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Challenges of Deadline-Aware Configurations for Hybrid TSN Networks

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Real-time performance of TSN networks

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- A key issue of focus
- Correctness in real-time communications
  - Task functional logic
  - Latency within defined upper bounds

Human Perception of Danger

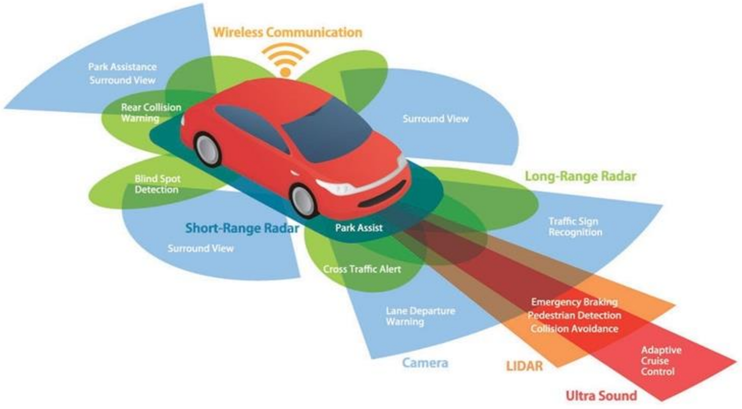
Brain Decision to Brake

Action Transmission to Brake

Manual Control ⇩ **Automatic Control**

Reaction Time ⇩ **Communication Deadline**

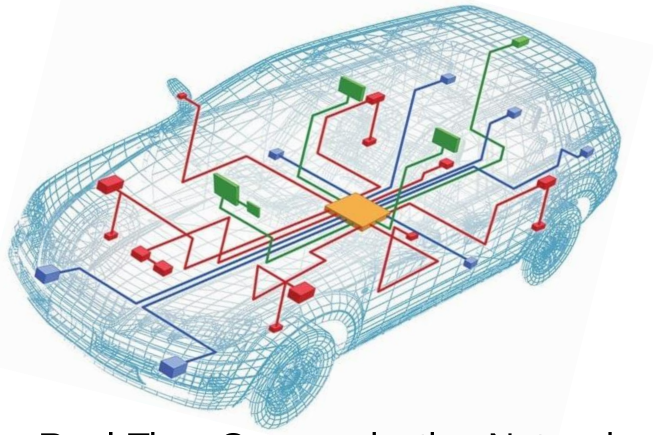
Functional logic correctness



Sensor Perception

System Decision-Making

Application deadline satisfaction



Real-Time Communication Network

Real-time performance of TSN networks

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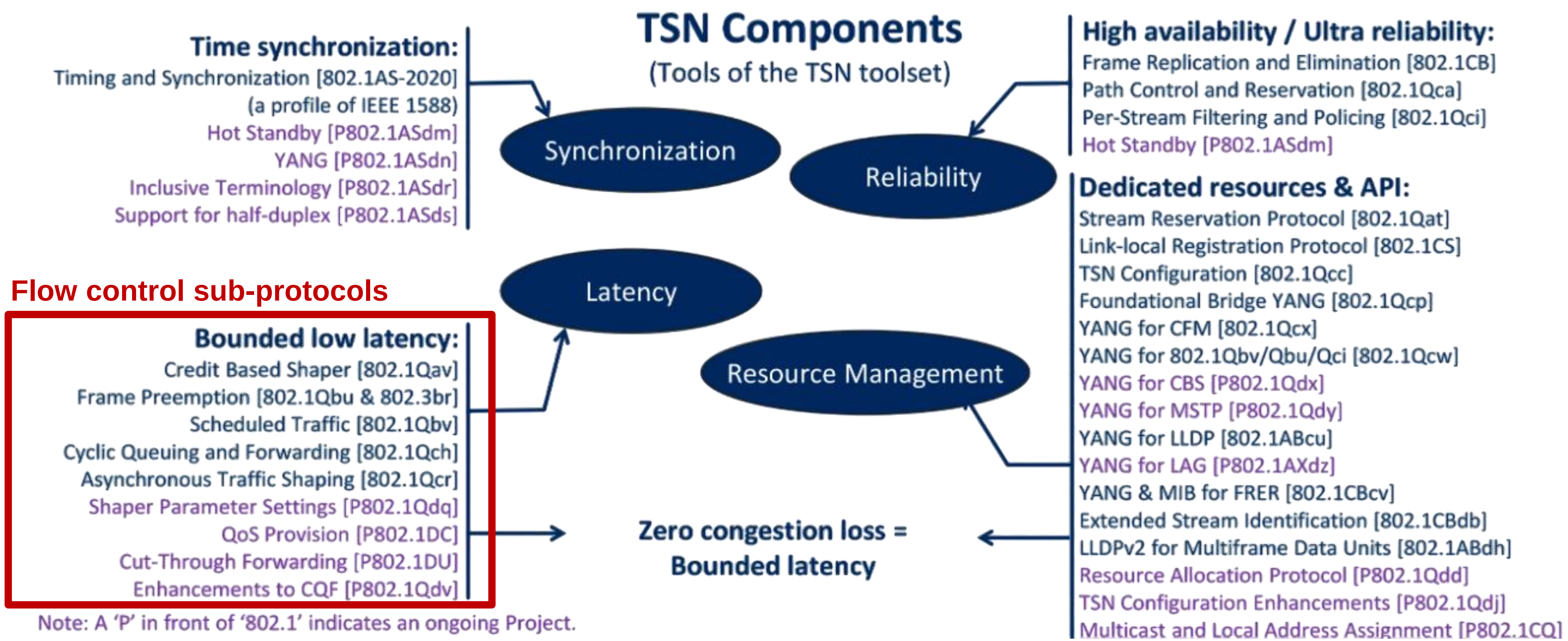
Does TSN Automatically Guarantee Real-Time Transmission? **NO**

- Flow control related sub-protocols
  - Provides a basic paradigm for network design
- Require algorithms and tools for achieving real-time communications



Real-time performance of TSN networks

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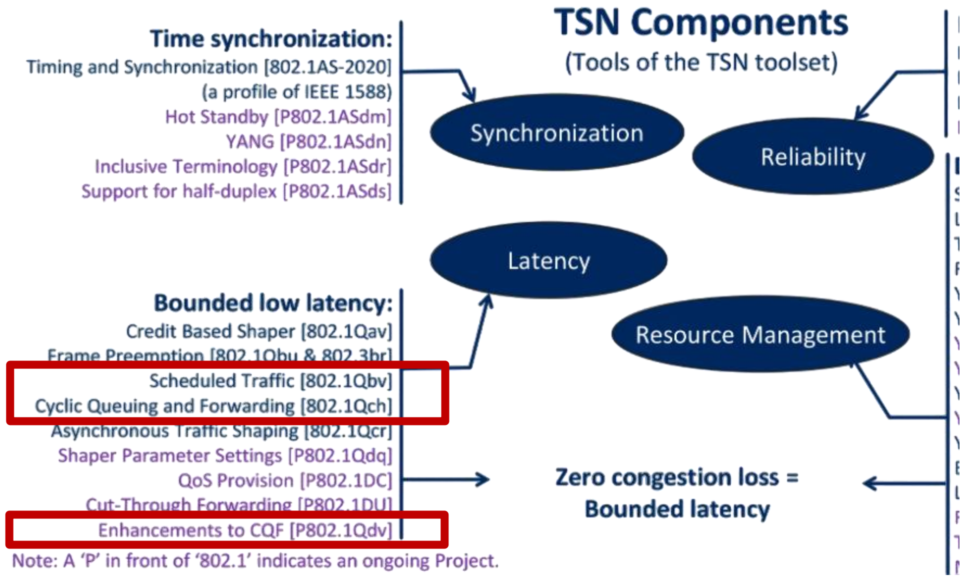
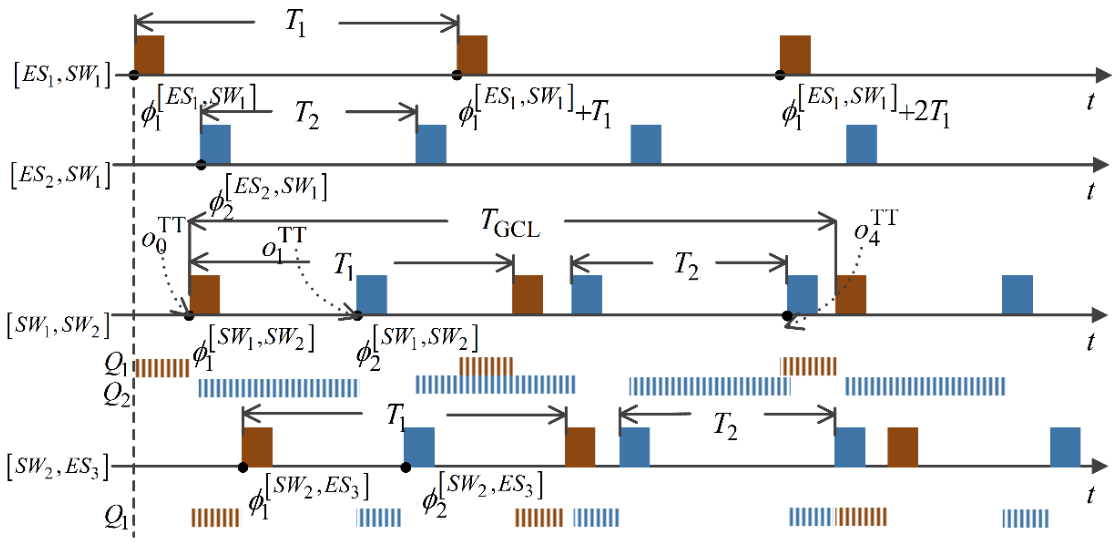
Real-time Guarantees for TIME-Triggered (TT) Communication

- Configuration goals: offsets, time slots, queue usage, etc.
- Configuration characteristic:
  - Real-Time Guarantees: at scheduling phase
  - Scope: periodic traffic flows
  - Algorithm Complexity: high
  - Global Clock Synchronization: yes

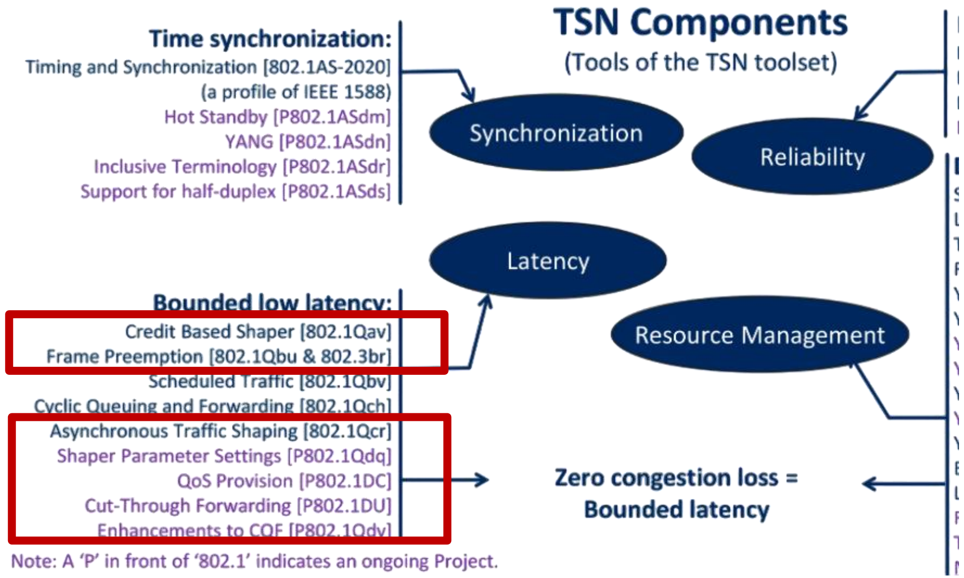


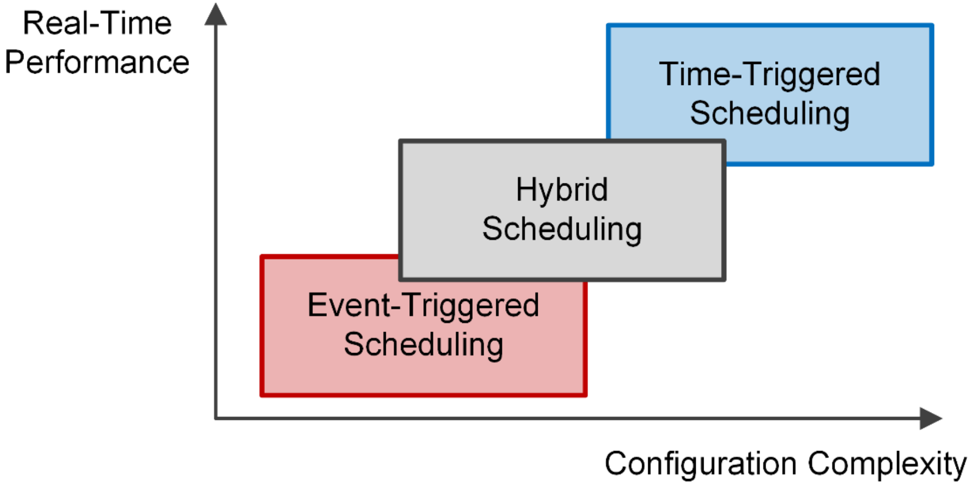


Real-time performance of TSN networks

Real-Time Guarantees for EVENT-Triggered (ET) Communication

- Configuration characteristic:
  - Real-Time Guarantees: dedicated performance analysis
  - Scope: periodic/sporadic traffic flows
  - Algorithm Complexity: low
  - Global Clock Synchronization: no





Challenges of deadline-aware configuration in TSN

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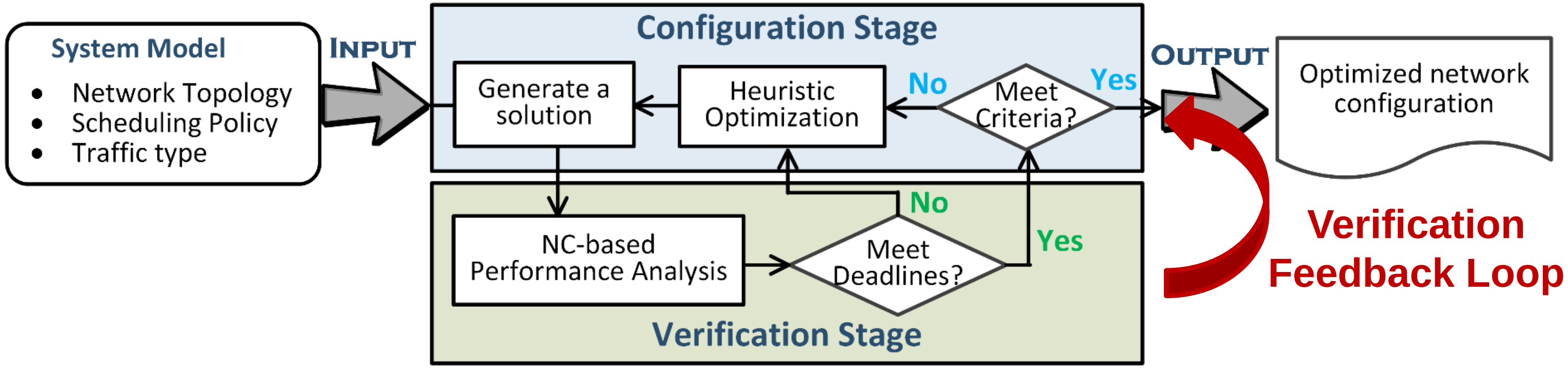
- Performance analysis methods:
  - event-triggered sub-protocols, hybrid TT and ET communication
  - network calculus, response timing analysis, ….

Beyond Just Analyzing the Real-Time Performance of a Fully Configured System

- Design and configure a system to meet performance requirements

Traditional Configuration Framework -- Post-Schedulability Verification



(a) Conventional framework based on ex-post verification

Challenges of deadline-aware configuration in TSN

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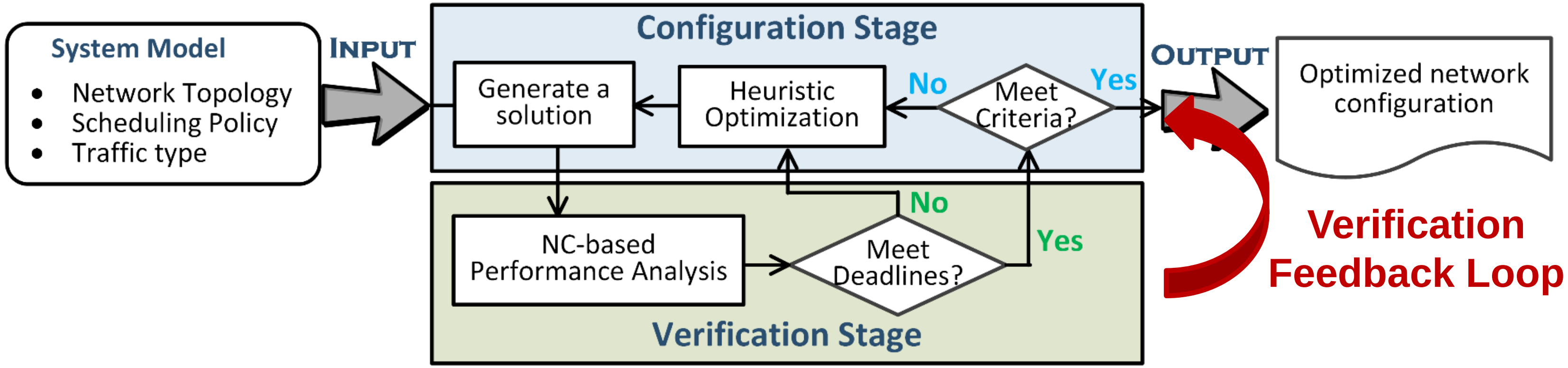
Traditional Configuration Framework -- Post-Schedulability Verification

- Verification stage:
  - Takes only a few seconds per configuration
- Configuration stage:
  - Repeated real-time verification with each configuration change
  - Consumes over 90% overall configuration time

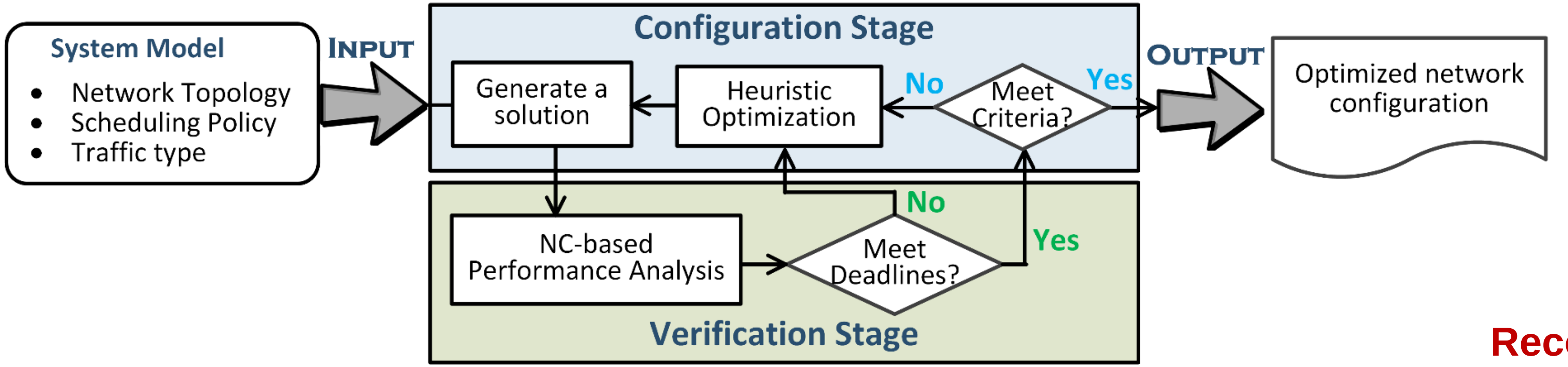


(a) Conventional framework based on ex-post verification

Challenges of deadline-aware configuration in TSN

What Comes Next? → Online Reconfiguration Scenario [1]

- Develop more efficient performance analysis framework to support network configuration
- Reduce verification overhead



(a) Conventional framework based on ex-post verification

Online Reconfiguration

[1] Boyer, M., and Henia, R. (2024). Industrial challenge: Embedded reconfiguration of TSN. *technical report*.

Insights from Two Perspectives

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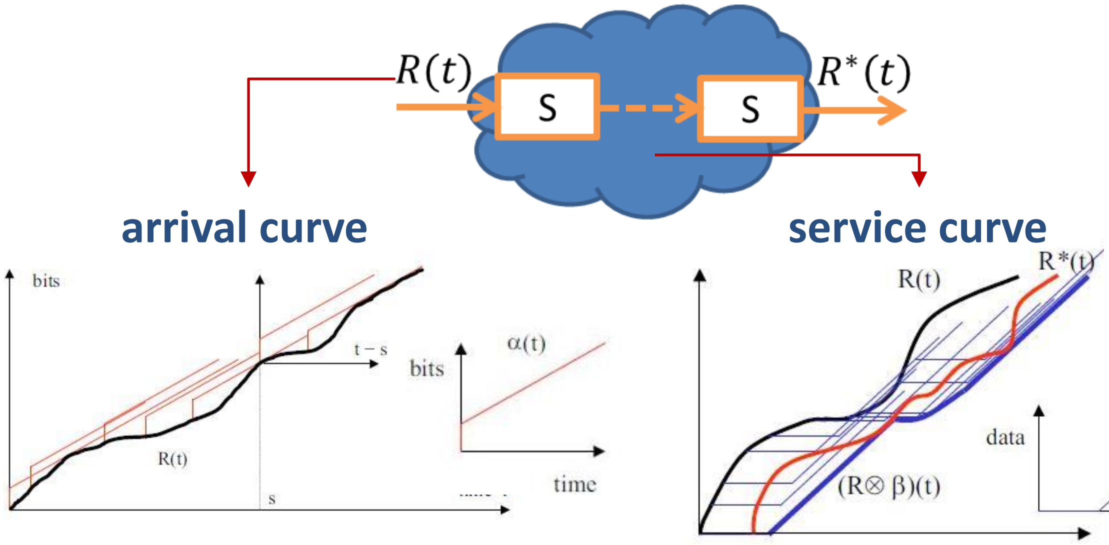
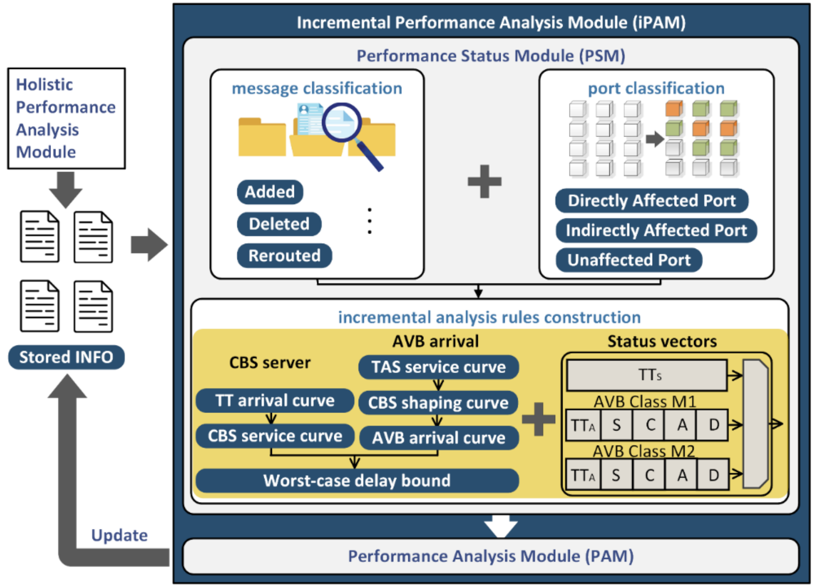
(1) Incremental Performance Analysis [2]

- Principal idea
  - Analyze only the changed portions of the network
  - Avoid full re-analysis of entire network traffic every time

Network Calculus Theory



Incremental Analysis Rules



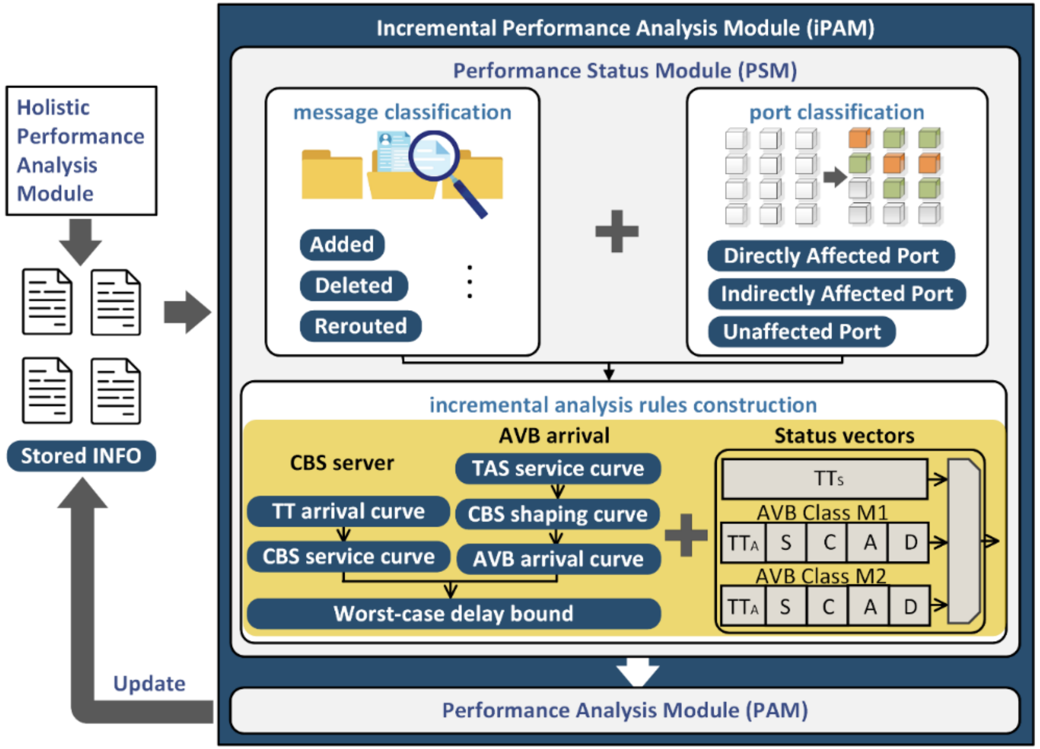
[2] Zhao, L., Zhang, X., He, F., et al. (2024). Incremental Performance Analysis for Accelerating Verification of TSN Network Reconfigurations. *IEEE Transactions on Network and Service Management*.

Incremental Performance Analysis [2]

Core Methods (TSN/TAS+CBS)

- Classify network node ports: directly affected, indirectly affected, unaffected
- Establish incremental rules to maximize reuse of existing analysis components
  - TT arrival curve
  - TAS service curve
  - AVB arrival curve
  - CBS service curve
  - CBS shaping curve
  - Delay bounds

Network Calculus Performance Model for TSN/TAS+CBS

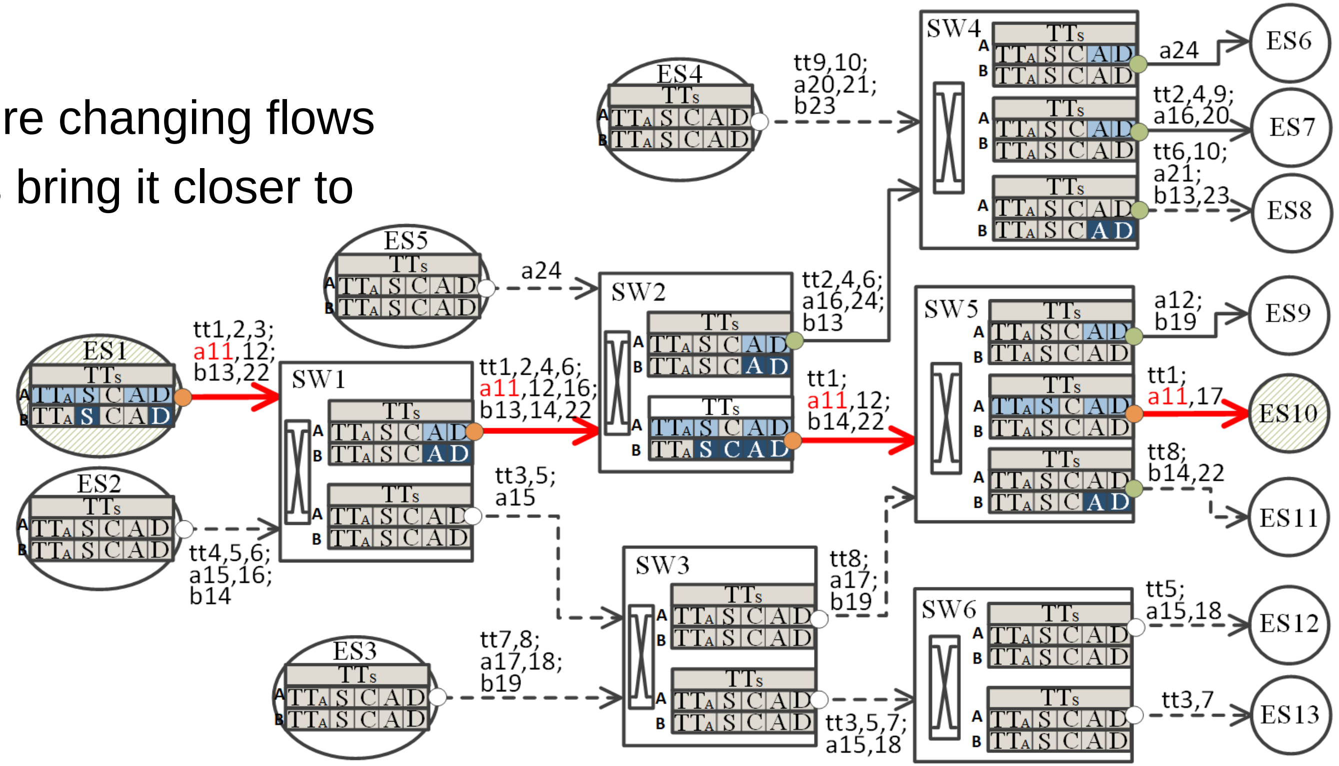


[2] Zhao, L., Zhang, X., He, F., et al. (2024). Incremental Performance Analysis for Accelerating Verification of TSN Network Reconfigurations. *IEEE Transactions on Network and Service Management*.

Incremental Performance Analysis [2]

Comparison with Traditional Performance Analysis

- Speed Improvement
  - 75% to 95% faster (simultaneous changing flows within 10%)
  - More effective with large-scale networks
- Limitations
  - Analysis time increases with more changing flows
  - More concurrent changing flows bring it closer to traditional performance analysis



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Incremental Performance Analysis [2]

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Advantages

- Significant improvement when networks have small changes
- Just constructs incremental analysis rules on top of the traditional analysis model
- Easily extends to other TSN flow control sub-protocols

Disadvantages

- Complexity can approach traditional analysis when there are large network changes
- Still relies on the real-time verification feedback loop

[2] Zhao, L., Zhang, X., He, F., et al. (2024). Incremental Performance Analysis for Accelerating Verification of TSN Network Reconfigurations. *IEEE Transactions on Network and Service Management*.

Insights from Two Perspectives

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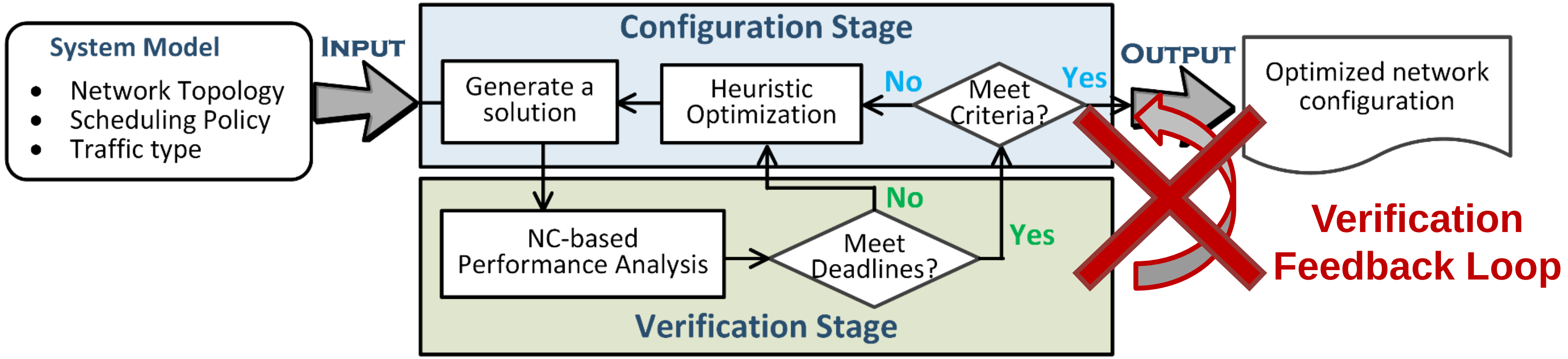
(2) Performance-Driven Configuration Optimization [3] [4]

- Principal idea
  - Can we automatically ensure real-time performance while configuration optimization, like TT scheduling?
  - Avoid the traditional real-time verification feedback loop

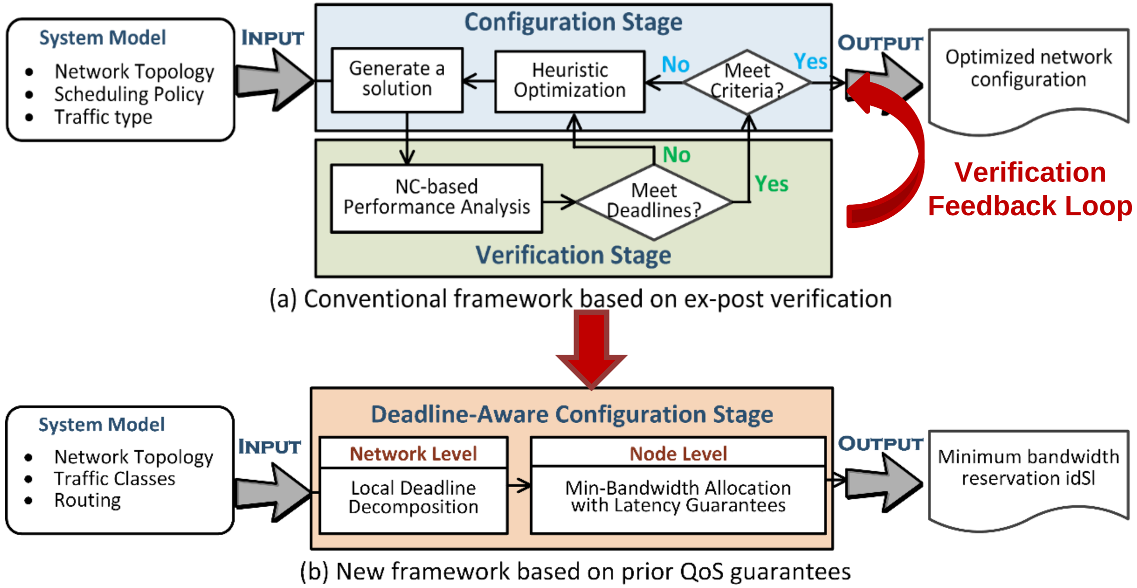


(a) Conventional framework based on ex-post verification

[3] Zhao, L., Yan, Y., & Zhou, X. (2023). Minimum Bandwidth Reservation for CBS in TSN With Real-Time QoS Guarantees. *IEEE Transactions on Industrial Informatics*.
[4] Xie, A., He, F., & Zhao, L. (2024) Optimizing Quantum Assignment for DRR in TSN: A Network Calculus-Based Method. *IEEE Real-Time Systems Symposium (RTSS).*

Performance-Driven Configuration Optimization [3] [4]

- Problem Motivation
  - CBS, DRR, TAS+CBS: optimize bandwidth to optimize residual bandwidth utilization while guarantees deadlines
  - Over-allocation
    - ✓ Leads to resource waste
    - ✓ Decreases service quality for lower-priority
  - Under-allocation
    - ✓ Risks missing deadlines for time-critical applications
- Overall framework
  - Network level
  - Node level



(a) Conventional framework based on ex-post verification

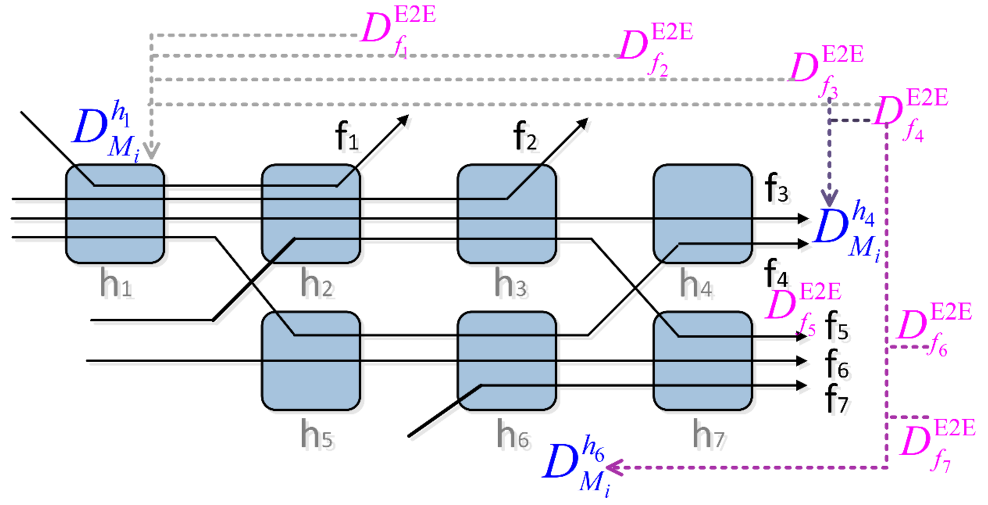
(b) New framework based on prior QoS guarantees

[3] Zhao, L., Yan, Y., & Zhou, X. (2023). Minimum Bandwidth Reservation for CBS in TSN With Real-Time QoS Guarantees. *IEEE Transactions on Industrial Informatics*.
[4] Xie, A., He, F., & Zhao, L. (2024) Optimizing Quantum Assignment for DRR in TSN: A Network Calculus-Based Method. *IEEE Real-Time Systems Symposium (RTSS).*

Performance-Driven Configuration Optimization [3] [4]

Network Level -- Deadline Decomposition Technique

- Problem
  - Upstream bandwidth changes impact downstream delays
  - Need to decouple traffic between nodes
- Solution
  - Decompose end-to-end deadlines into local deadlines at each node
  - Ensures end-to-end deadlines are met when all local deadlines are satisfied



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Performance-Driven Configuration Optimization [3] [4]

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Node Level – Optimize Configuration Parameters

- Coupled models
  - Integrate NC-based performance analysis model with bandwidth optimization problem
- Challenge
  - Derive closed-form or fast optimal solutions

Objective function: maximize residual bandwidth
Decision variables: idle slope $idSl_i^h$
Constraints: deadline guarantees – NC-based CBS performance analysis model

$$\mathbb{P}: \max_{idSl_1^h,\ldots,idSl_{N_{\mathrm{CBS}}}^h > 0} \mu^h(idSl_1^h,\ldots,idSl_{N_{\mathrm{CBS}}}^h) = C - \sum_{i=1}^{N_{\mathrm{CBS}}} idSl_i^h$$

$$\text{s.t.} \quad \mathbb{C}_1: D_i^h \geq hDev(\alpha_i^h, \beta_{i,\mathrm{CBS}}^h), \quad \forall i \in [1, N_{\mathrm{CBS}}]$$

$$\mathbb{C}_2: idSl_i^h \geq \sum_{f \in \mathcal{F}_i^h} \rho_f, \quad \forall i \in [1, N_{\mathrm{CBS}}]$$

Scheduling Policy: Credit-Based Shaping (CBS) [3]

Objective function: maximize residual bandwidth
Decision variables: quantum q_i^h, Q^h
Constraints: deadline guarantees – NC-based DRR performance analysis model

$$\mathbb{P}: \max_{Q^h, q_1^h,\ldots,q_{N_{\mathrm{cDRR}}}^h > 0} \mu^h(Q^h, q_1^h,\ldots,q_{N_{\mathrm{cDRR}}}^h) = 1 - \sum_{i=1}^{N_{\mathrm{cDRR}}} \frac{q_i^h}{Q^h} = 1 - \sum_{i=1}^{\mathrm{cDRR}} \eta_i^h$$

$$\text{s.t.} \quad \mathbb{C}_1: D_i^h \geq hDev(\alpha_i^h, \beta_{i,\mathrm{DRR}}^h), \quad \forall i \in [1, N_{\mathrm{cDRR}}]$$

$$\mathbb{C}_2: q_i^h \geq l_i^{h,\max}, \quad \forall i \in [1, N_{\mathrm{cDRR}}]$$

Scheduling Policy: Deficit Round Robin (DRR) [4]

[3] Zhao, L., Yan, Y., & Zhou, X. (2023). Minimum Bandwidth Reservation for CBS in TSN With Real-Time QoS Guarantees. *IEEE Transactions on Industrial Informatics*.
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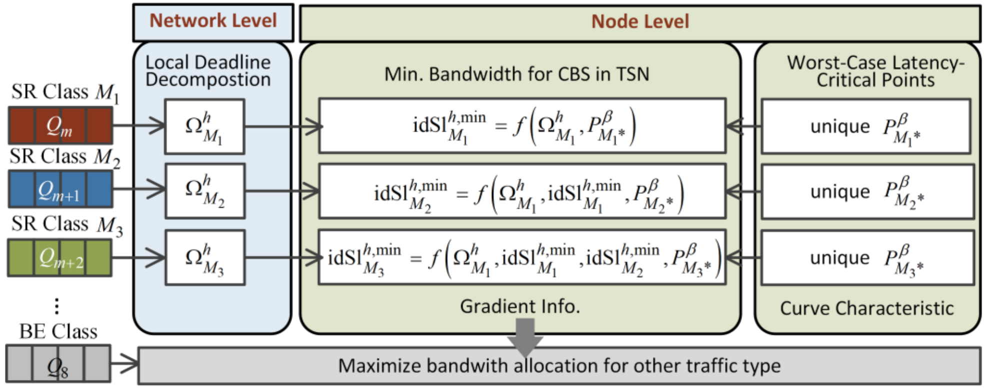
Performance-Driven Configuration Optimization [3] [4]

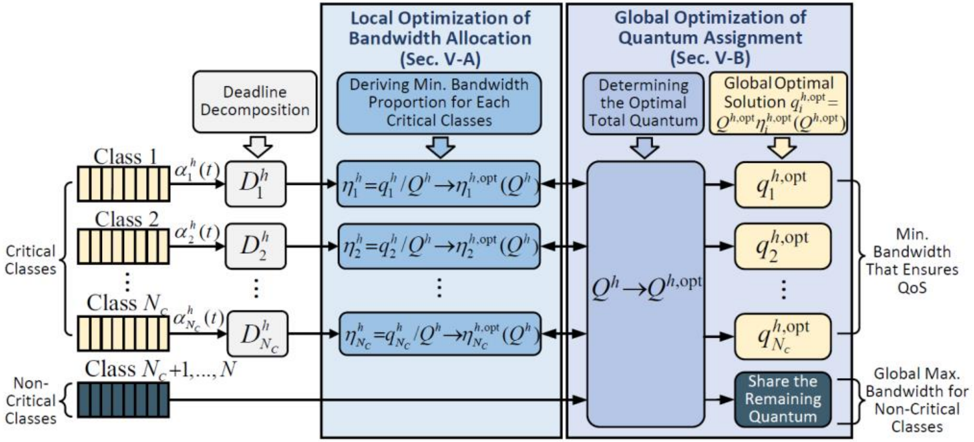
Node Level – Optimize Configuration Parameters

- Closed-form solution

CBS Scheduler: [3]
- Established equation linking idle slope $idSl_i^h$ to worst-case delay;
- By gradient information, derived closed-form expression for minimal bandwidth reservation $idSl_i^h$ required to meet local deadlines;
- **TAS+CBS hybrid architecture** - [under review]

DRR Scheduler: [4]
- Established equation linking quantum q_i^h, Q^h to worst-case delay;
- Derived closed-form solution for local optimal bandwidth with fixed Q^h;
- Used gradient ascent to find optimal total quantum Q^h for maximizing residual bandwidth;
- Formally proved gradient ascent avoids local optima





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Performance-Driven Configuration Optimization [3] [4]

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Comparison with Default idSl (75%) -- CBS

- Bandwidth Savings
  - Saves an average of 91.1% and up to 99.0% compared to default idSl (e.g., 75%)
- Correctness Validation
  - NC-based analysis confirms that all flows meet deadline requirements configured with optimized bandwidth
- Runtime Efficiency
  - Configuring optimal bandwidth reservations for all traffic classes across all ports takes just seconds

TABLE II
VALIDITY OF OUR PROPOSED APPROACH IDSLMIN/NC

SR Class	Port	idSlMin/NC	idSlMin/Std	idSl/Default
Class M_1	[ES1,SW1]	12.77%	4%	M_1+M_2=75%
	[ES2,SW1]	4.94%	1.6%	
	[ES3,SW1]	2.47%	0.8%	
	[SW1,ES4]	9.84%	3.2%	
	[SW1,ES5]	9.56%	3.2%	
Class M_2	[ES1,SW1]	7.93%	1.6%	
	[ES2,SW1]	0.72%	0.16%	
	[ES3,SW1]	5.11%	1.12%	
	[SW1,ES4]	8.74%	1.92%	
	[SW1,ES5]	4.42%	0.96%	
Average SR Class		13.3%	3.72%	75%

TABLE III
CORRECTNESS OF OUR PROPOSED APPROACH IDSLMIN/NC

SR Class	Flow	WCD (μs) idSlMin/NC	WCD (μs) idSlMin/Std	WCD (μs) idSl/Default	Deadline
Class M_1	f1	533.8	2038	129.8	1000
	f2	443.1	1740	106.1	500
	f3	499.8	1930	89.8	500
	f4	669.8	2438	97.8	1000
Class M_2	f5	1640.1	9316.4	122.8	5000
	f6	666.4	3882.5	221.3	1000
	f7	925.3	5017.3	245.3	5000
	f8	998.4	6459.2	186.8	1000

[3] Zhao, L., Yan, Y., & Zhou, X. (2023). Minimum Bandwidth Reservation for CBS in TSN With Real-Time QoS Guarantees. *IEEE Transactions on Industrial Informatics*.
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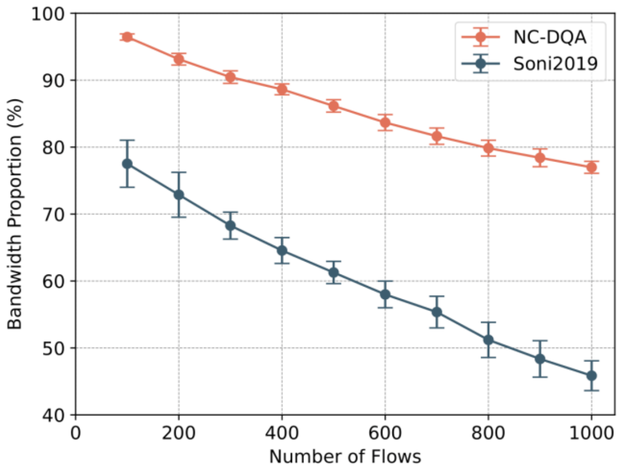
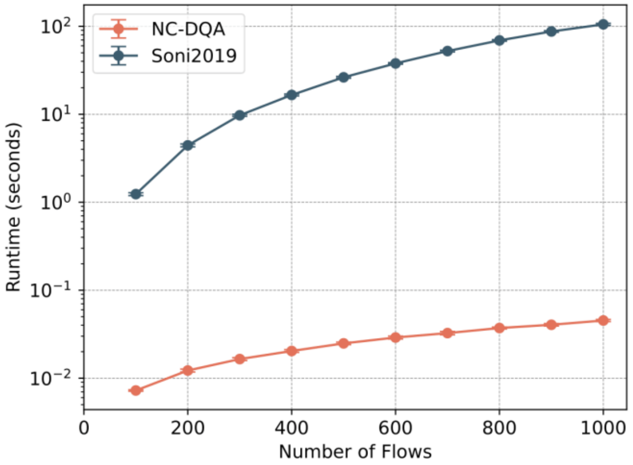
Performance-Driven Configuration Optimization [3] [4]

Comparison with Traditional Optimization -- DRR

- Bandwidth Efficiency
  - Saves over 85% residual bandwidth.
  - Traditional schedulability feedback-based method: Saves around 60% residual bandwidth.
- Runtime Improvement
  - At least 2-3 orders of magnitude faster





Improvements in both Objective Performance and Optimization Speed !

[3] Zhao, L., Yan, Y., & Zhou, X. (2023). Minimum Bandwidth Reservation for CBS in TSN With Real-Time QoS Guarantees. *IEEE Transactions on Industrial Informatics*.
[4] Xie, A., He, F., & Zhao, L. (2024) Optimizing Quantum Assignment for DRR in TSN: A Network Calculus-Based Method. *IEEE Real-Time Systems Symposium (RTSS).*

Performance-Driven Configuration Optimization [3] [4]

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Advantages

- Ensures QoS during optimization
- Removes real-time verification feedback-loop

Disadvantages

- Requires specific coupling models for different schedulers and optimization objectives
- Identifying suitable optimization methods can be challenging

[3] Zhao, L., Yan, Y., & Zhou, X. (2023). Minimum Bandwidth Reservation for CBS in TSN With Real-Time QoS Guarantees. *IEEE Transactions on Industrial Informatics*.
[4] Xie, A., He, F., & Zhao, L. (2024) Optimizing Quantum Assignment for DRR in TSN: A Network Calculus-Based Method. *IEEE Real-Time Systems Symposium (RTSS).*

References

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- [1] M. Boyer, and R. Henia, “Industrial challenge: Embedded reconfiguration of TSN.” technical report, 2024.
- [2] L. Zhao, X. Zhang, F. He, et al., “Incremental Performance Analysis for Accelerating Verification of TSN Network Reconfigurations.” *IEEE Transactions on Network and Service Management*, early access, 2024.
- [3] L. Zhao, Y. Yan, and X. Zhou, "Minimum Bandwidth Reservation for CBS in TSN With Real-Time QoS Guarantees." *IEEE Transactions on Industrial Informatics*, 20(4), 2023.
- [4] A. Xie, F. He, and L. Zhao, “Optimizing Quantum Assignment for DRR in TSN: A Network Calculus-Based Method.” *IEEE Real-Time Systems Symposium (RTSS)*, accepted, 2024.

Happy to answer questions ☺

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