DETERMINISTIC6G

Wireless-friendly Traffic Engineering

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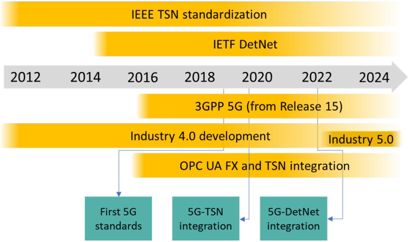
The Need for Wireless-Enabled Real-Time Communication

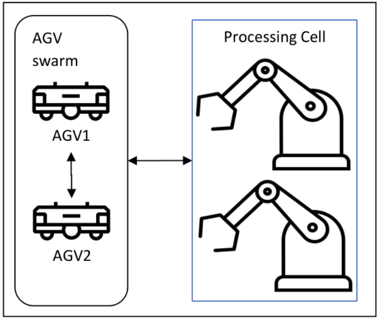
Modern System Requirements:

- Similar real-time guarantees (latency, jitter, packet-loss ratio) as in wired Time-Sensitive Networks
- Increased user/system mobility and deployment flexibility

Deliverable D1.1 [DETERMINISTIC6G]
Deliverables D4.3 and D4.4 [5G-SMART]



Example Use Case Description



Movement coordination service

- for Automated Guided Vehicles (AGVs)
- a top speed of 8 km/h.

Deterministic6G:[1]

AGV movement coordination packets are delivered within 10ms and with at most 5ms jitter. **The system can tolerate a packet loss of 2/3.**

[1] DETERMINISTIC6G D1.1: use cases and architecture principles

Presentation Outline

1. Integration of 5G and TSN
   - Modelling the 5G System as a Logical 5G-TSN Bridge
   - Control Plane Extensions
   - UPF-Based 5G-TSN Bridge
   - Hold-and-Forward Buffers & Packet Delay Correction
2. Wireless-Friendly TSN Scheduling
   - The Need for Robust Scheduling
   - Full Interleaving Packet Scheduling (FIPS)
   - 6G-DetCom Evaluation

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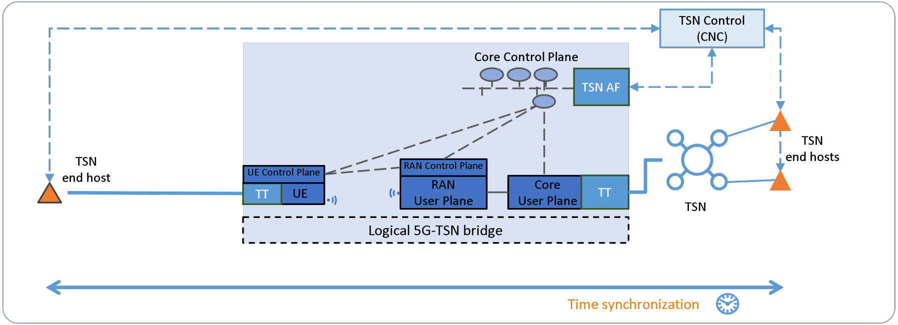
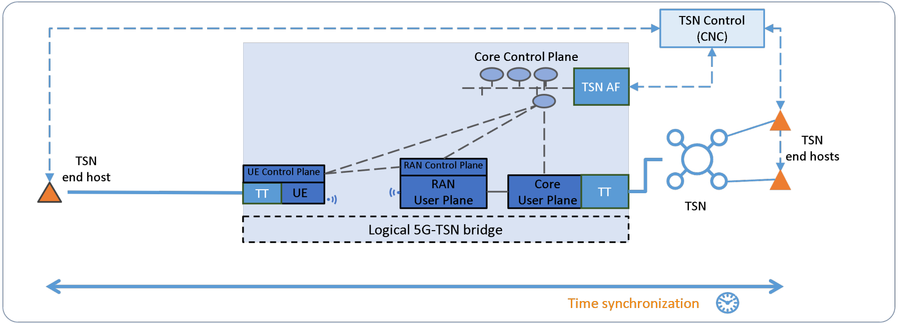
The Logical 5G-TSN Bridge



5G Data-Plane: TSN Translators (TT) on device-side and network side

- support basic TSN functionality (e.g., time synchronization, traffic shaping, PSFP)
- enable configuring the 5G system "like any other TSN bridge"

The Logical 5G-TSN Bridge

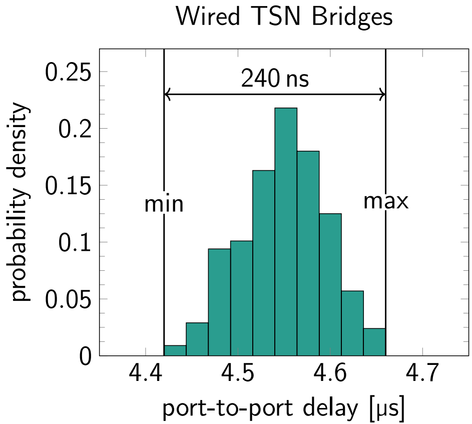


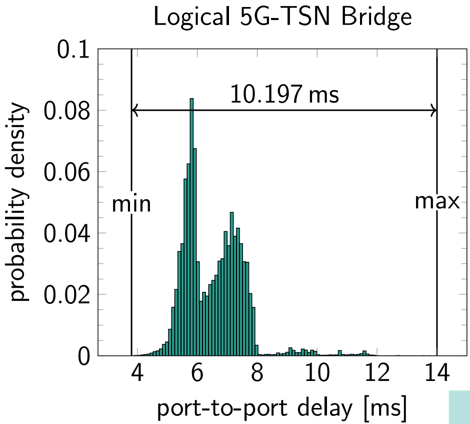
5G Control-Plane: TSN Application Function (AF)

- collects information from the 5G system, DS-TTs, and the NW-TT
- reports them to / interfaces with the CNC

Packet Delay Characteristics

DETERMINISTIC6G Measurements:[2]





[2] DETERMINISTIC6G D4.1: first DetCom simulator framework release (datasets)

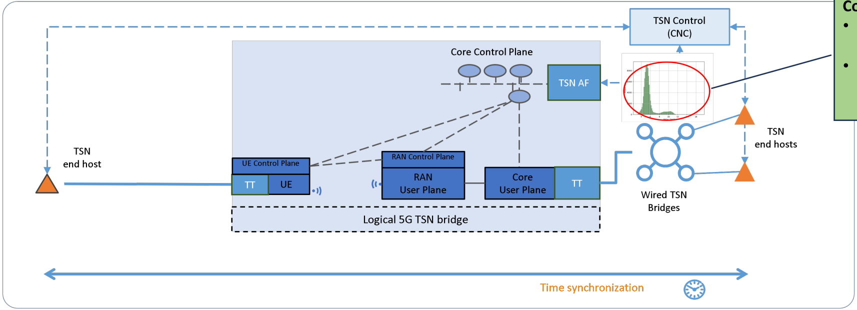
The Cost of Transparency

While the 5G packet delays and packet delay variations are significantly larger, the histogram masks:

- Small-scale fading effects and 5G-internal adaptation
  - MCS selection based on 5G channel quality
  - 5G retransmissions
  - ⇝ Much faster adaptation rates (few milliseconds) than what the CNC could support
- 5G-internal session management and configuration
  - Wireless-bypass can span much larger areas
  - 5G handovers (if the PDU session still routed via same UPF/NW-TT)
  - ⇝ Transparent to the CNC and reduces configuration parameters for the 5G system (attack surface, possibility of misconfiguration, system certifiability)

5G-TSN Control-Plane Extensions

P802.1Qee: Traffic Engineering for Bridged Networks with Significant Delay Variance

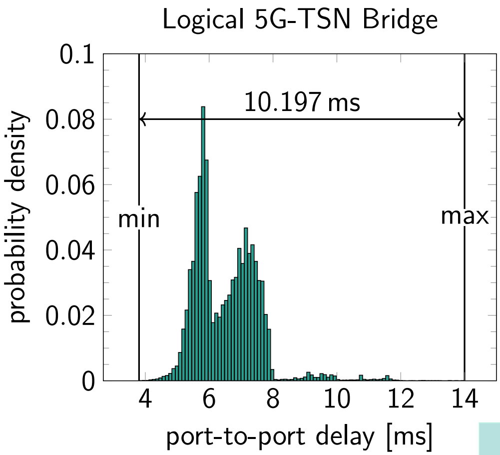


Control plane extensions

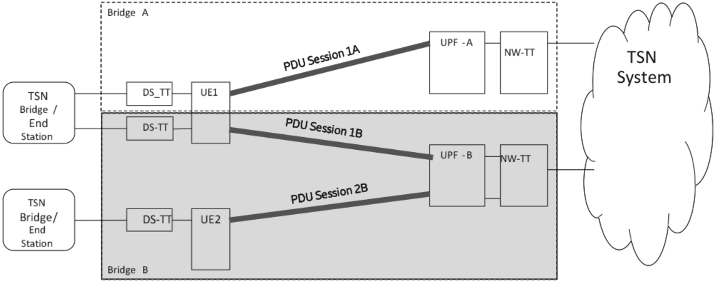
- YANG models for port-to-port delay distributions
- NETCONF protocol to update delay information at CNC (push & pull)

5G-TSN Control-Plane Extensions

```
grouping delay—histogram {
    leaf start {
        type uint64;
    }
    leaf bin—count {
        type uint32;
        mandatory true;
    }
    list bin {
        key index;
        leaf index {
          type uint32;
          mandatory true;
        }
        leaf width {
          type uint64;
          mandatory true;
        }
        leaf count {
          type uint32;
        mandatory true;
        }
    }
}
```



UPF-Based Logical 5G-TSN Bridge



Logical 5G-TSN bridges are split by the UPF/NW-TT:[3]

- Contains all PDU sessions connected to the same 5G UPF
- One-to-one binding between DS-TT and PDU session

[3]For more details, see 3GPP TS 23.501 (v18.10.0)

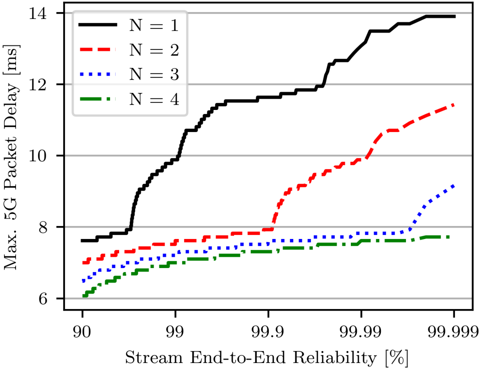
FRER-Like 5G Packet Replication

Reduce latency/reliability requirement per PDU session ("Fastest packet wins"):

$$\mathbb{P}(D \leq d^{max}) = 1 - \sqrt[N]{1 - F.rel}$$

where

- D: r.v. of fastest 5G PDU delay
- d^{max}: 5G packet delay budget



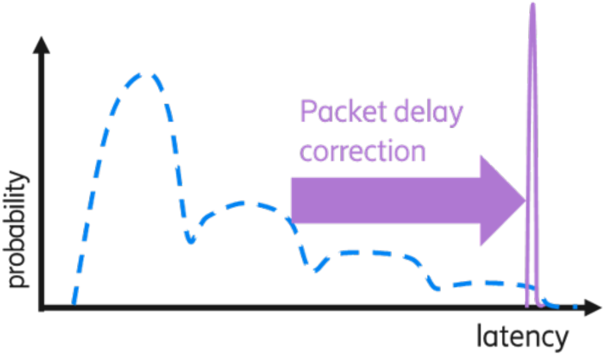
Hold and Forward Buffering Mechanism

TS 23.501 (v18.10.0):

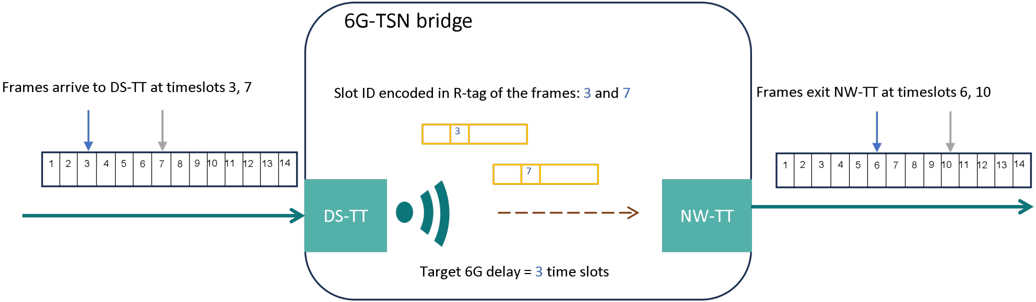
> *DS-TT ports and NW-TT ports support a hold and forward mechanism to schedule traffic as defined in IEEE Std 802.1Q ... [for] observable behaviour identical to scheduled traffic with up to eight queues ...*

Per-Queue Buffering but not Per-Stream Buffering!

Packet Delay Correction



Packet Delay Correction



1) De Andrade, M., Sachs, J., Haug, L., Egger, S., Dürr, D., Varga, B., Farkas, J., Miklós, G., "Compensating the Packet Delay Variation for 6G Integrated with IEEE Time-Sensitive Networking" (in Submission)
2) Egger, S., Dürr, F., Varga, B., De Andrade, M., Sharma, G. P., Sachs, J., Harmatos, J., Gross, J. (2025). "Wireless-Aware TSN Engineering: Implications for 5G and Upcoming 6G Networks". IEEE Network.

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2. **Wireless-Friendly TSN Scheduling**[4]
   - **The Need for Robust Scheduling**
   - **Full Interleaving Packet Scheduling (FIPS)**
   - **6G-DetCom Evaluation**

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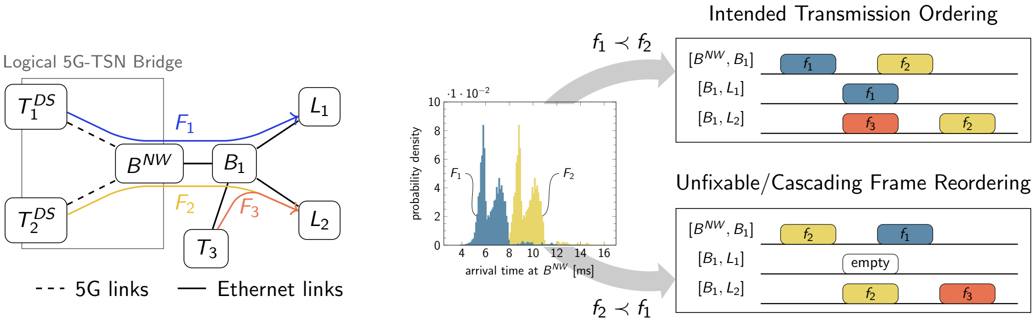
[4] Egger et al. "End-to-End Reliability in Wireless IEEE 802.1 Qbv Time-Sensitive Networks." IEEE/ACM IWQoS 2025, arXiv preprint arXiv:2502.11595.

The Need for Robust Scheduling



Without robust scheduling, significant delay variations

- result in unintended transmission orderings & missed transmission slots
- with cascading effects throughout the entire network

Wireless-Friendly Scheduling

Guiding Design Questions:

Q1) What control does the CNC have over 5G-internal resource allocation?

$\rightsquigarrow$ *Goal: QoS contract between 5G and TSN*

Q2) How to provide formal QoS guarantees under stochastic 5G packet delays?

$\rightsquigarrow$ *Goal: Fault-tolerance for high-criticality streams*

Q3) How can we provide these guarantees at scale?

$\rightsquigarrow$ *Goal: Relax constraint limitations and improve scheduling efficiency*

Wireless-Friendly Scheduling

Q1) What control does the CNC have over 5G-internal resource allocation?

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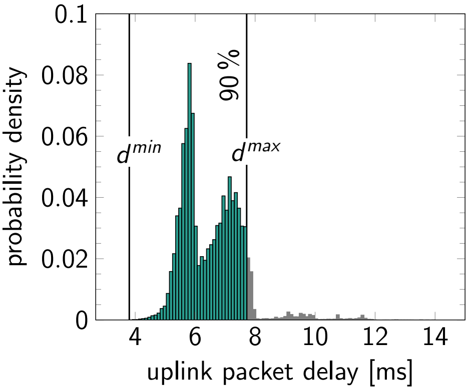
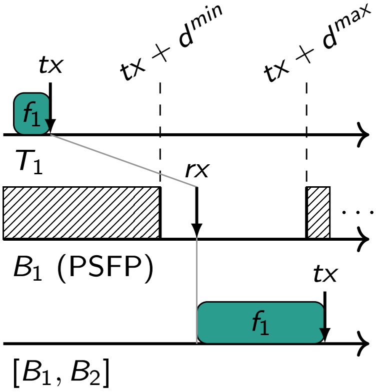
Q1) 5G Packet Delay Budgets

From a 5G perspective (left) and a TSN perspective (right):





Q1) 5G Packet Delay Budgets (PDBs)

For a TSN stream F, compute the following 5G PDB:[5]

$$\mathbf{d}^{min}(F) = \text{hist}[0].\text{low},$$
$$\mathbf{d}^{max}(F) = \min\left\{\text{hist}[i].\text{up} \mid \sum_{j=0}^{i} \text{hist}[j].\text{count} \geq F.rel\right\}.$$

5G-TSN Contract: With a probability of at least $F.rel$, frames of f arrive at the NW-TT within the interval

$$[tx + \mathbf{d}^{min}(F), tx + \mathbf{d}^{max}(F)].$$

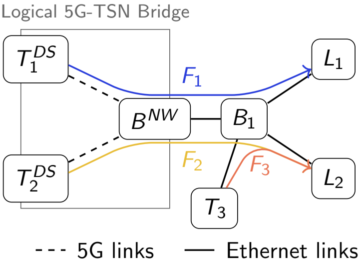
[5] The generalization for multiple 5G links is straight-forward.

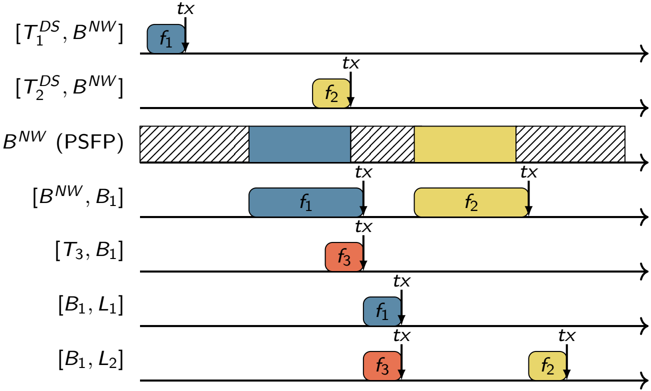
Wireless-Friendly Scheduling

Q2) How to provide formal QoS guarantees under stochastic 5G packet delays?

$\rightsquigarrow$ *Goal: Fault-tolerance for high-criticality streams*

Q2) Robustness Criterion





Q2) Robustness Criterion

Intuitive Idea (Application View): If a frame $f \in F$

- is sent out by the talker at the correct time and
- every subsequent transmission is correct (i.e., no packet corruption and delay bounded by PDBs)

Then it should arrive at the listener within the expected interval $\mathcal{R}\left(v_F^{n_F}, f\right)$.

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Then it should arrive at the listener within the expected interval $\mathcal{R}\left(v_F^{n_F}, f\right)$.

Intuitive Idea (Network View): The above only captures the last hop.

- It should hold for every intermediate TSN bridge
  - $\rightsquigarrow$ e.g., to ensure f is not filtered by PSFP
- Inductive extension for all $v_F^k \in F.path$.

Q2) Robustness Criterion

Definition (Robustness)

The TSN configuration $\mathcal{C} = (\mathcal{S}_{GCL}, \mathcal{R})$ robustly schedules a stream $F \in \mathcal{F}$ if for every execution sequence $\mathcal{E} = (\mathcal{T}, \mathcal{D})$, every frame $f \in F$, and every hop $v_F^k \in F.path$ the following holds true: If, up to bridge v_F^k, the packet delays lie within their PDBs, i.e.,

$$\mathcal{D}\big([v_F^l, v_F^{l+1}], f\big) \in \mathbf{d}([v_F^l, v_F^{l+1}], F), \quad \forall 1 \leq l < k,$$

then v_F^k receives f within its expected PSFP interval, i.e.,

$$\big(\mathcal{T} + \mathcal{D}\big)\big([v_F^{k-1}, v_F^k], f\big) \in \mathcal{R}\big(v_F^k, f\big).$$

Q2) Feasible Schedule

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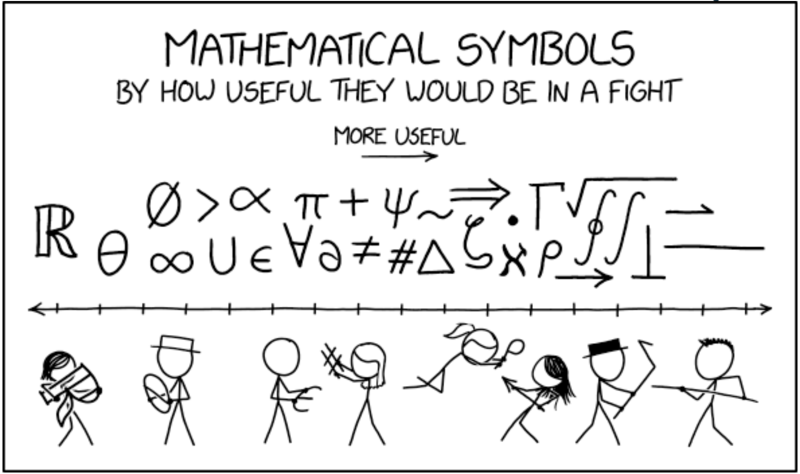
Theorem

A TSN configuration $\mathcal{C} = (\mathcal{S}_{GCL}, \mathcal{R})$ feasibly schedules a stream $F \in \mathcal{F}$ if

1. *$\mathcal{C}$ robustly schedules F,*
2. *$\mathcal{C}$ allocates sufficiently large PDBs, according to Q1, and*
3. *$\mathcal{C}$ bounds for all $f \in F$*

$$\mathcal{R}^{max}\left(v_F^{n(F)}, f\right) - \mathcal{S}^{min}\left([v_F^1, v_F^2], f\right) \leq F.lat \quad (1)$$

$$\left(\mathcal{R}^{max} - \mathcal{R}^{min}\right)\left(v_F^{n(F)}, f\right) \leq F.jitter \quad (2)$$



https://xkcd.com/2343/

Q2) But What Does That Actually Mean?

5G-TSN Contract:

With a 5G reliability of 99.99 %*, the 5G packet delays for stream F are lower- and upper-bounded by the budget interval* [3 ms, 15 ms]*.*

Robust E2E Guarantees:

With an end-to-end reliability of 99.99 %*, each frame of F arrives at the TSN listener with a latency below* 20 ms *and jitter below* 100 µs*.*

Wireless-Friendly Scheduling

Q3) How can we provide these guarantees at scale?

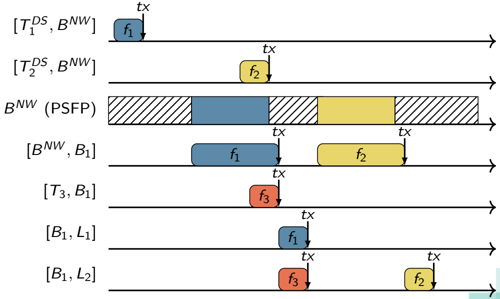
$\rightsquigarrow$ *Goal: Relax constraint limitations and improve scheduling efficiency*

Q3) Strict Transmission Isolation (STI)

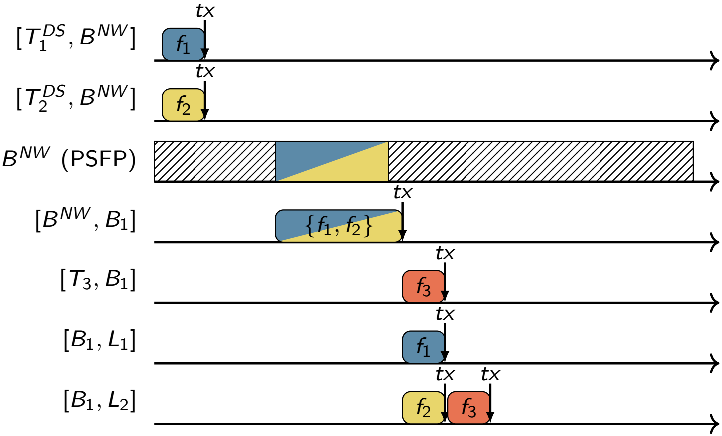
STI yields the simplest realization of robust scheduling, but the exclusive time-slot reservation requires T_2^{DS} to defer the transmission start $\mathcal{S}([T_2^{DS}, B^{NW}], f_2)$

General Case:

$$\left(\mathcal{S} + \mathbf{d}^{max}\right)\left([T_1^{DS}, B^{NW}], f_1\right) - \mathbf{d}^{min}([T_2^{DS}, B^{NW}], f_2)$$



Q3) Full Interleaving Packet Scheduling (FIPS)



Full Interleaving Packet Scheduling (FIPS)

What decision problem lies at the core of IEEE 802.1Qbv scheduling?

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At each egress port $[u, v]$*, the scheduler has to decide the transmission order of frames*

$$f_{i_1} \prec f_{i_2} \prec \ldots \prec f_{i_n}.$$

From there, deriving a TSN configuration $\mathcal{C} = (\mathcal{S}_{GCL}, \mathcal{R})$ *is very easy (linear run-time complexity in the number of transmissions).*

Full Interleaving Packet Scheduling (FIPS)

DETERMINISTIC6G

What decision problem lies at the core of IEEE 802.1Qbv scheduling?

At each egress port $[u, v]$*, the scheduler has to decide the transmission order of* **frame batches**

$$B_1 = \{f_{i_1}, f_{i_2}, \ldots, f_{i_{k_1}}\} \prec B_2 \prec \ldots \prec B_n.$$

From there, deriving a TSN configuration $\mathcal{C} = (\mathcal{S}_{GCL}, \mathcal{R})$ *is very easy (linear run-time complexity in the number of transmissions).*

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Let's assume the ordering is given...[6]

[6] We present a possible heuristic in the paper (but that's the boring part)

Full Interleaing Packet Scheduling (FIPS)

The formal way...

C1) Sequential Transmissions. For each frame $f \in B_i$, the transmission start $\mathcal{S}\big([u,v],B_i\big)$ is deferred until the latest arrival of f at the bridge u, i.e.,

$$\mathcal{S}\big([u,v],B_i\big) \geq \mathcal{R}^{max}\big(u,f\big).$$

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$$\mathcal{S}\big([u,v], B_i\big) \geq \mathcal{R}^{max}\big(u, f\big).$$

C2) Transmission Ordering. If B_i is not the first batch (within the hypercycle) to be transmitted over $[u,v]$, its transmission is deferred until B_{i-1} is fully transmitted, i.e.,

$$\mathcal{S}\big([u,v], B_i\big) \geq \big(\mathcal{S} + \mathbf{d}^{max}\big)\big([u,v], B_{i-1}\big).$$

Full Interleaing Packet Scheduling (FIPS)

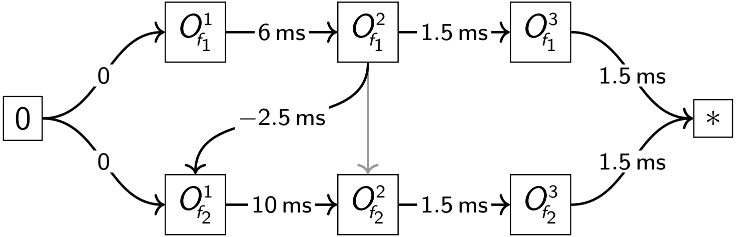
The formal way...

C3) Batch Fault Isolation. For each frame $f \in B_i$, it must be ensured that f takes its intended transmission slot over the subsequent hop $[v, w]$. Let B'_j denote the frame batch of f at $[v, w]$. To ensure f never takes the slot of B'_{j-1}, the transmission start of $\mathcal{S}\big([u, v], B_i\big)$ is delayed so that f never arrives at v before the transmission of B'_{j-1} has finished, i.e.,

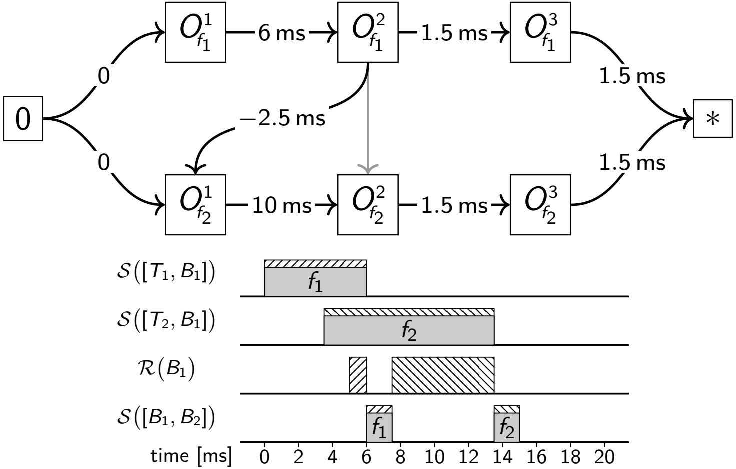
$$\mathcal{S}\big([u, v], B_i\big) \geq \big(\mathcal{S} + \mathbf{d}^{max}\big)\big([v, w], B'_{j-1}\big) - \mathbf{d}^{min}([u, v], f).$$

Transmission Graphs

The intuitive way...

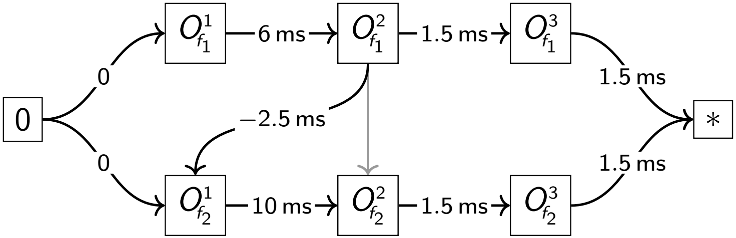


Transmission Graphs



Transmission Graphs

Somehow overlooked in prior TSN literature (but well-known as the disjunctive graph model in job-shop scheduling):



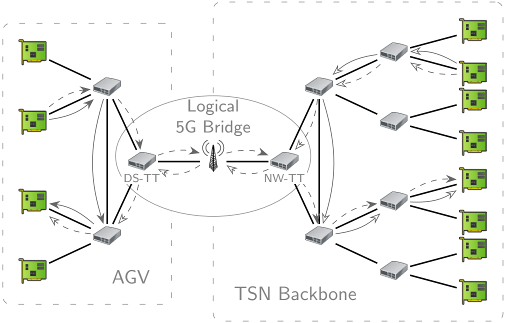
Offers intuitive and efficient scheduling heuristics and schedule augmentation!

Egger, et al. "An (m, k)-firm Elevation Policy to Increase the Robustness of Time-Driven Schedules in 5G Time-Sensitive Networks." arXiv preprint arXiv:2508.09769 (2025).

Evaluation

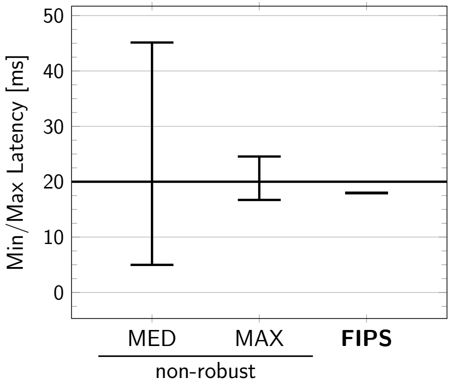
Methodology:

- Real 5G PD histograms
- 100 Mbps Ethernet links
- Frames per 20 ms hypercycle: 90 wireless + 10 wired
- Simulation: 1M hypercycles



type	*f.size*	*f.period*	*f.reliability*	*f.latency*	*f.jitter*
wireless	100	20 ms	50–99.99 %	20 ms	100 µs
wired	100	5 ms	100 %	500 µs	1 µs

The Importance of Robust End-to-End Scheduling



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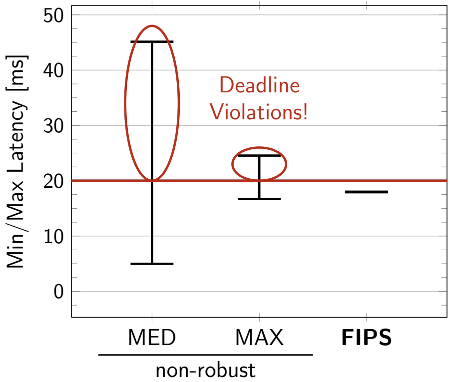
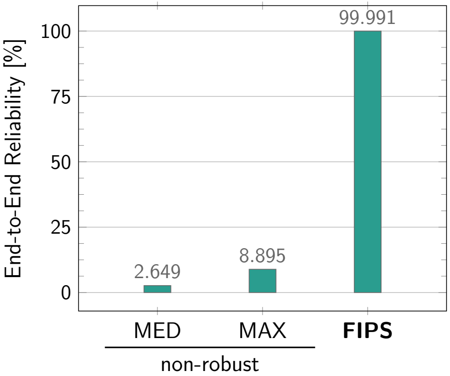
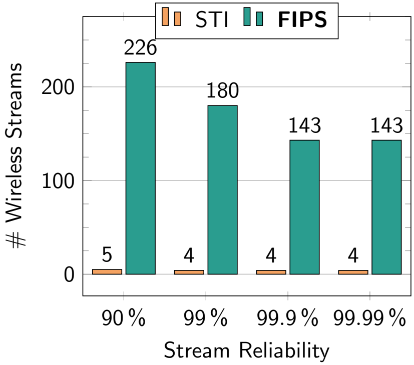




Stationary 5G channel assumptions cannot provide formal end-to-end guarantees!

Scalability of FIPS



Conventional scheduling techniques for wired TSN do not scale for significant 5G packet delay variations!

Key Take Aways

Q1) What control does the CNC have over 5G-internal resource allocation?

- ⇝ *Goal: QoS contract between 5G and TSN*
- ⇝ *Proposed Solution: 5G Packet Delay Budgets*

Q2) How to provide formal QoS guarantees under stochastic 5G packet delays?

- ⇝ *Goal: Fault-tolerance for high-criticality streams*
- ⇝ *Proposed Solution: Robust Scheduling*

Q3) How can we provide these guarantees at scale?

- ⇝ *Goal: Relax constraint limitations and improve scheduling efficiency*
- ⇝ *Proposed Solution: Full Interleaving Packet Scheduling*

Links

DETERMINISTIC6G

FIPS (MIT license):

- https://github.com/deterministic6g/fips

6G-DetCom (LGPL-3.0 license):

- https://github.com/DETERMINISTIC6G/6GDetCom_Simulator

5G Packet Delay Histograms (CC BY-ND 4.0 license):

- https://deterministic6g.eu/index.php/library-m/releases

DETERMINISTIC6G Grant Agreement No. 101096504

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or visit: www.deterministic6g.eu

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