority traffic, while CBS can specify bandwidth reservation for each priority traffic;
  - Due to the credit controlling by CBS, the long-term rate of AVB traffic arrival is reduced, backlog bounds of AVB traffic are possible lower than SP traffic.
- ATS vs. SP, CBS
  - ATS has limited advantages for high-priority traffic;
  - Only when the average traffic load of high priority traffic exceeds a certain value (around 70% in MM for example), ATS can show its superiority;
  - The positive effect of ATS on low priority traffic is more obvious.
- TAS vs. SP, CBS, ATS
  - TAS implement flow-based TT scheduling, has the highest performance with ultra low latency, jitter and backlog;
  - TAS requires the synthesis of optimized GCLs, to which is difficult to scale to large networks with many flows.
- TAS+ATS+X vs. TAS+X
  - Combined use of ATS with TAS will make ATS play a more active role, of which the effect is similar to the reshaping impact of ATS used individually on low priority traffic.
  - TAS will maintain unchanged its advantages of ultra low latency and jitter.

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Thank you!