Real-Time Scheduling for 802.1Qbv Time-Sensitive Networking (TSN): A Systematic Review and Experimental Study

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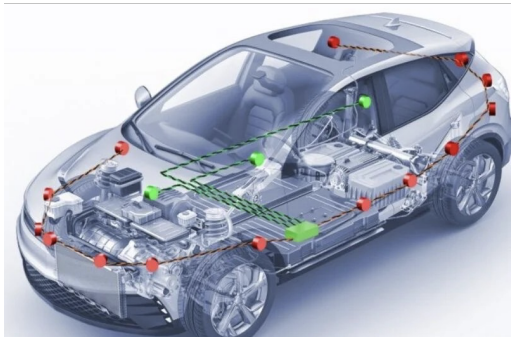
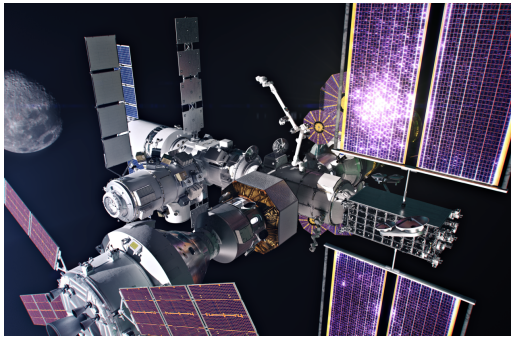
[4]NASA Johnson Space Center

Time-Sensitive Networking

Time-sensitive networking (TSN):

- IEEE 802.1 standards based on Ethernet.
- Provides deterministic Layer-2 communications.
- Essential for real-time industrial applications.





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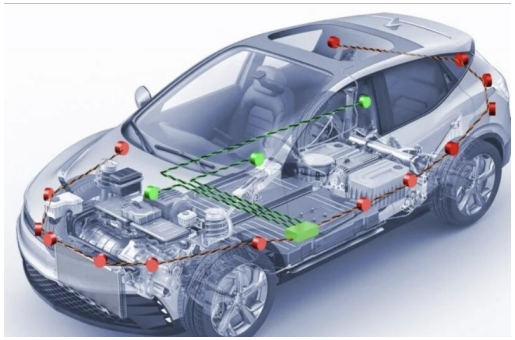

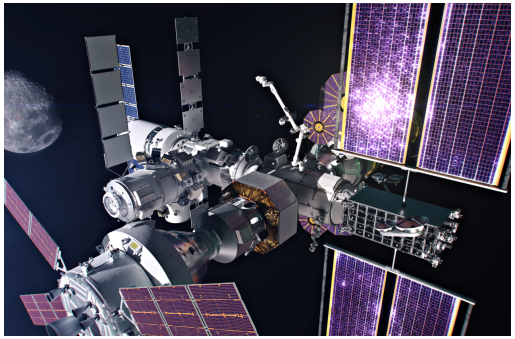

Shapers and schedulers:

- Credit-Based Shaper (CBS), Strict-Priority Shaper (PS), Asynchronous Traffic Shaper (ATS), Time-Aware Shaper (TAS).
- Handle different traffic types and real-time requirements.

Time-Aware Shaper

Time-aware shaper (TAS) stands out in providing most stringent real-time performance guarantees, e.g., ultra-low latency and zero jitter.

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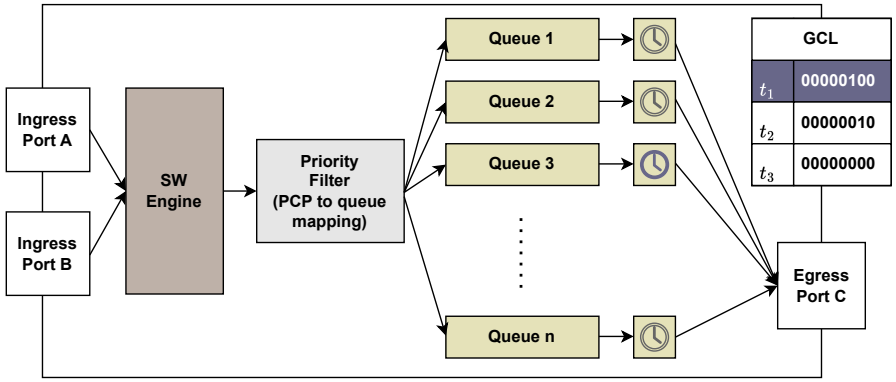

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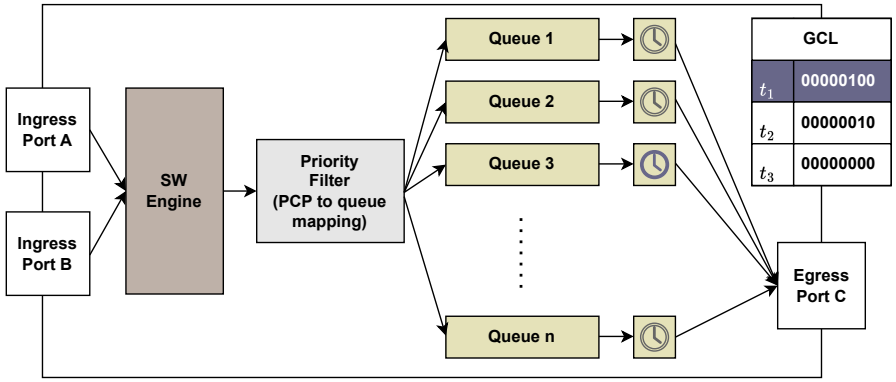
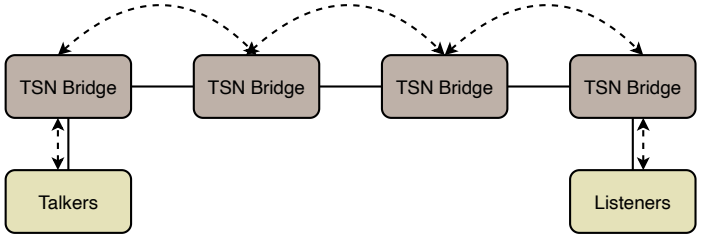
- Network-wide schedule generated by the Centralized Network Configuration (CNC).





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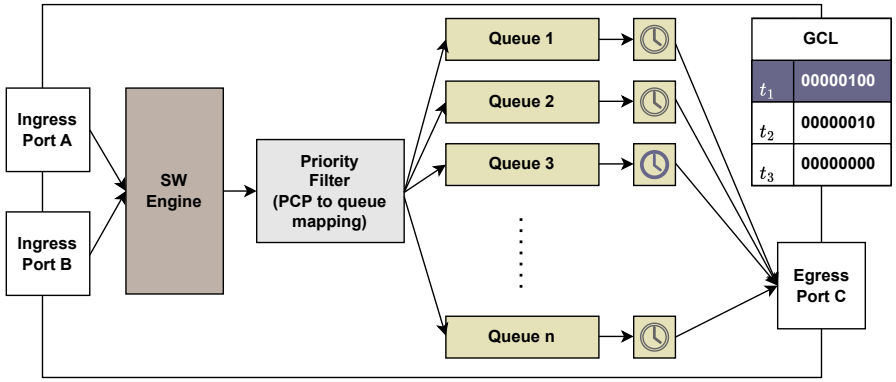

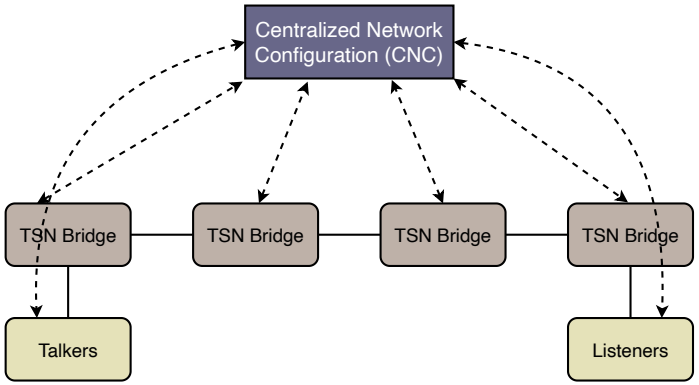

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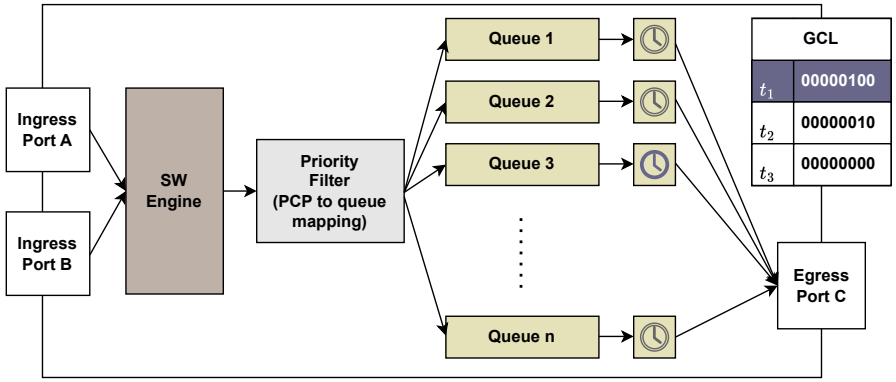
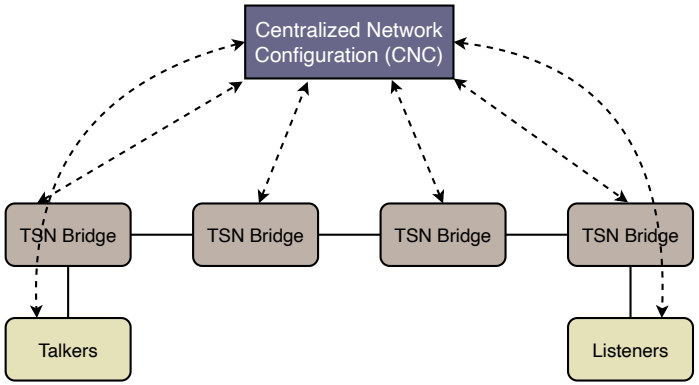
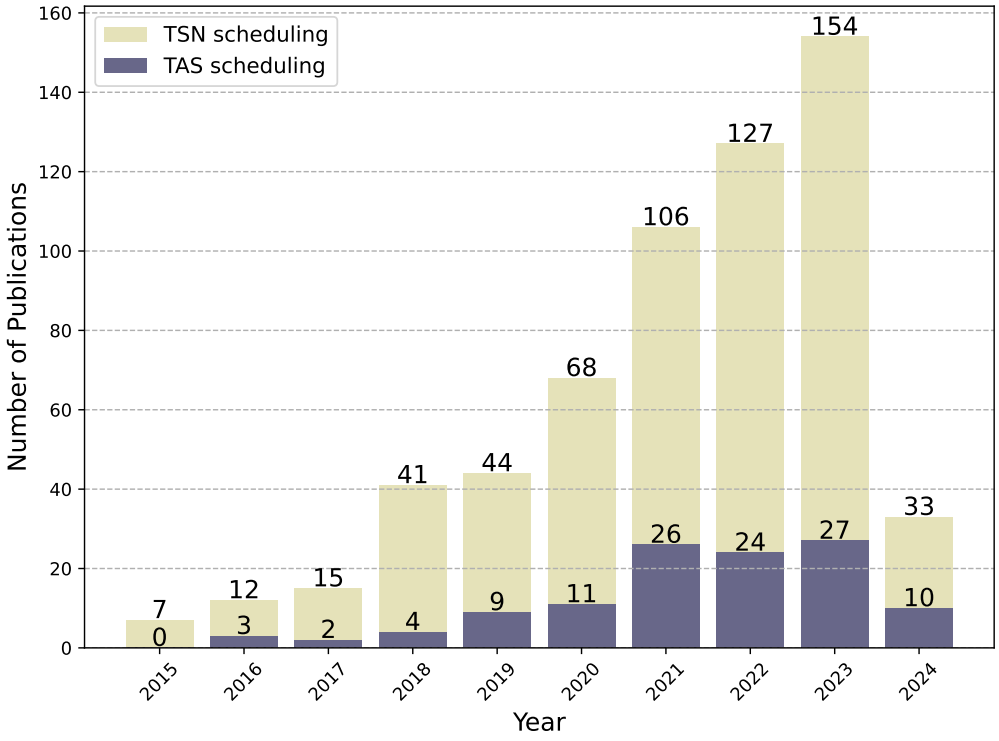




Generating a network-wide schedule for TAS-based network has no clear best practice

Existing Work

Number of publications about TAS scheduling from 2015 to 2024.



Search results for time-aware shaper from Sematic Scholar

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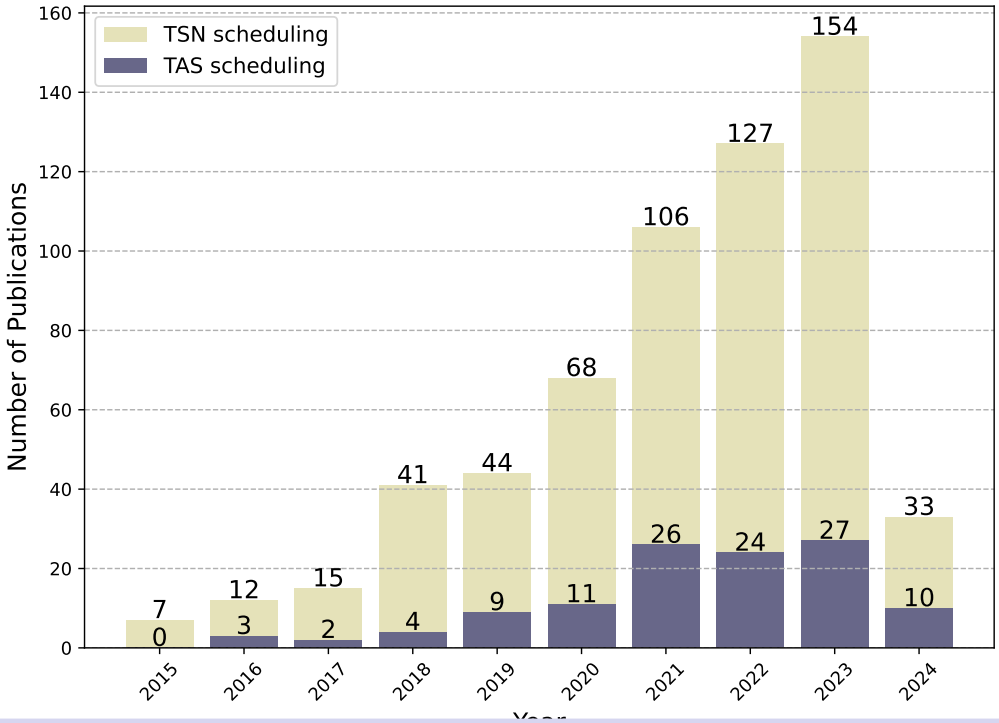

Motivation

There is no comprehensive benchmark for TAS-based scheduling methods

Open Problems

Problem #1:
No systematic model-based categorization for TAS-based scheduling methods

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Problem #2:
No comprehensive quantitative comparisons for TAS-based scheduling methods

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Problem #2:
No comprehensive quantitative comparisons for TAS-based scheduling methods

Problem #3:
The correctness of existing methods has not been validated on real hardware

Contributions

1) Multi-dimensional model-based categorization

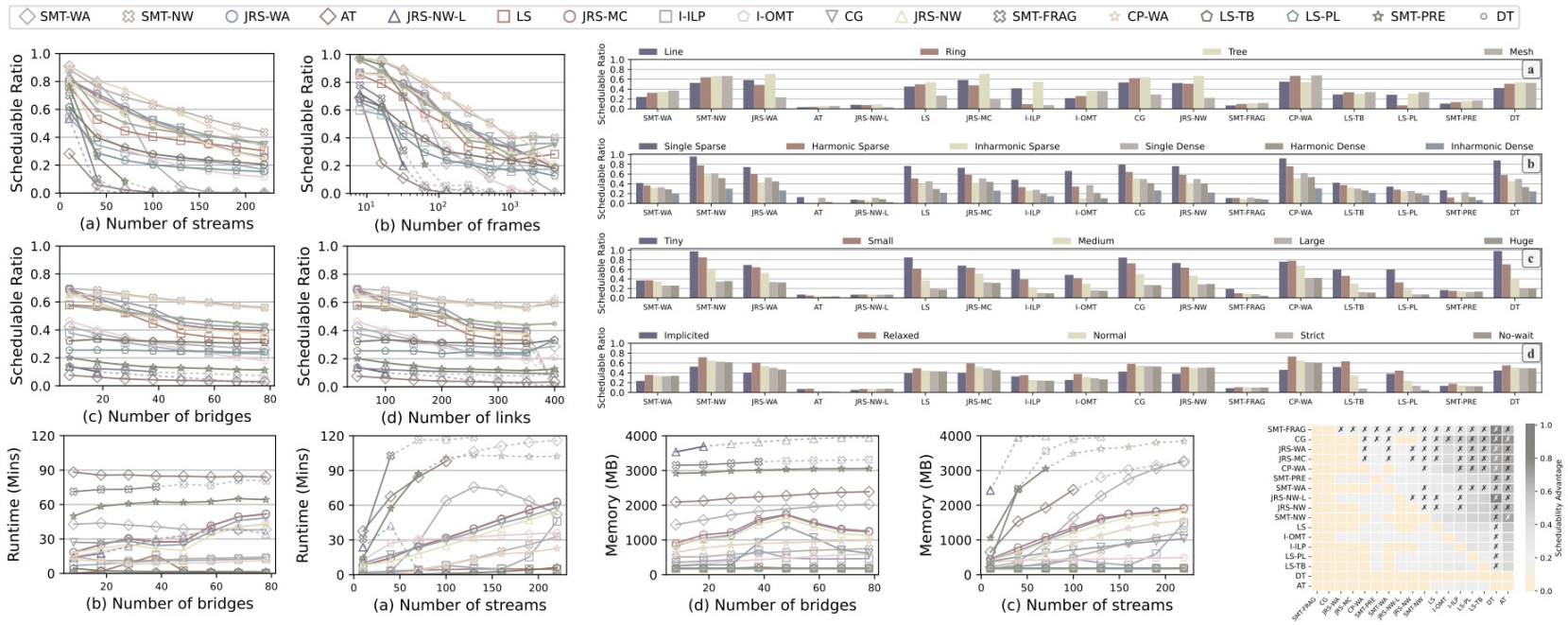
System models | Algorithms

17 methods

Article	Year	Fully schedulable	Strictly periodic	No-wait	Window -based	Queuing isolation	Routing	Multicast	Heuristic	Exact	Algorithms	Enhancements
Dürr et al. (SMT-NW)	2016	✓	✓	✓					(✓)	✓	ILP (Tabu)	
Craciunas et al. (SMT-WA)	2016	✓	✓			✓				✓	SMT	
Schweissguth et al. (JRS-WA)	2017	✓	✓				✓			✓	ILP	Paths reduce
Oliver et al. (AT)	2018	✓			✓	✓				✓	SMT	Array-theory
Falk et al. (JRS-NW-L)	2018	✓	✓	✓			✓			✓	ILP	Logic indicator
Pahlevan et al. (LS)	2019	✓	✓	✓			✓		✓		List scheduler	
Schweissguth et al. (JRS-MC)	2020	✓	✓				✓	✓		✓	ILP	Paths reduce
Atallah et al. (I-ILP)	2020	✓	✓	✓			✓	✓	✓		Iterative-ILP	
Jin et al. (I-OMT)	2020				✓	✓			✓	(✓)	Iterative-OMT	
Falk et al. (CG)	2020	✓	✓	✓			✓		✓	(✓)	Conflict-graph	
Hellmanns et al. (JRS-NW)	2021	✓	✓	✓			✓			✓	ILP	Path cut-off
Jin et al. (SMT-FRAG)	2021	✓	✓	✓					(✓)	✓	SMT (WCRT)	Fragmentation
Vlk et al. (CP-WA)	2021	✓	✓			✓			(✓)	✓	CP (Decompose)	
Vlk et al. (LS-TB)	2022		✓			✓			✓	(✓)	List scheduler	Traceback
Bujosa et al. (LS-PL)	2022		✓			✓			✓		List scheduler	Per-link search
Zhou et al. (SMT-PRE)	2022	✓								✓	SMT	Preemption
Zhang et al. (DT)	2022	✓	✓	✓					✓	(✓)	Divisibility	

Contributions

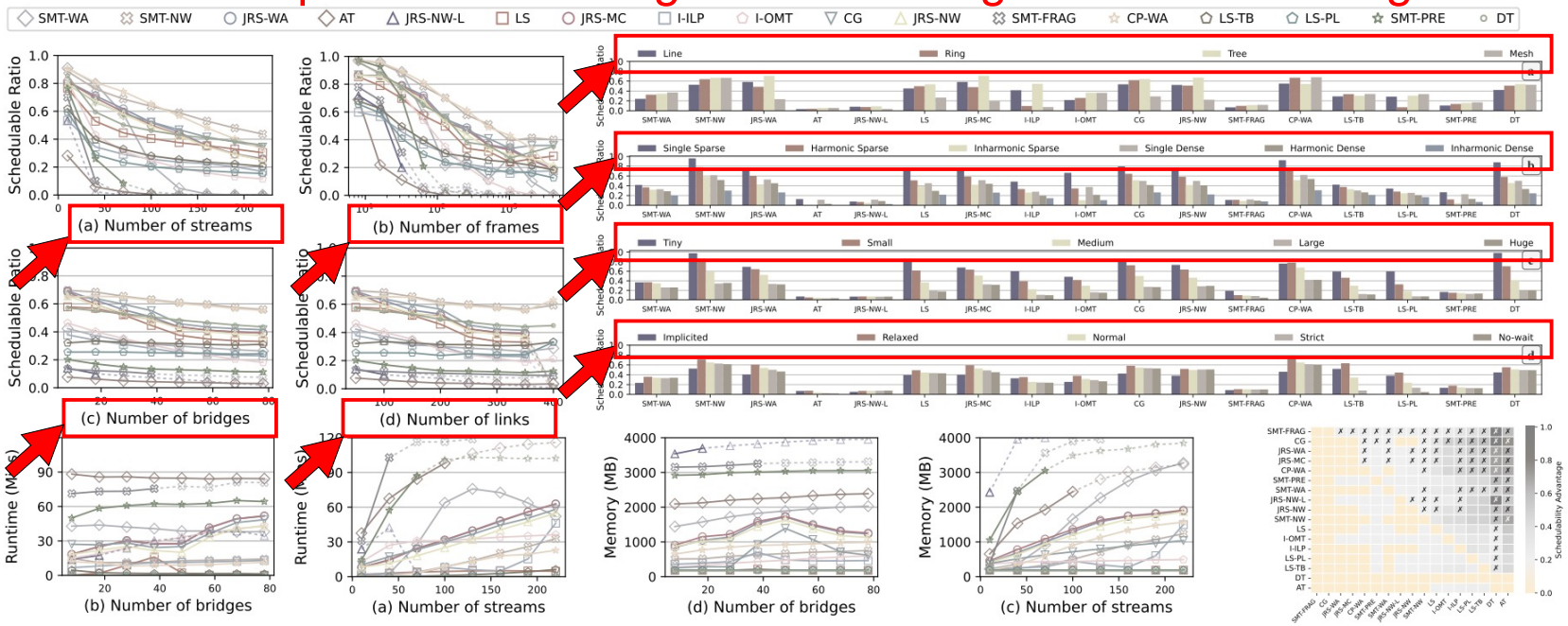
2) Benchmark in considering relevance, fairness, and reproducibility



Contributions

2) Benchmark in considering relevance, fairness, and reproducibility

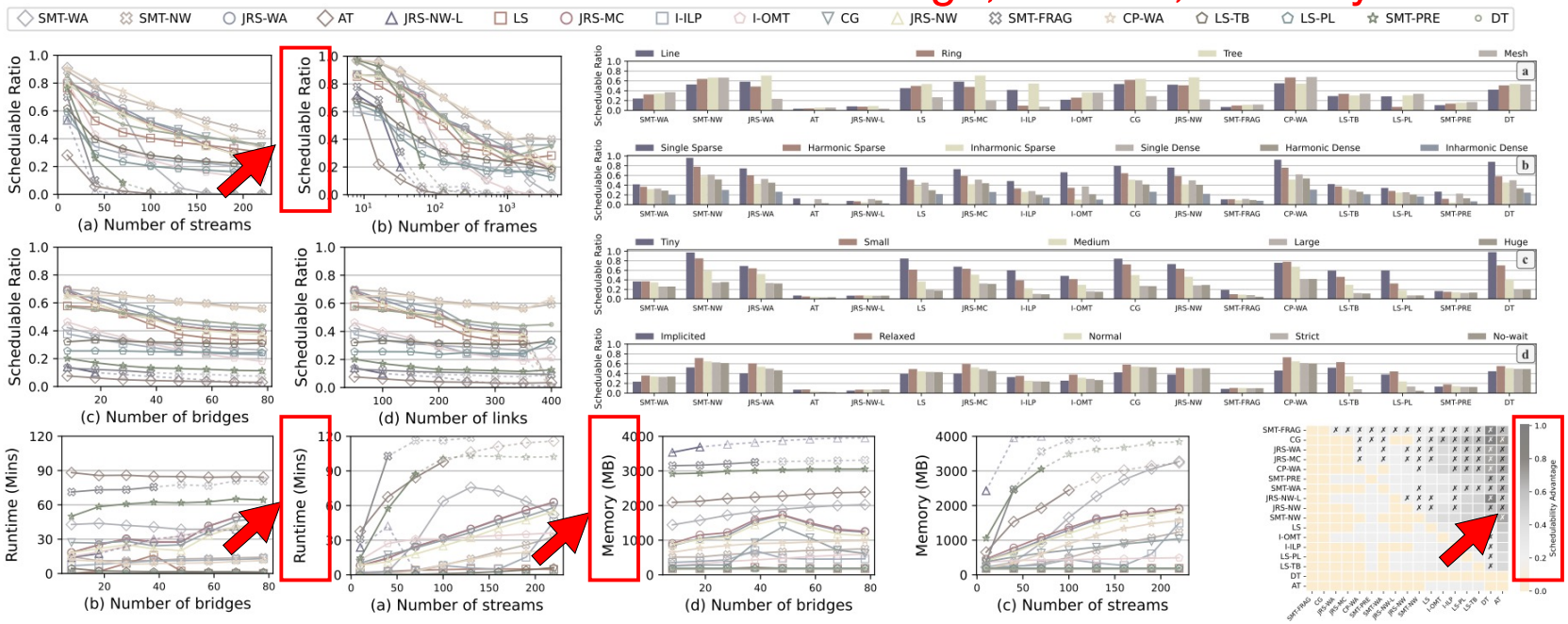
Extensive experimental settings: traffic settings + network settings



Contributions

2) Benchmark in considering relevance, fairness, and reproducibility

Various metrics: schedulable ratio/advantage, runtime, memory



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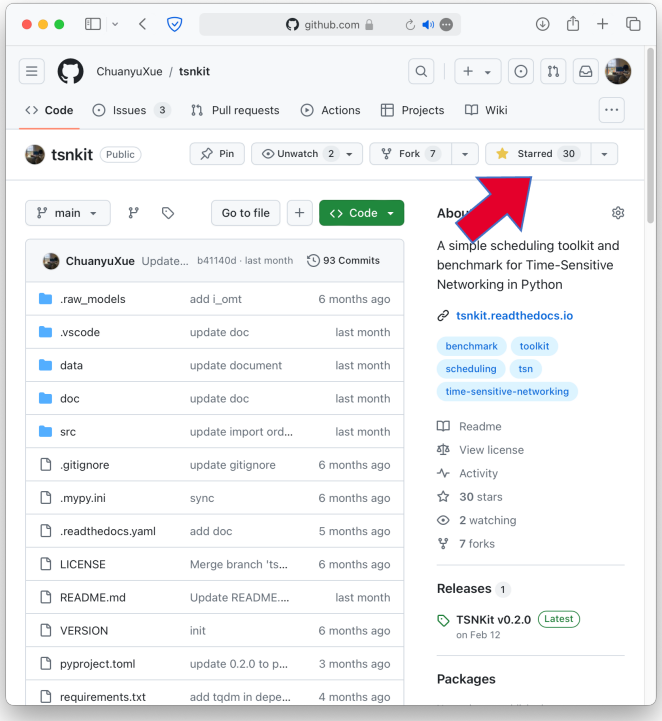

Github page

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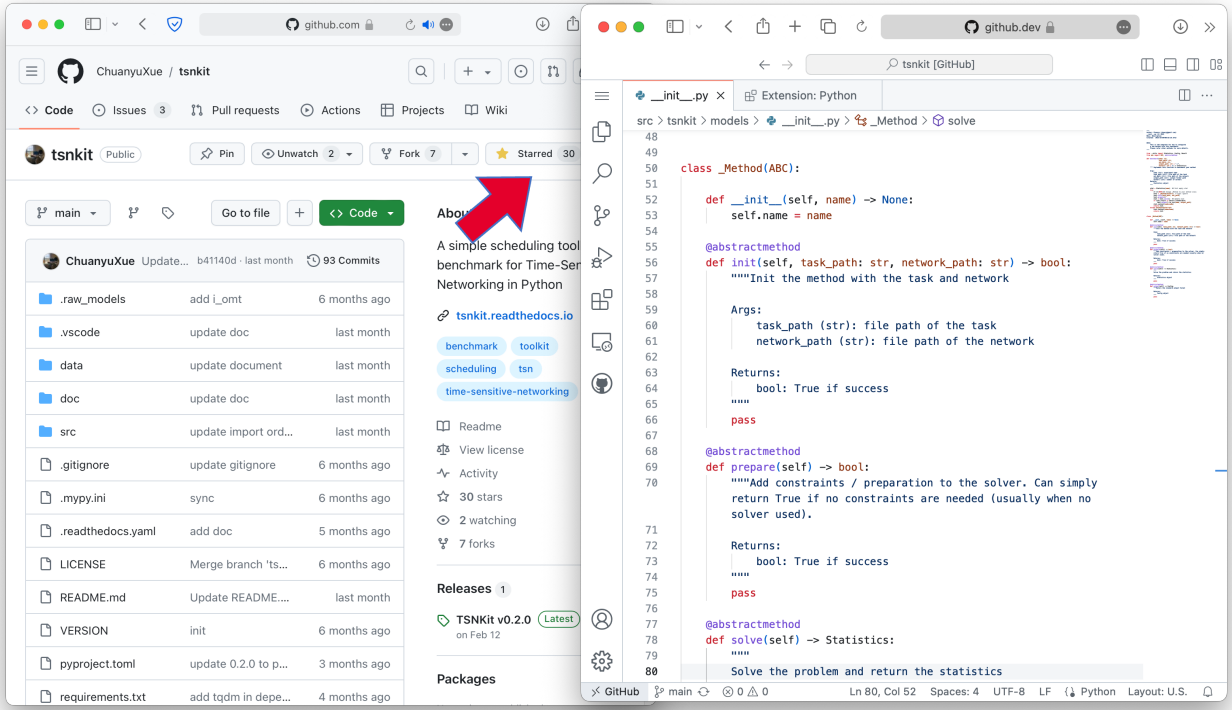

Github page Extendable framework

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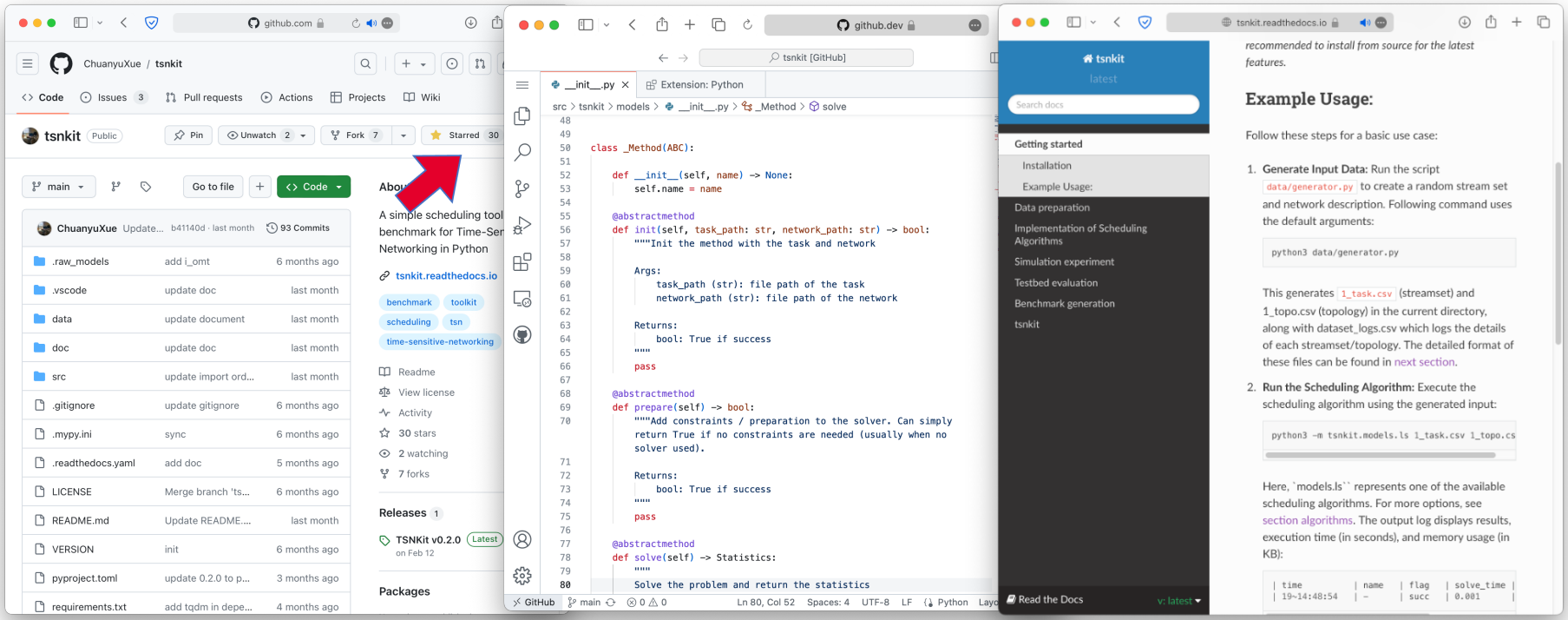
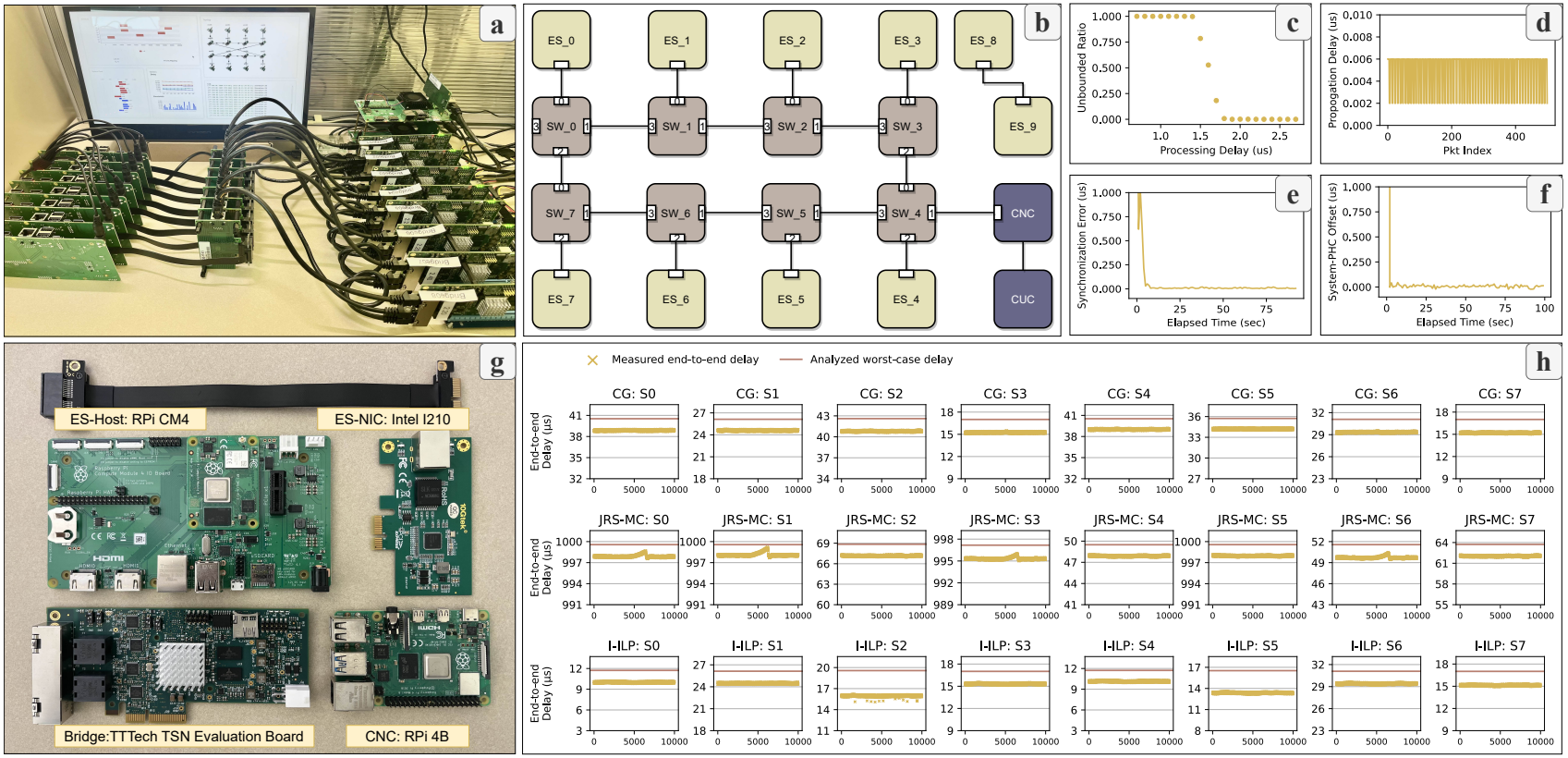


Github page Extendable framework Documentation

Contributions

3) Real-world testbed for performance validation



Model-based Categorization

Motivation:

- For experimental study: Conduct model/algorithm-based experimental comparisons
- For the community: Quick identification of relevant methods

Principle: A 3-dimension model-based categorization to cover most existing TAS scheduling methods.

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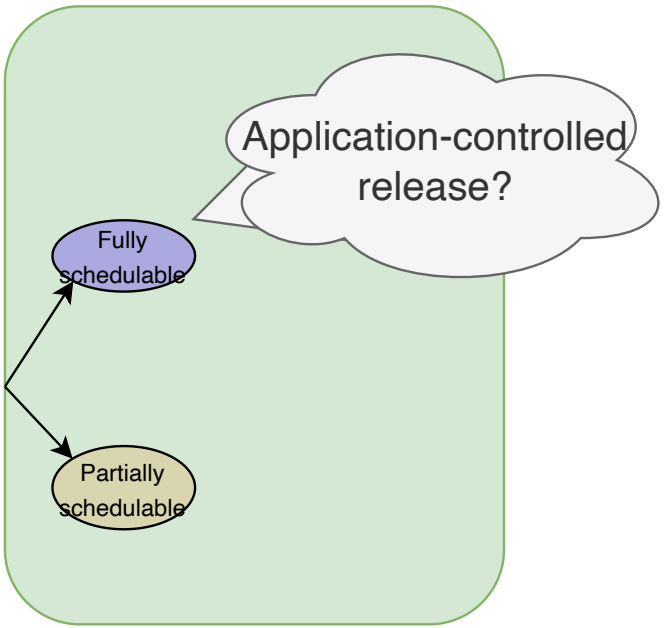

Traffic model

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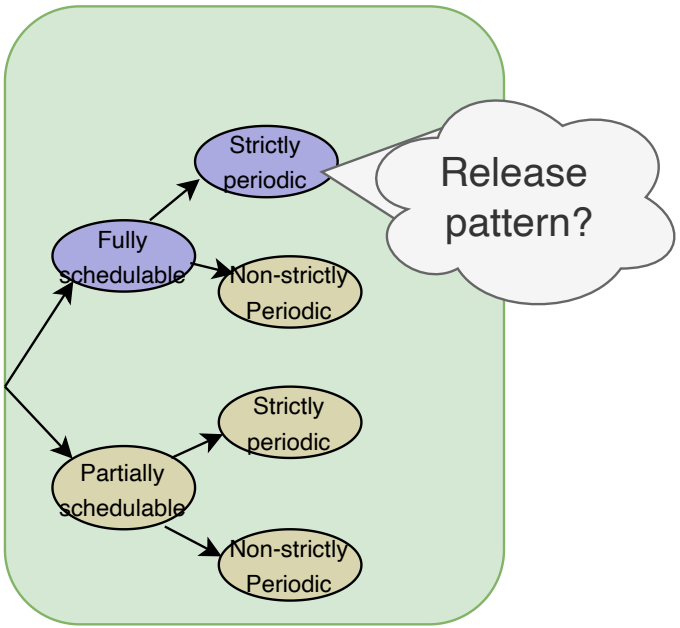

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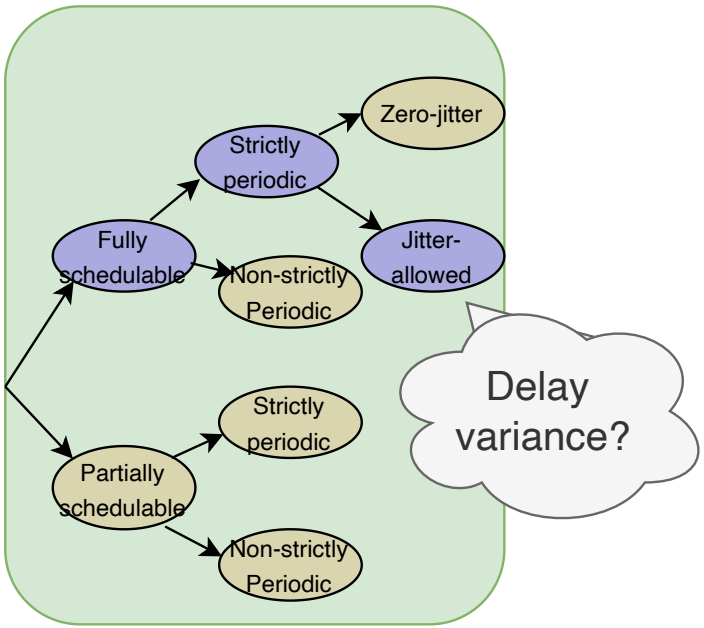

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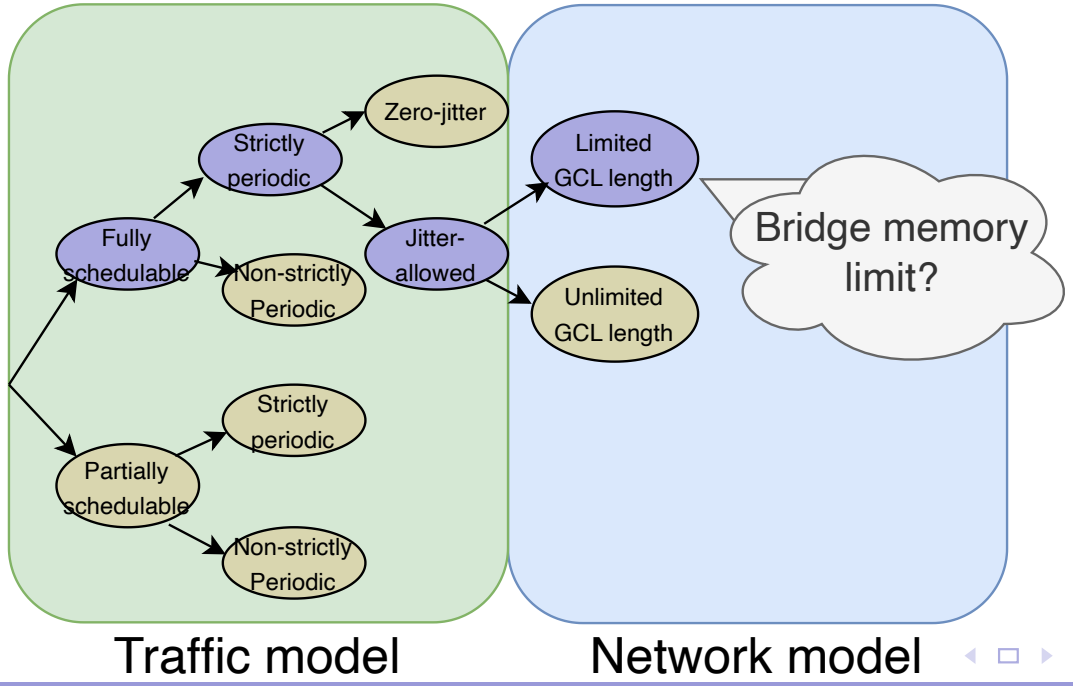

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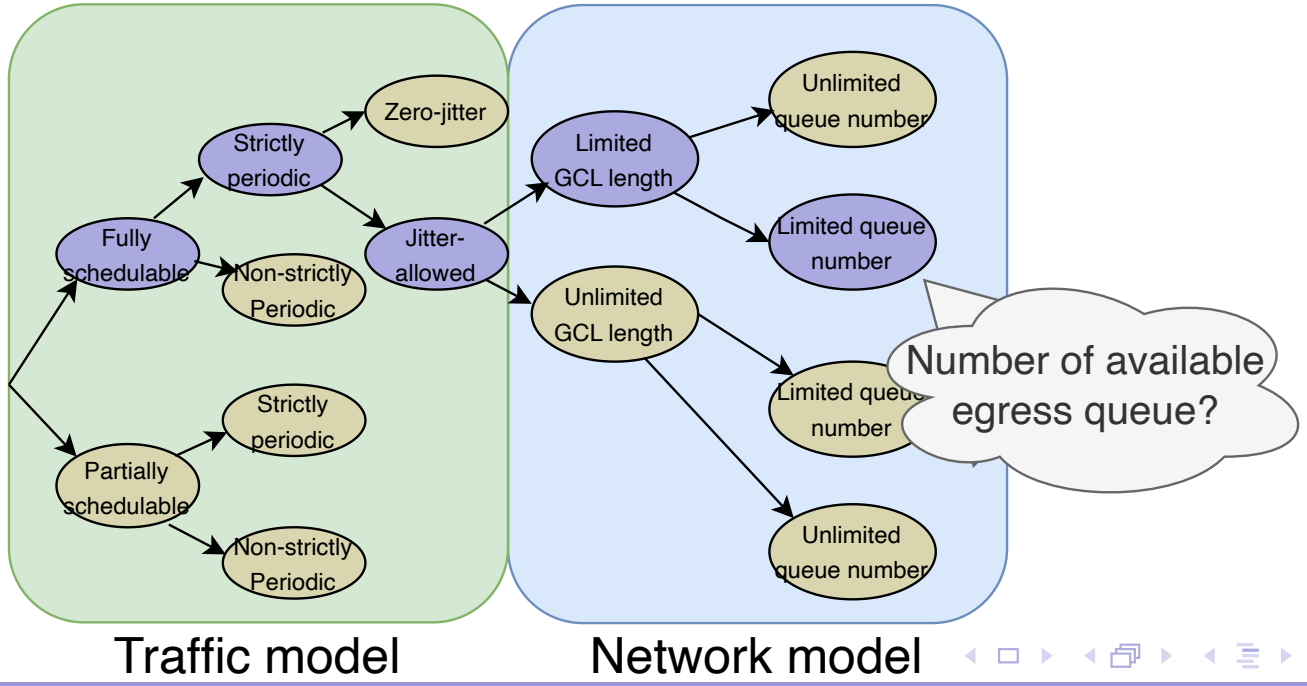

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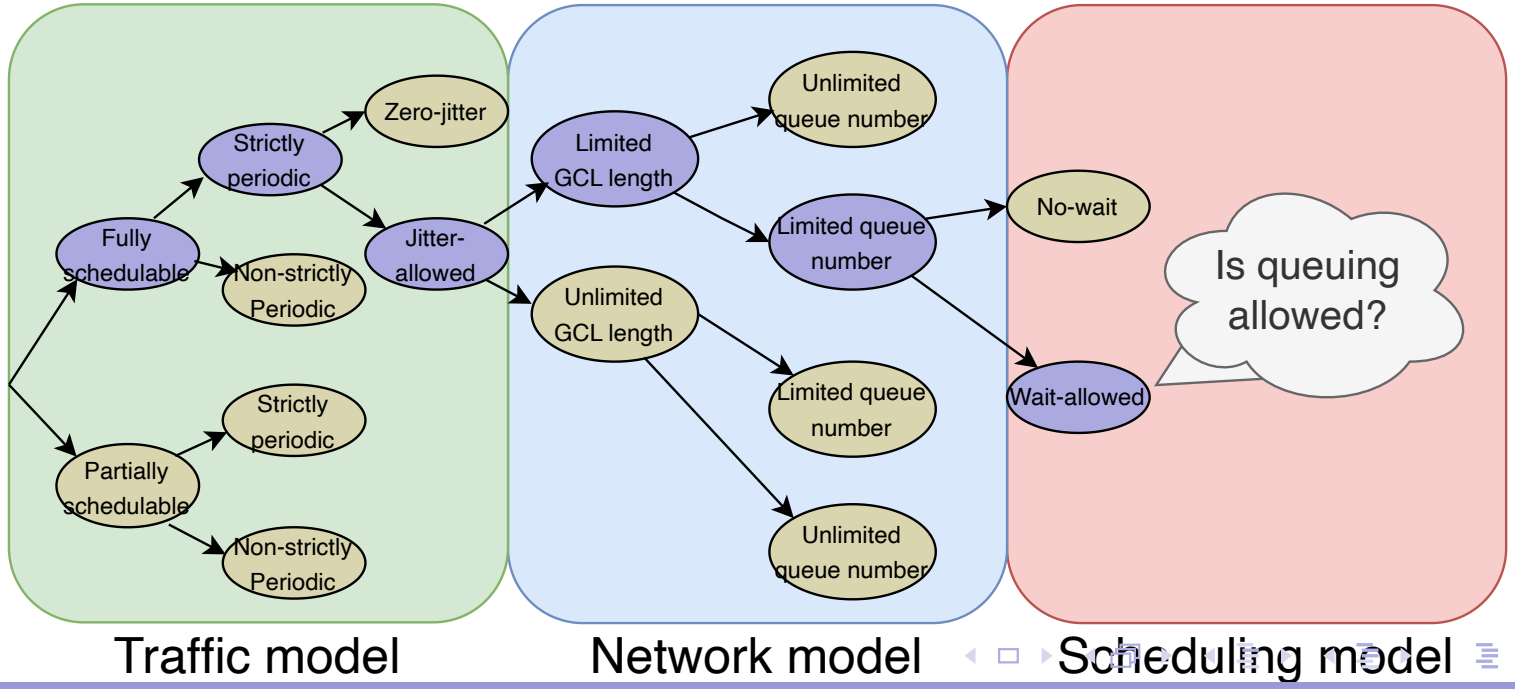

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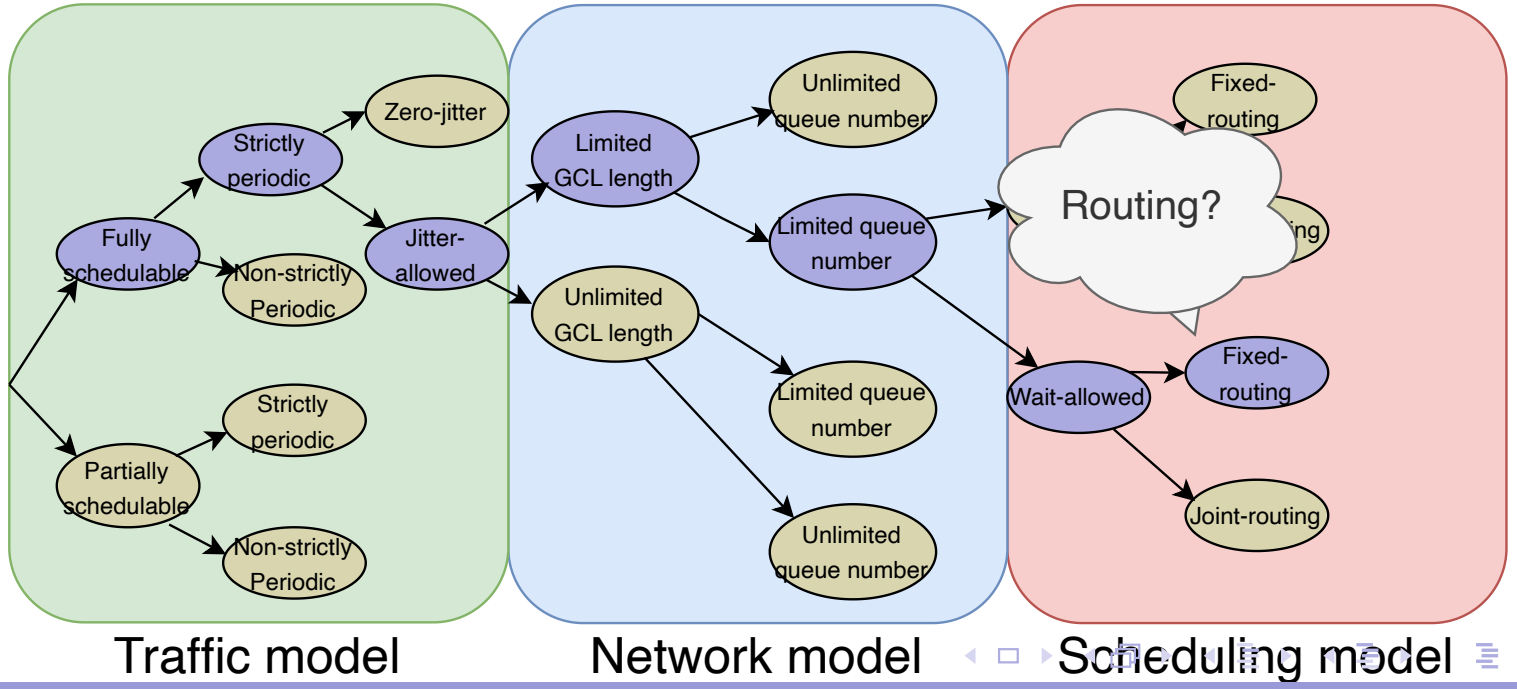

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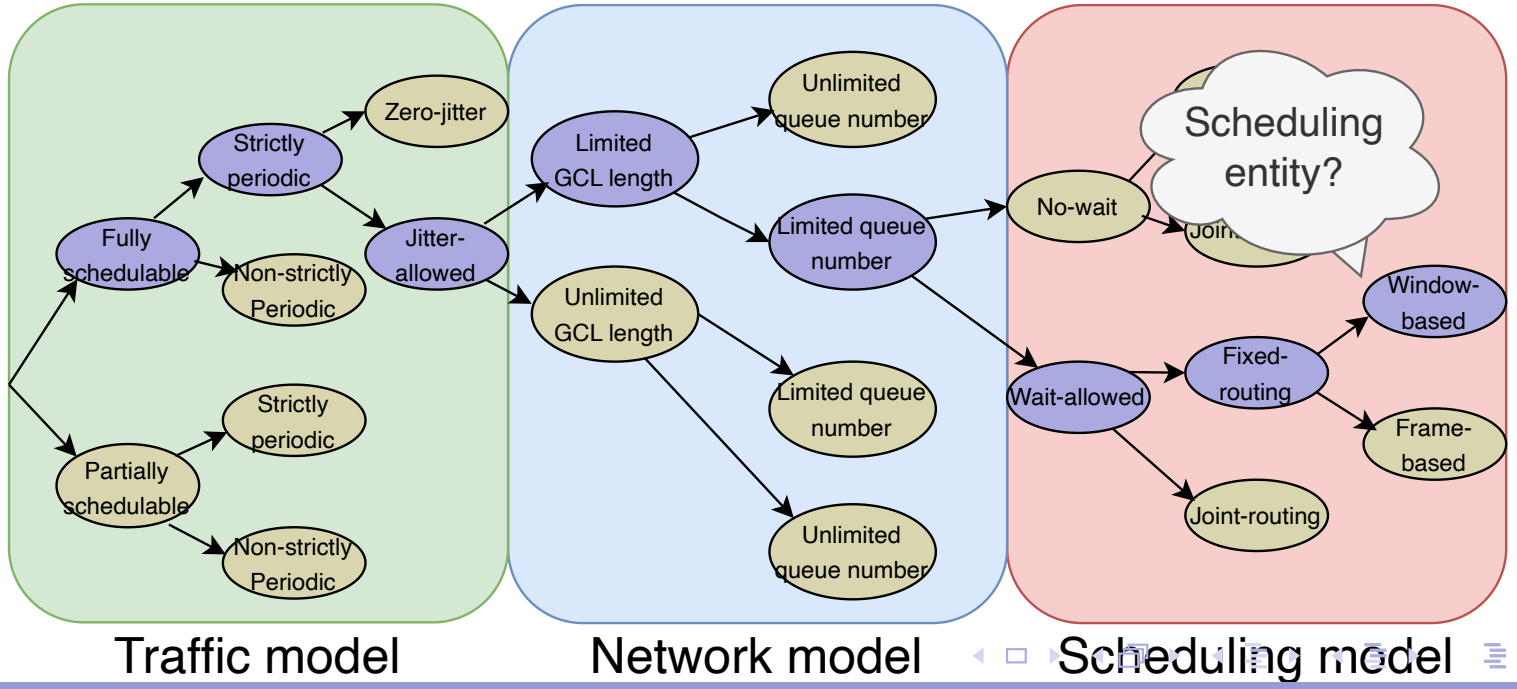

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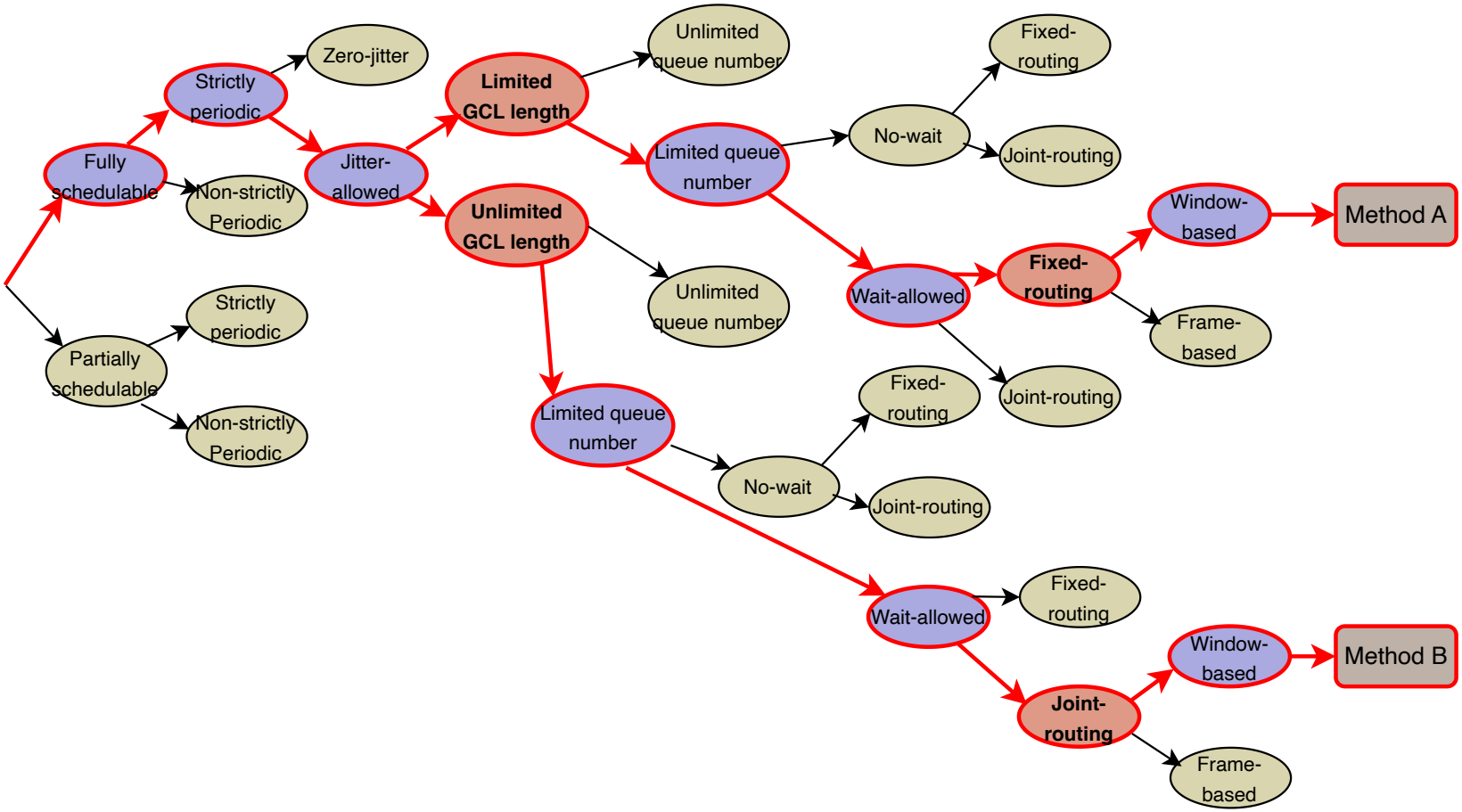

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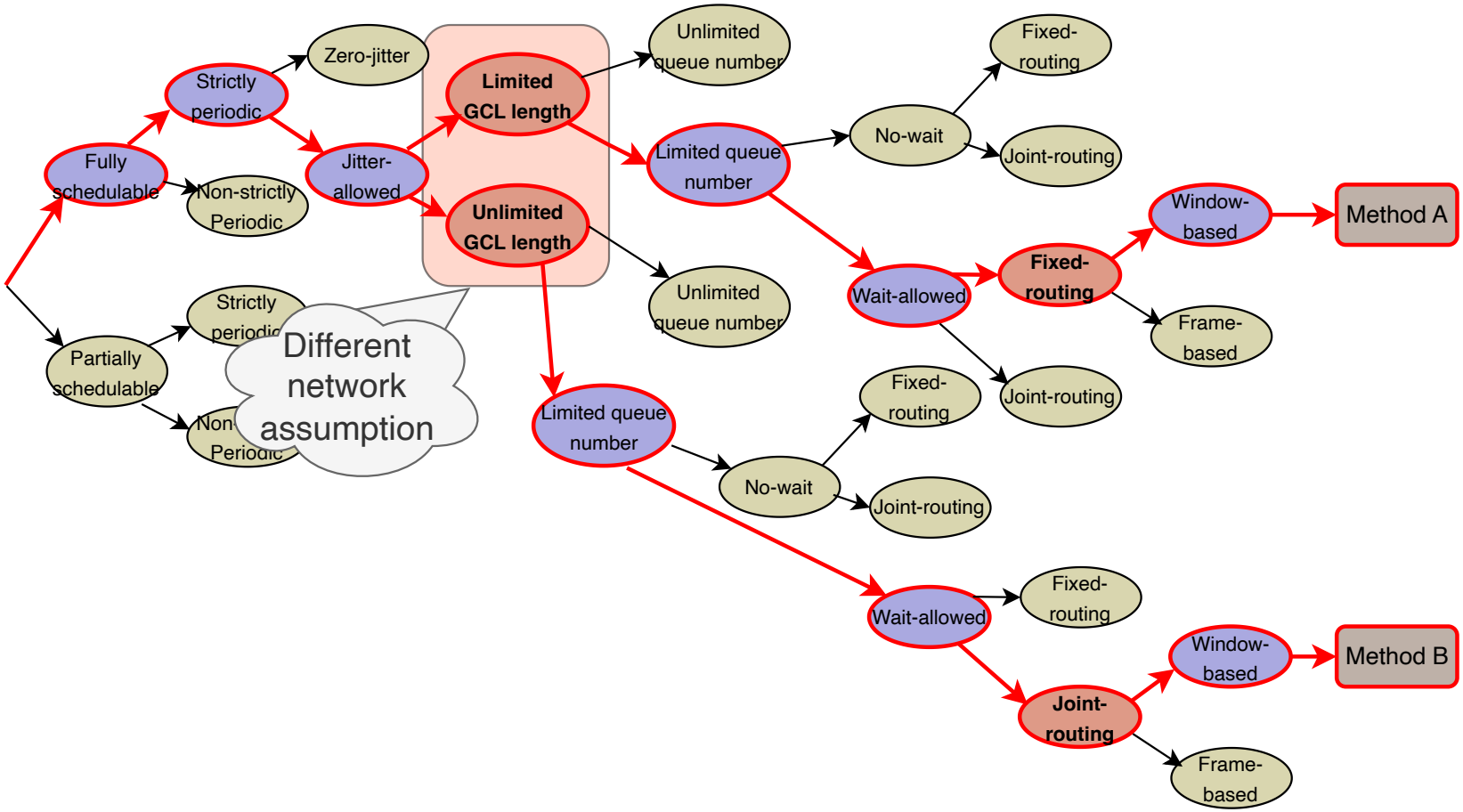

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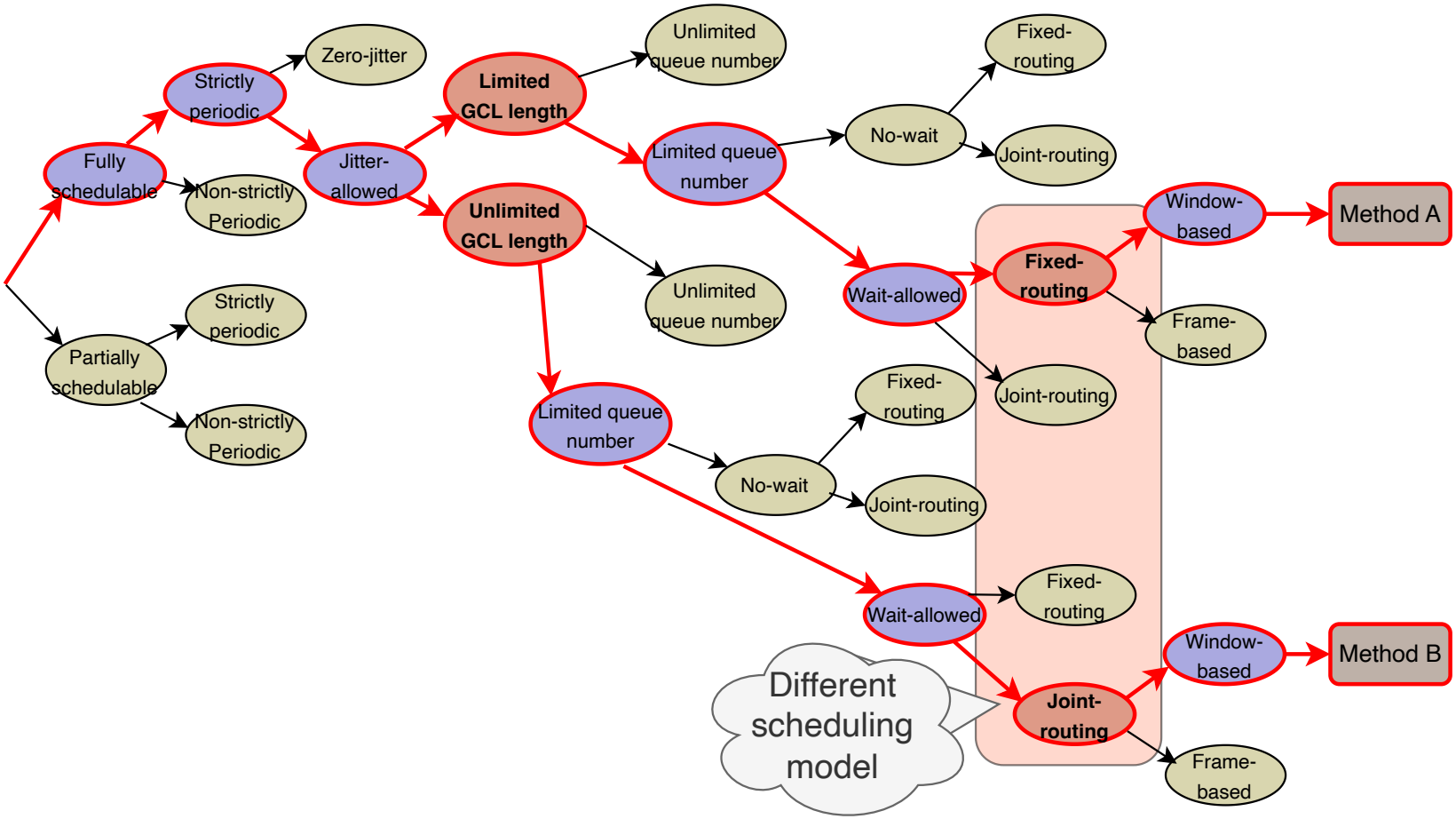

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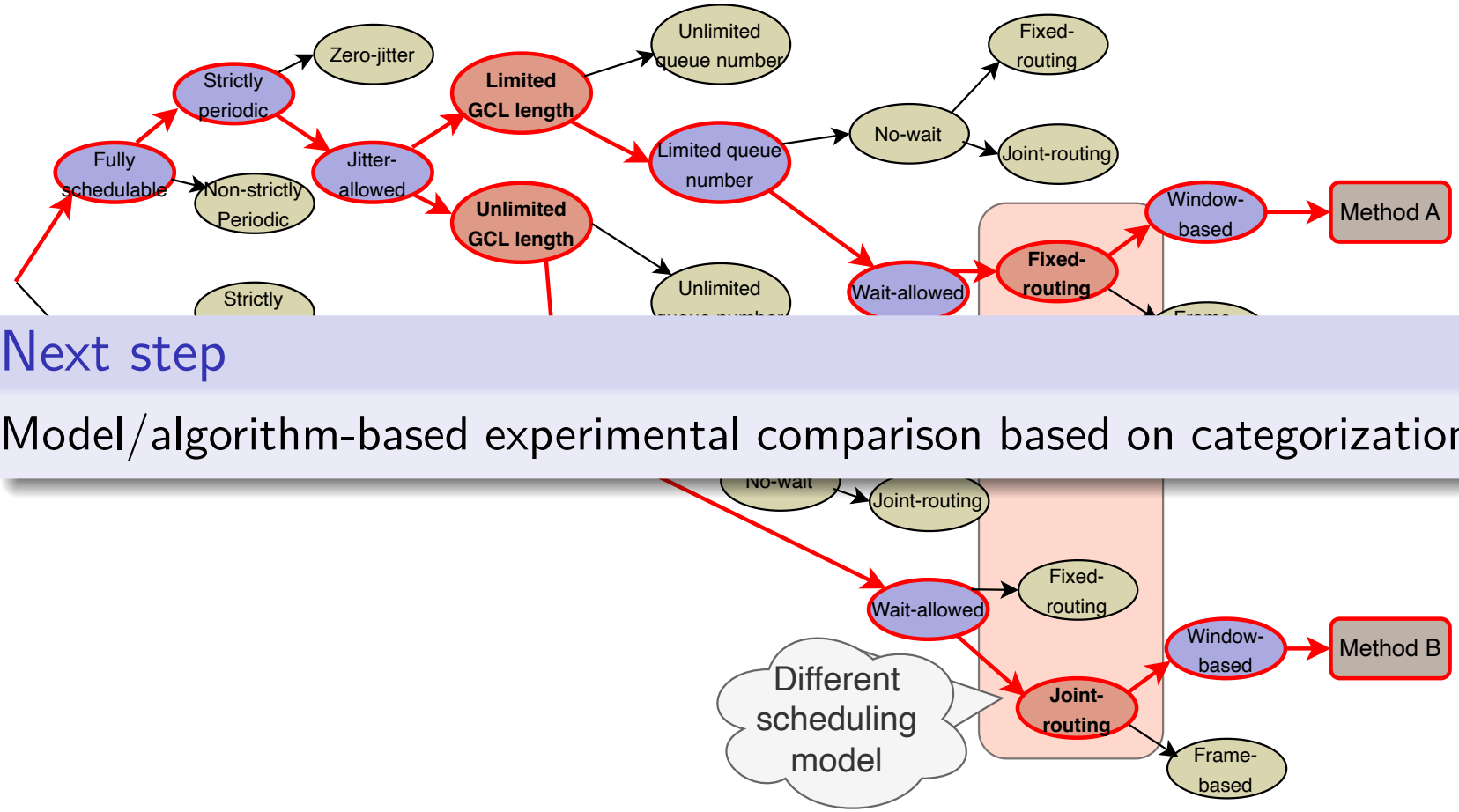


Next step

Model/algorithm-based experimental comparison based on categorization.

Quantitative Comparisons

Motivation: Standardized benchmarks have become widely accepted tools in multiple fields of computer science and beyond, e.g., CPU/GPU, database, and machine/deep learning.

- Industry: Use the right tool for the right scenario
- Researchers: Understand the current limitations and potential research directions

Challenge

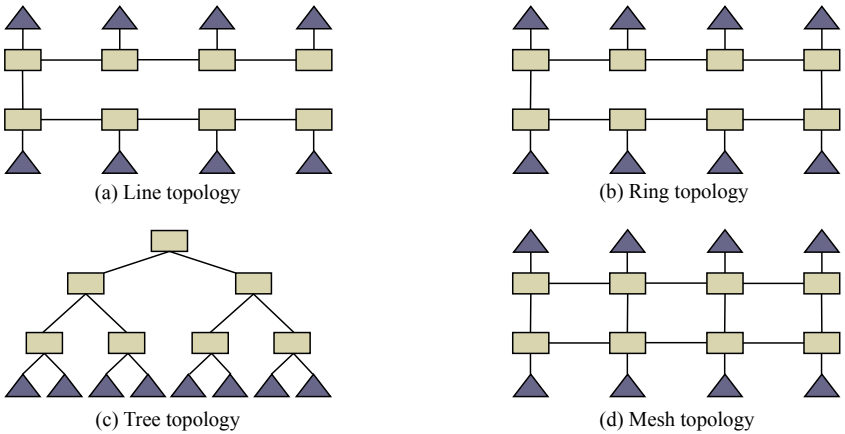
Design a high quality benchmark is a non-trivial task, it requires careful consideration of relevance, fairness, and reproducibility.

Relevance

Relevance: How closely the benchmark settings reflect the needs from the real-world application

- Include as board range of parameter settings as possible
- Reference to real-world scenario from standards or profiles, e.g., IEC/IEEE 60802, IEEE 802.1DP

	Parameter	Type	Value
Stream set	Number of streams	-	{10, 40, 70, . . . , 190, 220}
	Stream period (ms)	Sparse single	{2}
		Dense single	{0.4}
		Sparse harmonic	{0.5, 1, 2, 4}
		Dense harmonic	{0.1, 0.2, 0.4, 0.8}
		Sparse inharmonic	{0.25, 0.5, 1.25, 2.5, 4}
		Dense inharmonic	{0.05, 0.1, 0.25, 0.5, 0.8}
	Number of frames	-	{8, 16, 32, . . . , 2048, 4096}
	Stream payload (bytes)	Tiny size	50
		Small size	50 – 500
		Medium size	200 – 1500
		Large size	500 – 4500
		Extra size	1500 – 4500
	Stream deadline (ms)	Implicit deadline	Equal to period
		Relaxed deadline	NW + {0.1, 0.2, 0.4, 0.8, 1.6}
		Normal deadline	NW + {0.01, 0.025, 0.05, 0.1, 0.2, 0.4}
		Strict deadline	NW + {0, 0.01, 0.02, 0.025, 0.05}
		No-wait deadline	NW
Network	Topology	Linear, Ring, Tree, Mesh	
	Number of bridges	-	{8, 18, 28, . . . , 78}
	Number of links	-	{30, 32, 36, . . . , 386}
	Number of queues	-	{8}



Total 38,400 problem instances = traffic settings × network settings

Fairness

Timeout limit (2 hours): A common practice in experiment due to the NP-complete nature of TSN scheduling problem.

- Schedulable, unschedulable, unknown

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Debias: Use two evaluation metrics for schedulability

- Metric 1: Scheduleable ratio (SR). Assume unknown results as unschedulable
  - Unfairness: Small timeout value $\rightarrow$ many unknown of methods require to run long time $\rightarrow$ low schedulability ratio

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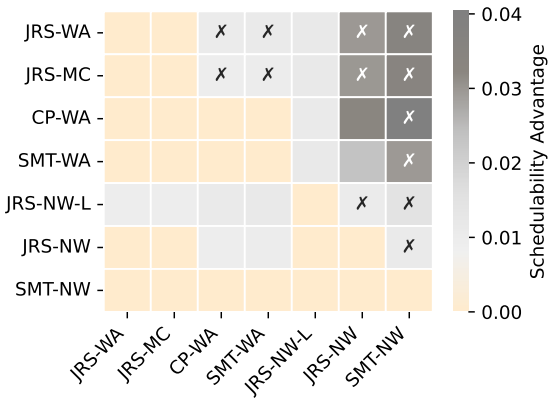
  - Unfairness: Small timeout value $\rightarrow$ many unknown of methods require to run long time $\rightarrow$ low schedulability ratio
- Metric 2: Schedulability advantage (SA). Novel pairwise performance metric without considering unknown
  - $\Phi(A, B)$: The number of instances that A is schedulable but B is unschedulable
  - $\Phi(A, B) > \Phi(B, A) = 0$: Method A dominates method B

Model-based Experimental Study

Finding 1: Complex models may improve SA but be counterproductive on SR.

Example: Joint-routing vs. Fixed routing model (with both no-wait and wait-allowed models)



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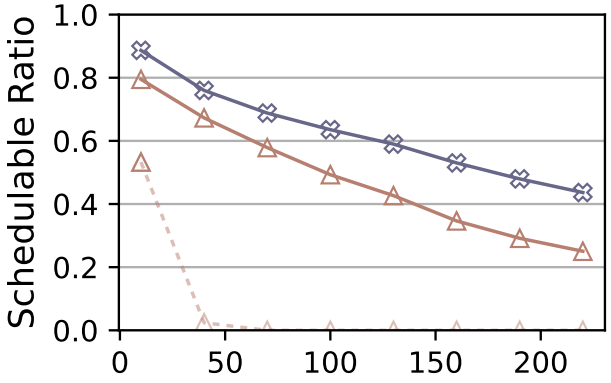

SR under no-wait model
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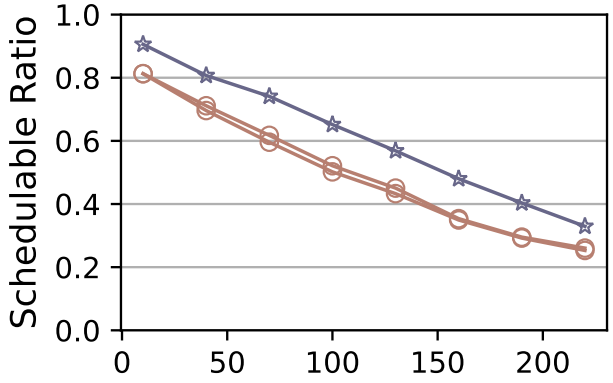

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Other inconsistent SR and SA: No-wait vs. wait-allowed, FRAG/PRE vs. non-FRAG/non-PRE

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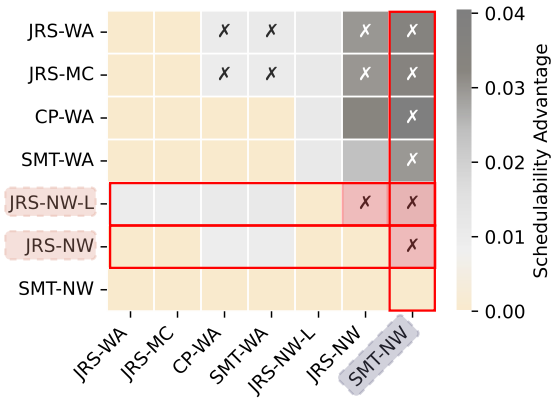

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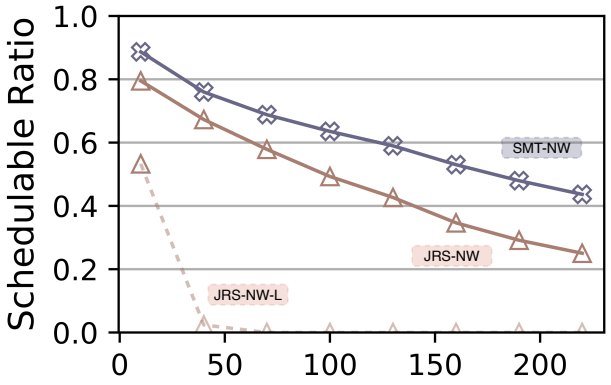

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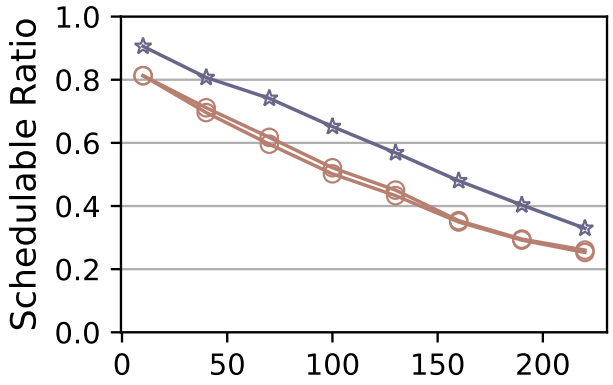

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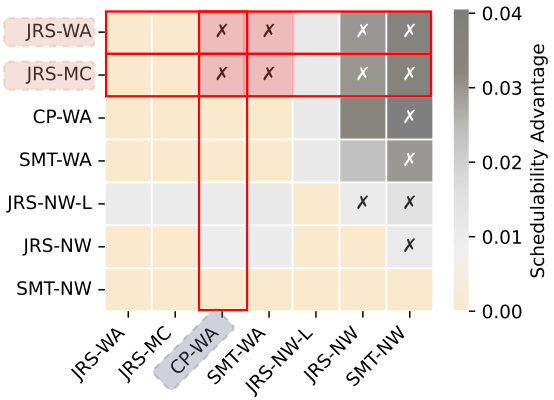

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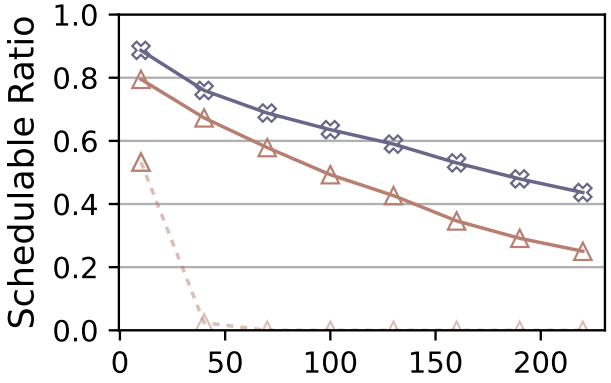

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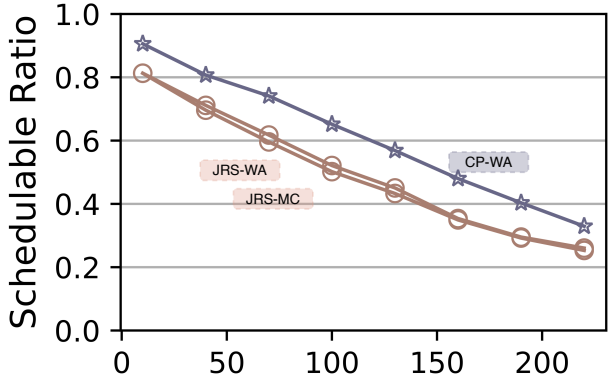

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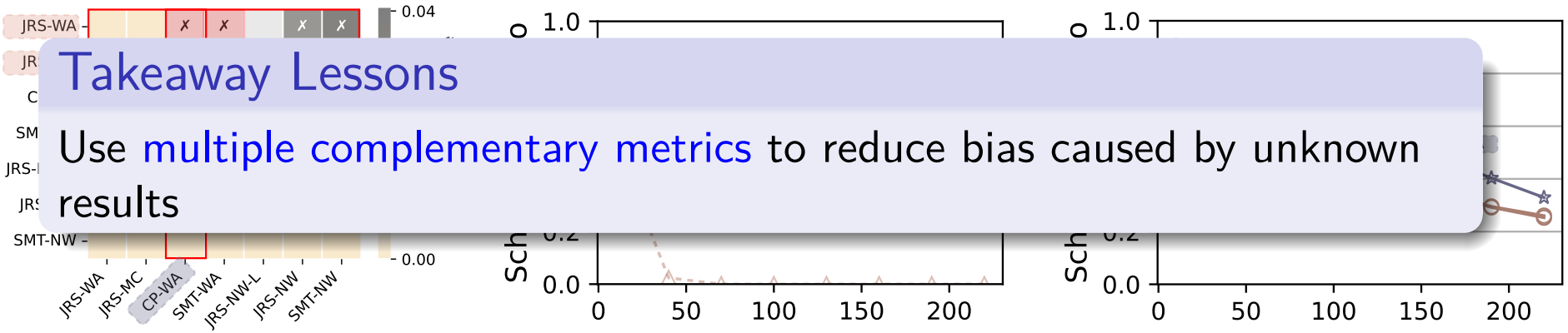

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Takeaway Lessons

Use multiple complementary metrics to reduce bias caused by unknown results

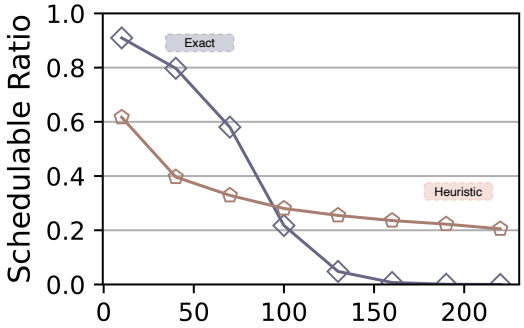
Other inconsistent SR and SA: No-wait vs. wait-allowed, FRAG/PRE vs. non-FRAG/non-PRE

Algorithm-based Experimental Study

Finding 2: Schedulability varies under different settings, even using the same evaluation metric.

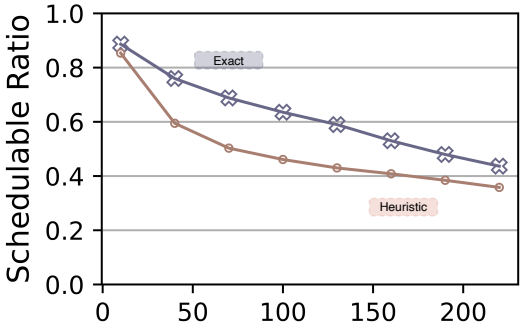
- Heuristic performs similar/better than exact algorithm in large-scale

FR and wait-allowed



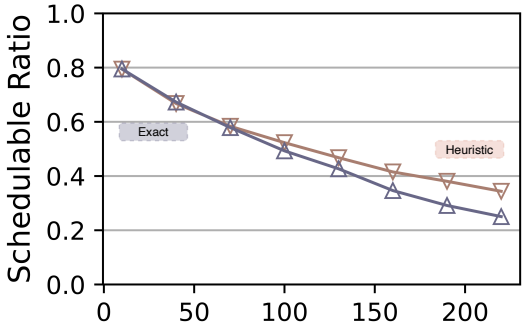
SMT-WA vs. LS-TB

FR and no-wait



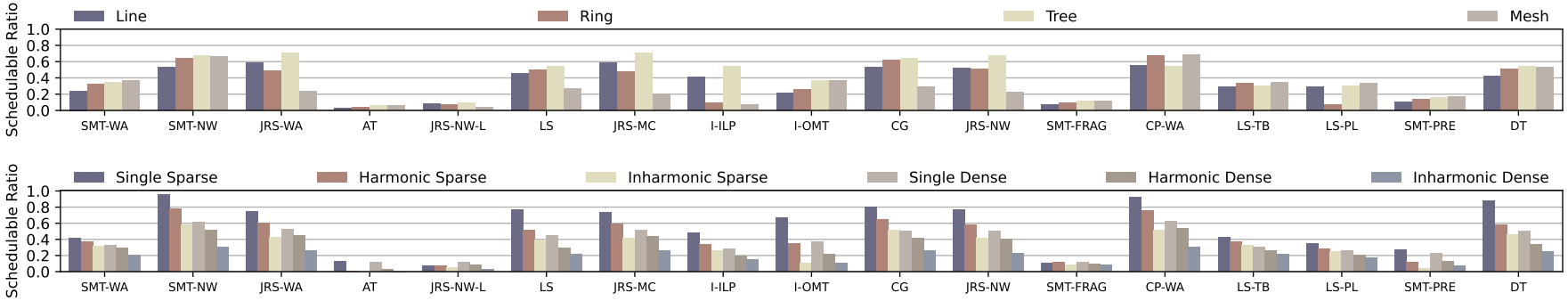
SMT-NW vs. DT

JRS and no-wait



JRS-NW vs. CG

- Some heuristic methods suffer under certain settings



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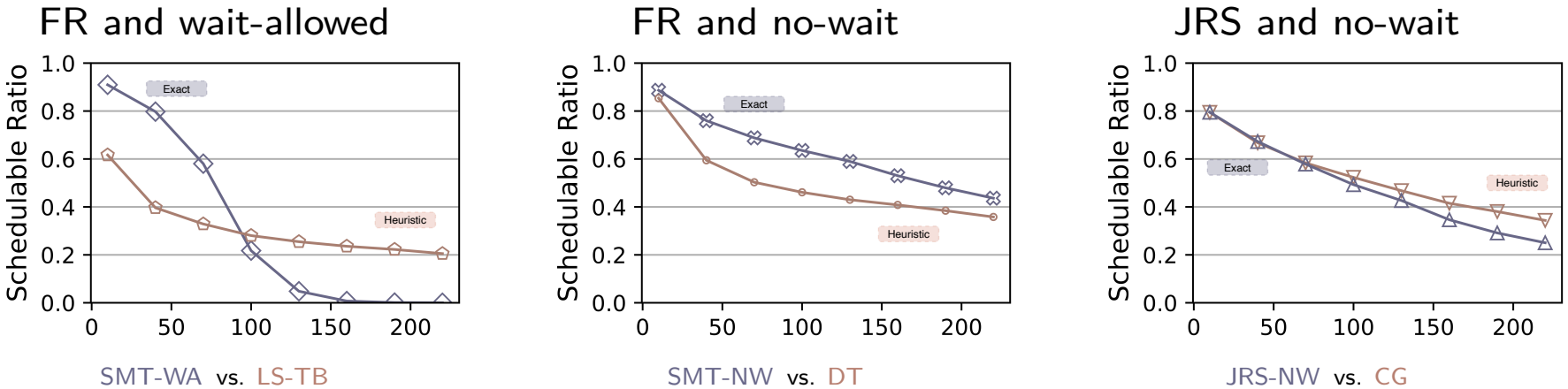

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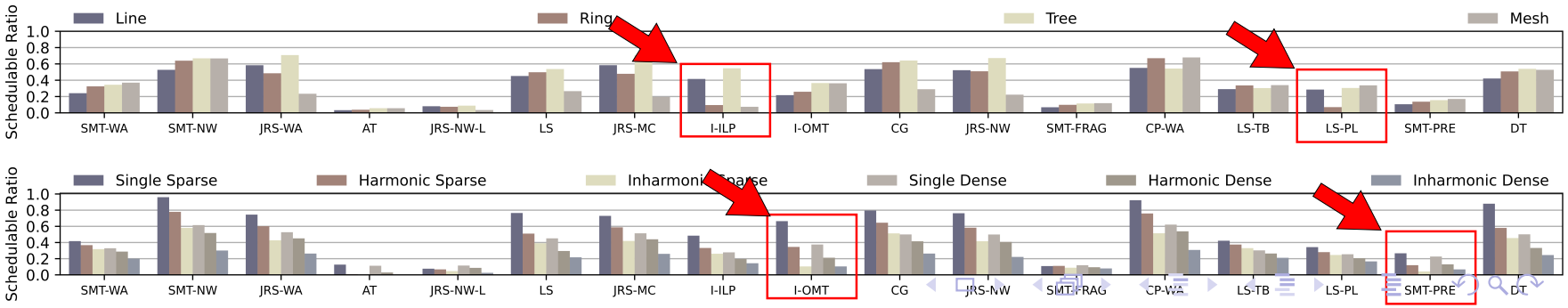

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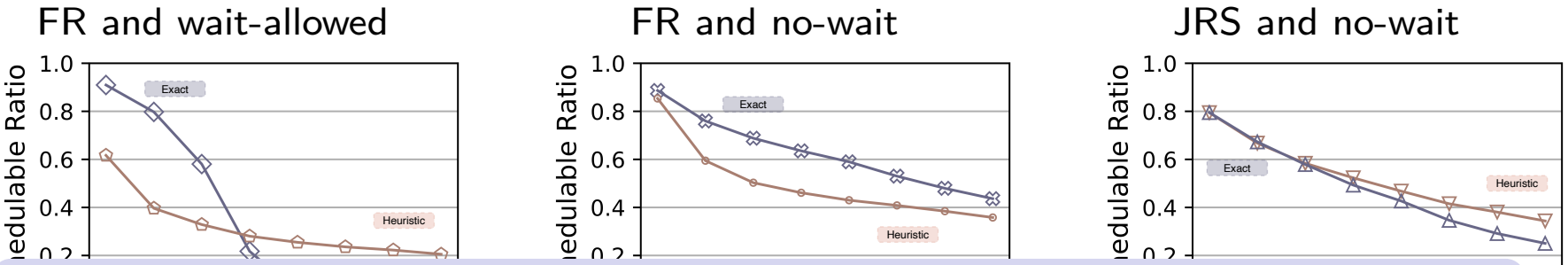
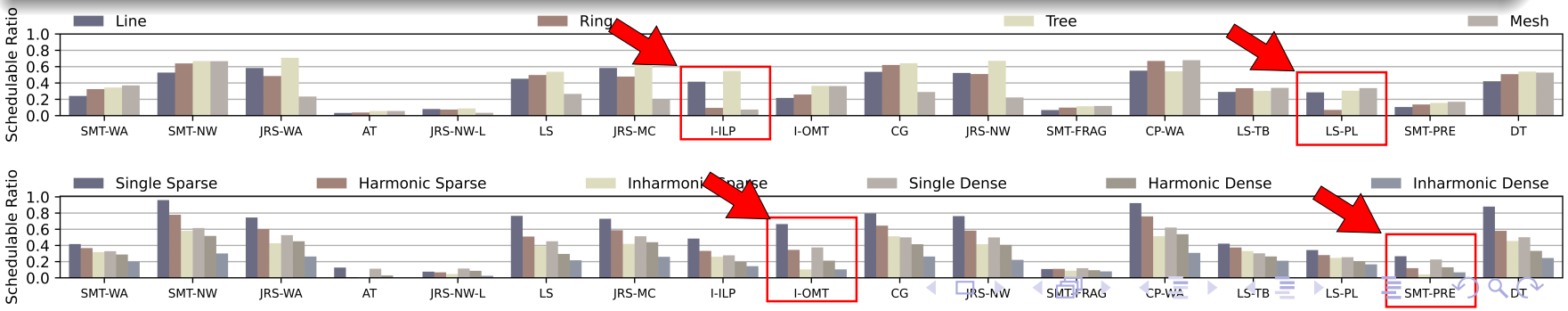


Takeaway Lessons

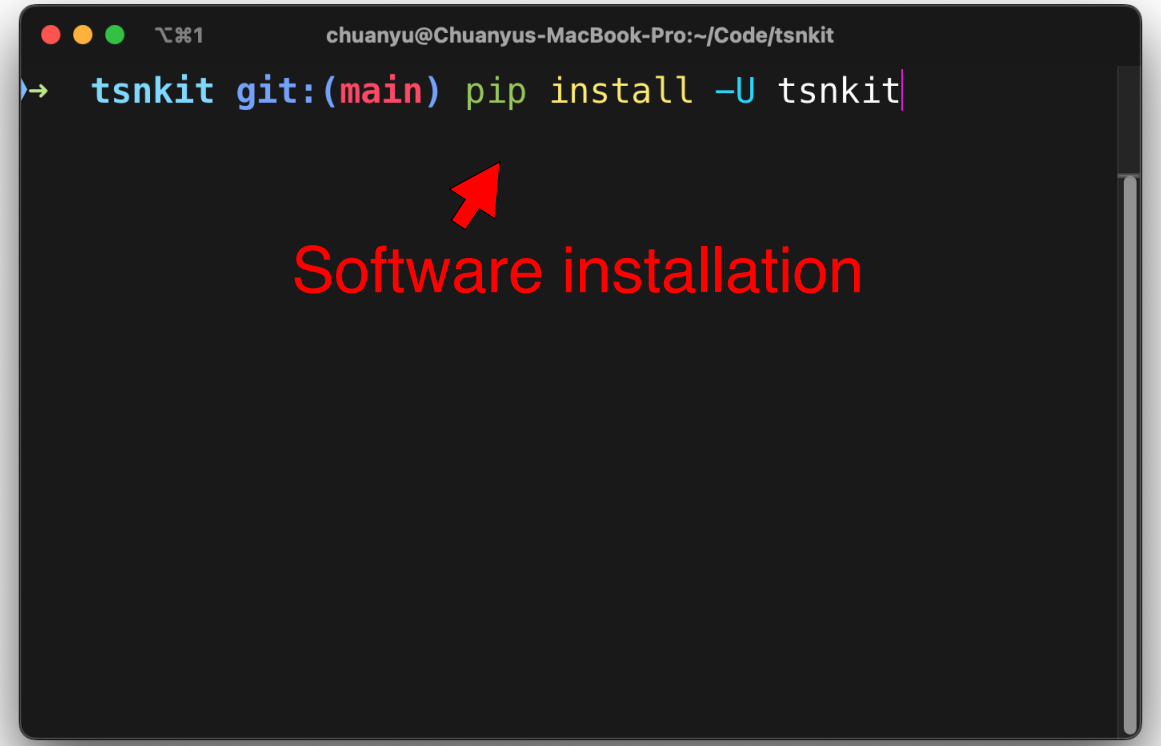
Use a wide range of experimental settings to fairly evaluate the strengths and limitations of different methods



Reproducibility

An open-source toolkit is available for the community

- Available at: `github.com/ChuanyuXue/tsnkit`
  - 32 Stars, 9 Forks, 6 issues closed
- Easy to install and use for future research



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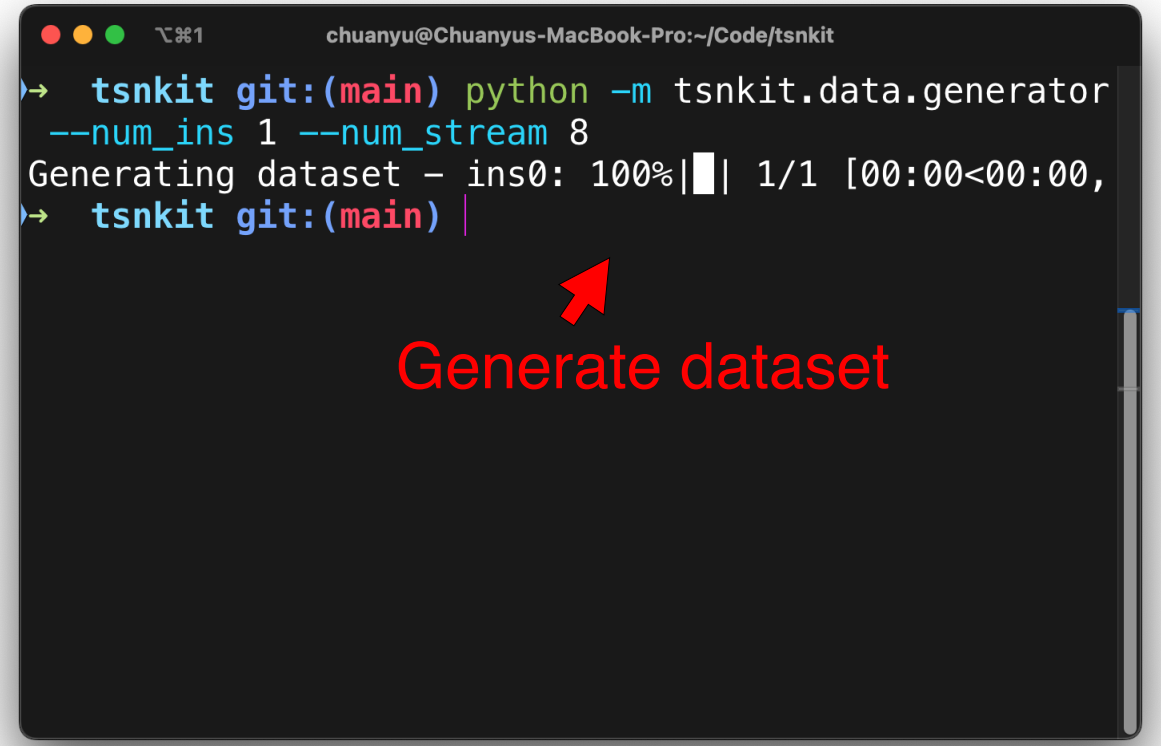

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```
chuanyu@Chuanyus-MacBook-Pro:~/Code/tsnkit
➜  tsnkit git:(main) python -m tsnkit.data.generator
 --num_ins 1 --num_stream 8
Generating dataset - ins0: 100%|▉| 1/1 [00:00<00:00,
➜  tsnkit git:(main) cat dataset_logs.csv
id,size,period,deadline,topo,num_stream,num_sw
1,2,1,1,0,8,8
➜  tsnkit git:(main) python -m tsnkit.models.ls 1_ta
sk.csv 1_topo.csv
| time          | name          | flag    | solve_tim
e | total_time | total_mem
| 06~22:14:56   | -             | succ    | 0.004
  | 1.058      | 86400.0
➜  tsnkit git:(main)
```

Calculate schedule

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```
chuanyu@Chuanyus-MacBook-Pro:~/Code/tsnkit
→  tsnkit git:(main) python -m tsnkit.simulation.tas
 ./1_task.csv ./
  0%|                    | 0/200000 [00:00<?, ?it/s]
[Bridge (10, 2)]:   Flow 0 - Trans at 0
[Bridge (11, 3)]:   Flow 6 - Trans at 0
[Bridge (12, 4)]:   Flow 7 - Trans at 0
[Bridge (15, 7)]:   Flow 3 - Trans at 0
[Bridge (9, 1)]:    Flow 5 - Trans at 0
[Talker 10]:        Flow 0 - Send at 2800
[Bridge (2, 1)]:    Flow 0 - Arrive at 2800
[Bridge (2, 1)]:    Flow 0 - Trans at 2800
[Talker 12]:        Flow 7 - Send at 3600
[Bridge (4, 3)]:    Flow 7 - Arrive at 3600
[Bridge (4, 3)]:    Flow 7 - Trans at 3600
[Talker 11]:        Flow 6 - Send at 4400
[Bridge (3, 4)]:    Flow 6 - Arrive at 4400
```

Run simulation

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Testbed Setup

Motivation: The correctness of scheduling methods/model has not been validated on real hardware.

- Calibrate model parameters (e.g., delays, synchronization error)
- Validate the correctness of each scheduling method

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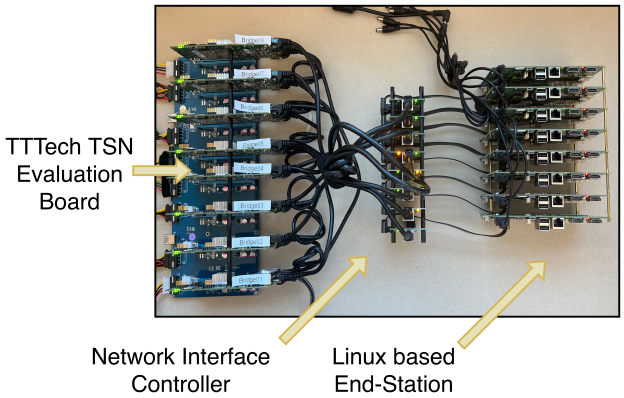
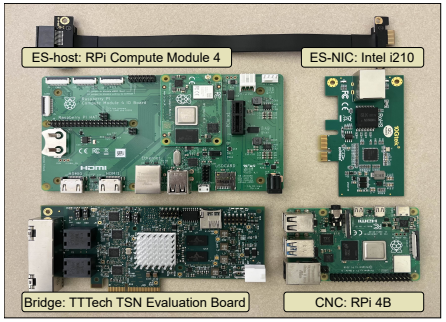
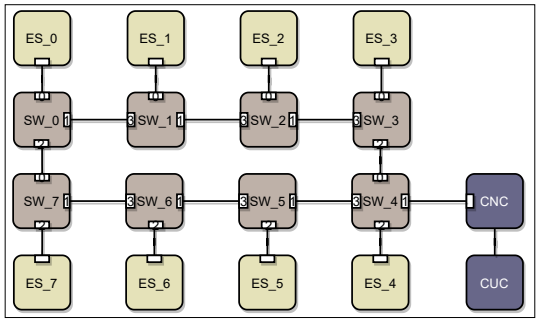
Components:

- 8 Bridges: FPGA hardware-based TTTech TSN evaluation board
- 8 End-stations: Intel i210 NIC + Linux Ethernet stack
- Connected into a ring topology







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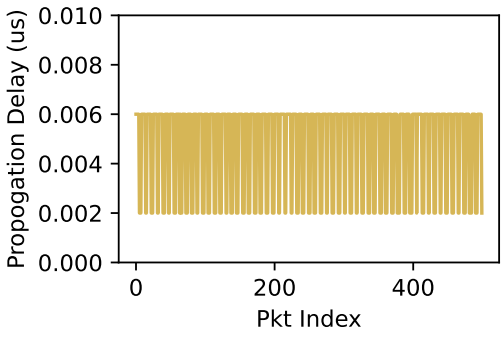
Motivation: Incorrect model assumptions may generate a feasible schedule but invalid on real hardware

Solution: Measurements of delays and synchronization error

- Propagation delay: $\leq$ 6 ns



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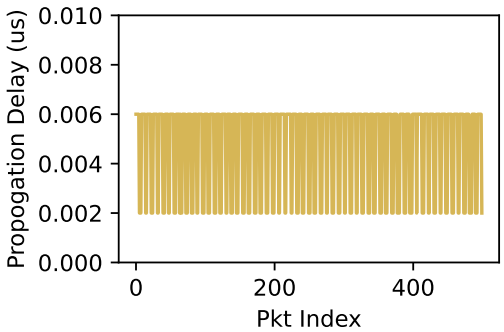
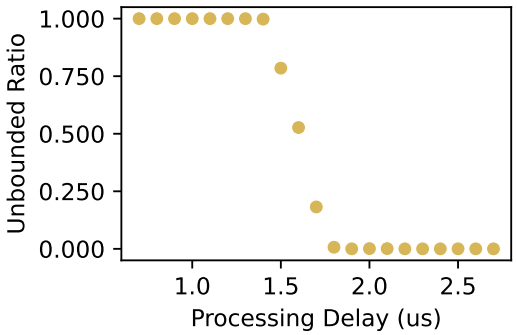
- Propagation delay: $\leq$ 6 ns
- Processing delay: $\leq$ 1.9 μs





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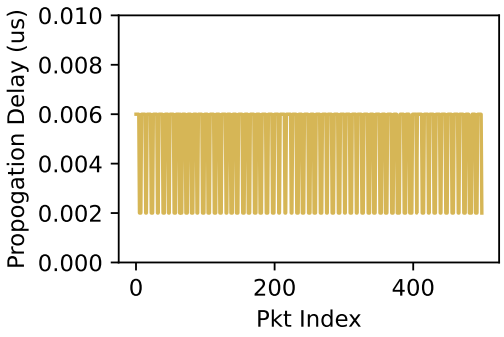
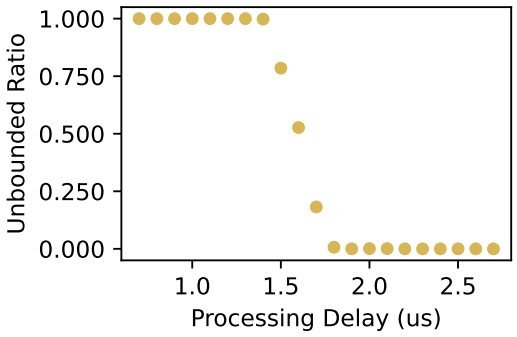
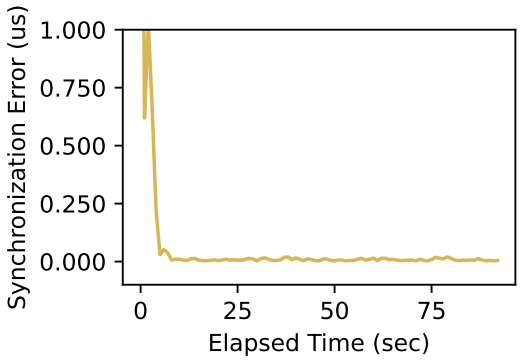
- Processing delay: $\leq$ 1.9 μs
- Synchronization error: $\leq$ 10 ns (after 5 secs)



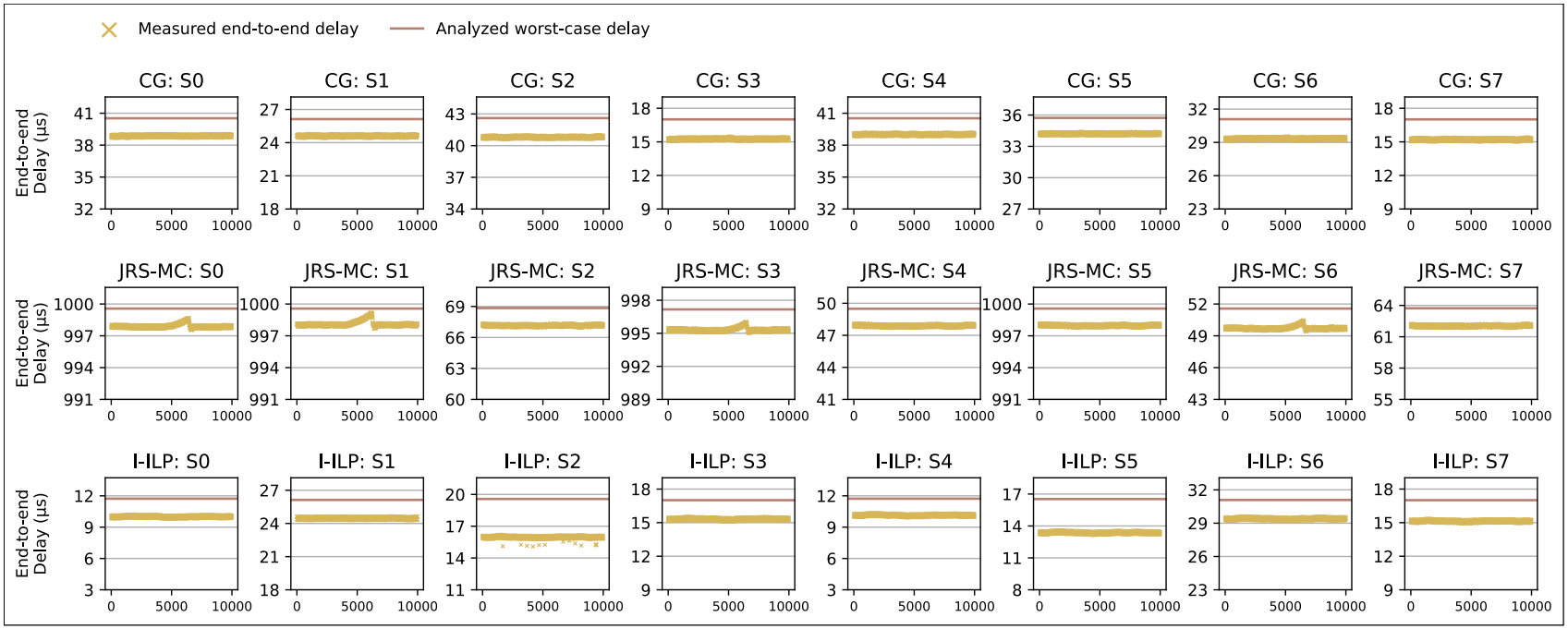




Testbed Validation

Performance validation of scheduling methods.

- Measured end-to-end delay vs. calculated worst-case delay
- Delay for reproduced methods are validated
- Jitter is observed due to collision between sync and TT traffic



Conclusion and Future work

Conclusion:

- Systematically categorization of TAS-based real-time scheduling models
- Quantitatively comparisons among 17 representative TAS-based real-time scheduling methods in TSN
- Real-world testbed for the performance validation of existing scheduling model and methods

Future Work:

- Incorporating fault tolerance scenarios and various traffic shapers
- More comprehensive empirical experiments on real-world testbed
- Encourage the community to utilize our open-source toolkit

Thank you

Q & A

Evaluation Metrics

Two evaluation scenarios:

- Scenario 1: Scheduleable ratio (SR). Assume unknown results as unschedulable
  - The ratio of schedulable instances to the total instances.
  - Example: $\mathrm{SR(A)} = 0.25 < \mathrm{SR(B)} = 0.5$
- Scenario 2: Schedulability advantage (SA). Pairwise performance comparison without considering unknown
  - $\Phi(A, B)$: The number of instances that A is schedulable but B is unschedulable.
  - $\Phi(A, B) > \Phi(B, A) = 0$: Method A dominates method B.
  - Example: $\Phi(A, B) = 1 > \Phi(B, A) = 0$

	Instance 1	Instance 2	Instance 3	Instance 4
Method A	✓	?	✗	?
Method B	✗	✓	?	✓