Wireless-Friendly TSN Scheduling

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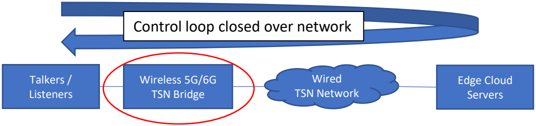
6G Programmable Deterministic Webinar

The DETERMINISTIC6G has received funding from the European Union's Horizon Europe programme under grant agreement No 10109504.

Motivation

- Safety-critical networked systems require **real-time communication**
  - **Time-Sensitive Networking (TSN)** supports hard latency and deadline guarantees in wired Ethernet networks
- Many novel applications benefit from **wireless connectivity** [1], e.g.:
  - Automated Guided Vehicles
  - Exo-skeleton
  - Smart farming
- **Reliable end-to-end scheduling** with wireless network elements required



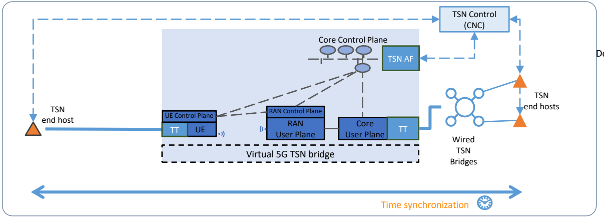
1. DETERMINISTIC6G Deliverable 1.1 "Use Cases and Architecture Principles"

DETERMINISTIC6G

5G Standard Support for TSN

Standardized: 5G support for TSN (and for DetNet similarly)

- The 5G System represented as a **Virtual (Wireless) TSN bridge** in the end-to-end TSN view
  - External behavior (functionality) same for wired and wireless bridges
  - Including in particular gates and Gate-Control List (time table) for scheduled traffic (IEEE 802.1Qbv)
- Upper-bound latency via *ultra-reliable and low latency* (URLLC) communication



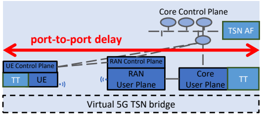
3GPP TS 23.501
5G-ACIA: 5G-TSN and 5G for IIoT
Deliverables D1.4, D1.5, D5.1, D5.2, D5.3, D5.4, D5.5 and
5G-SMART Booklet [5G-SMART]

UE : User Equipment
RAN: Radio Access Network
CNC: Centralized Network Configuration
TT: TSN Translator
AF: Application Function

Port-to-Port Delay:
Wired TSN Bridge vs. 5G Virtual TSN Bridge

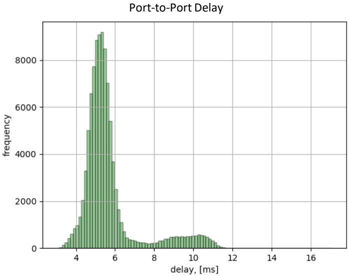
Port-to-Port Delay:

- ❑ Delay from ingress to egress port
- ❑ Without transmission selection
  - ❑ No queuing in egress queue (gates open)



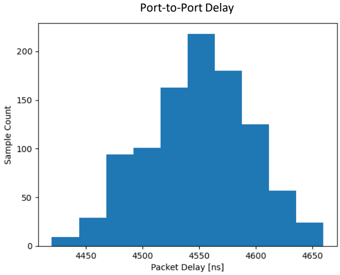
Port-to-Port Delay Characteristics of Virtual Bridge:

- ❑ Greater than for wired TSN bridges
  - ❑ But support for upper bound provided by URLLC
- ❑ Stochastic
  - ❑ Heavy-tailed

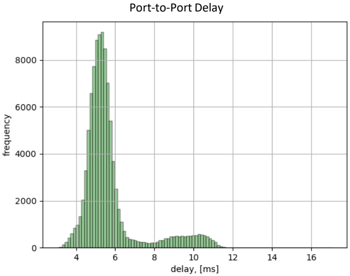


Port-to-Port Delay:
Wired TSN Bridge vs. 5G Virtual TSN Bridge

Wired TSN Bridge



5G Virtual TSN Bridge



Delay data from measurements available here:
https://github.com/DETERMINISTIC6G/deterministic6g_data

How to Schedule with Large (Port-to-Port) Packet Delay Variation (PDV)?

Wireless-Friendly End-to-End Scheduling

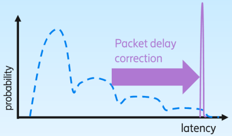
- Novel approaches to calculate e2e schedules with large PDV:
  - Guaranteed e2e reliability
  - Efficient: high utilization, number of streams

?

Discussed today!

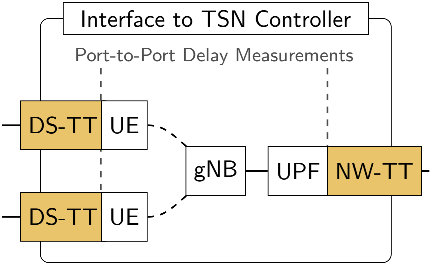
Scheduling-Friendly Data Plane: Packet Delay Correction [2]

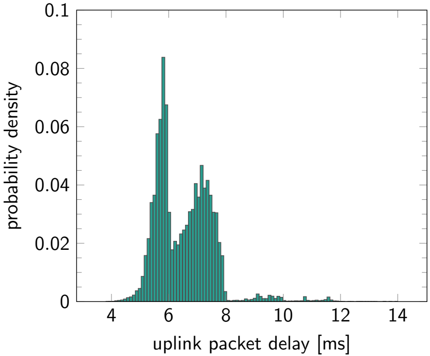
- Correction within the 5G System
- Compresses PDV at the Cost of Increased Latency



[2] DETERMINISTIC6G Deliverable 2.1 "First report on 6G centric enablers"

5G Systems as Logical TSN Bridges

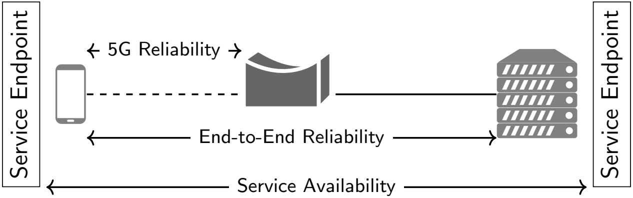




Challenge 1:

5G packet delay variation is three orders of magnitude larger compared to wired networks!

End-to-End Reliability vs. 5G Reliability



Challenge 2:

5G reliability does not suffice to ensure end-to-end reliability!

Deterministic6G Contributions

1. **Provable End-to-End Reliability:**
   - FIPS bridges the gap between 5G and end-to-end reliability
   - Epoch-based updates of 5G packet delay histograms
2. **Graceful Degradation:**
   - Gracefully lower reliability or latency guarantees
   - Instead of having to drop streams entirely
3. **Minimal Resource Over-Provisioning:**
   - Controlled frame interleaving
   - Improves scalability by a factor of up to $\times 76$

Related Work

Scheduling in Wired Time-Sensitive Networks:[1,2]

- Often assume (near-)deterministic models for TSN
  - ⇝ time synchronization errors and sporadic frame loss
- Robustness is achieved with strict transmission isolation
  - ⇝ Does not scale for large 5G PDV!

[1] F. Dürr and N. G. Nayak, "No-wait packet scheduling for IEEE time-sensitive networks (TSN)," RTNS 2016

[2] S. S. Craciunas, R. S. Oliver, M. Chmelík, and W. Steiner, "Scheduling real-time communication in IEEE 802.1Qbv time sensitive networks," RTNS 2016

Related Work

Scheduling in Wired Time-Sensitive Networks:

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  - ⇝ time synchronization errors and sporadic frame loss
- Robustness is achieved with strict transmission isolation
  - ⇝ Does not scale for large 5G PDV!

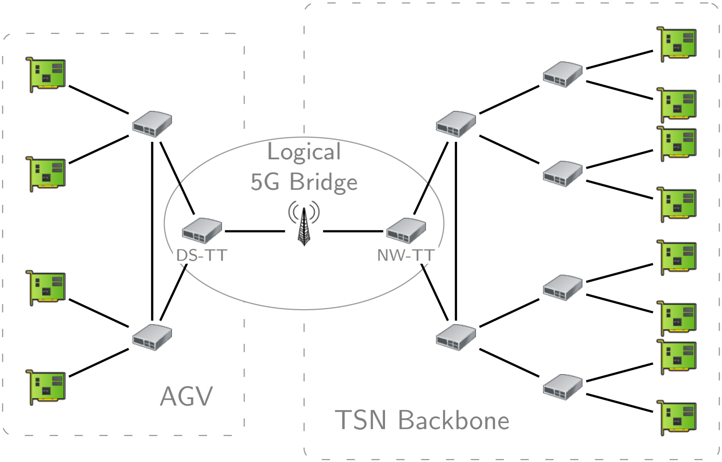
Scheduling in Wireless Time-Sensitive Networks:[4,5]

- Joint configuration of IEEE 802.1Qbv and 5G resource allocation
  - ⇝ Worst-case or stationary 5G channel assumptions!

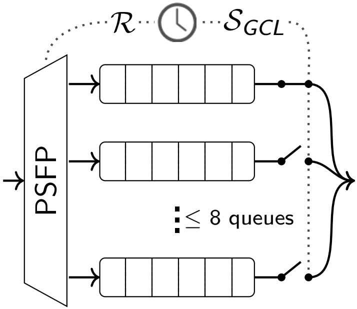
[4] J. Yang and G. Yu, "Traffic scheduling for 5G-TSN integrated systems," ISWCS 2022

[5] D. Ginthör, R. Guillaume, J. von Hoyningen-Huene, M. Schüngel, and H. D. Schotten, "End-to-end optimized joint scheduling of converged wireless and wired time-sensitive networks," ETFA 2020

Network Topology



TSN Bridges: Port-to-Port Model



IEEE 802.1Qbv Time-Aware Shaper (TAS)

⇝ governs gates at each egress queue

IEEE 802.1Qci Per-Stream Filtering and Policing (PSFP)

⇝ specifies allowed frame arrival intervals at each bridge

Robust Scheduling

Robustness can (informally) be achieved through

- the allocation of sufficiently large 5G packet delay budgets, and
- the isolation of transmission faults.

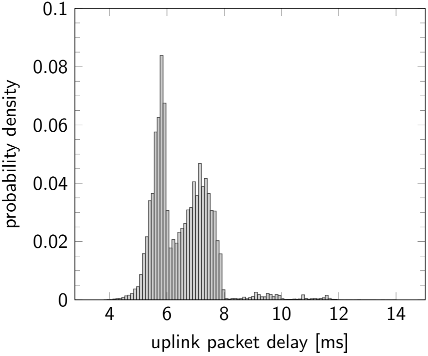
To compute provably robust TSN schedules, we introduce

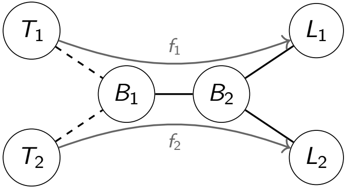
- Zero Interleaving Packet Scheduling (ZIPS)
- Full Interleaving Packet Scheduling (FIPS)

Central Result

Robust Schedules Extend 5G Reliability to End-to-End Reliability.

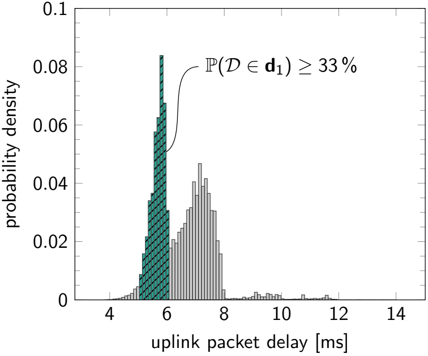
5G Packet Delay Budgets

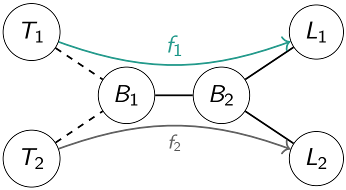




Stream	Link	Reliability	$\mathbf{d}^{min}$	$\mathbf{d}^{max}$
f_1	$[T_1, B_1]$	33%		
f_2	$[T_2, B_1]$	99%		

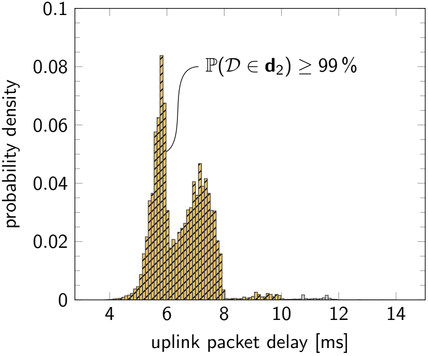
5G Packet Delay Budgets

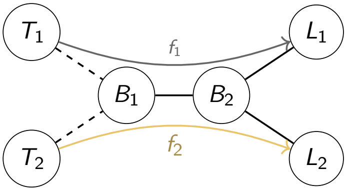




Stream	Link	Reliability	$\mathbf{d}^{min}$	$\mathbf{d}^{max}$
f_1	$[T_1, B_1]$	33%	5ms	6ms
f_2	$[T_2, B_1]$	99%		

5G Packet Delay Budgets





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f_1	$[T_1, B_1]$	33%	5ms	6ms
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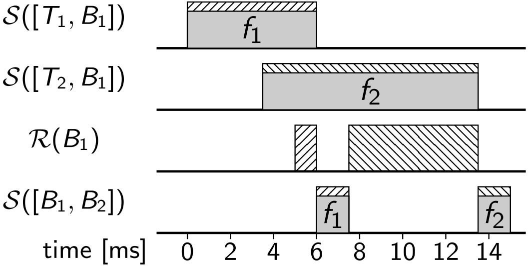
Zero Interleaving Packet Scheduling (ZIPS)



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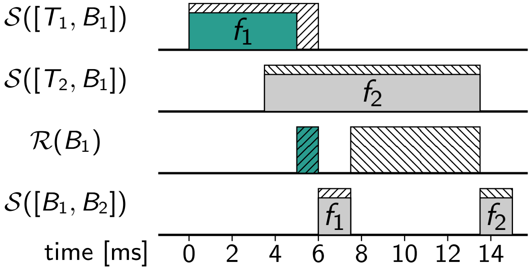

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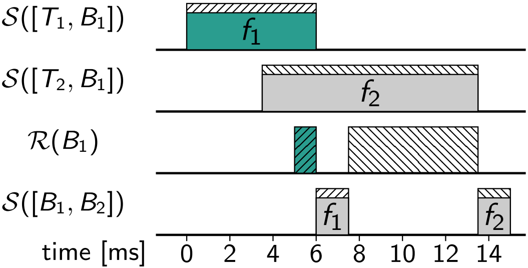

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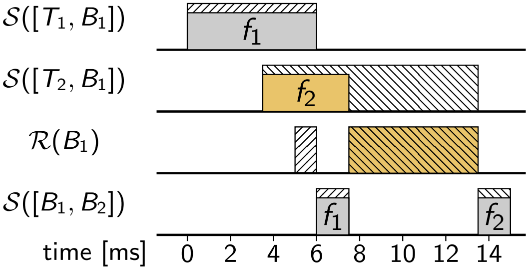

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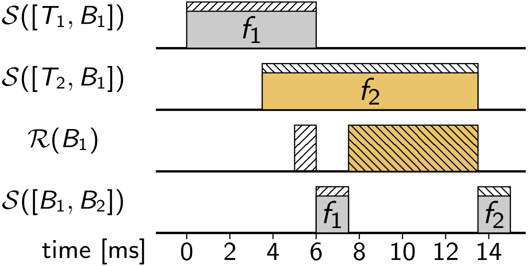

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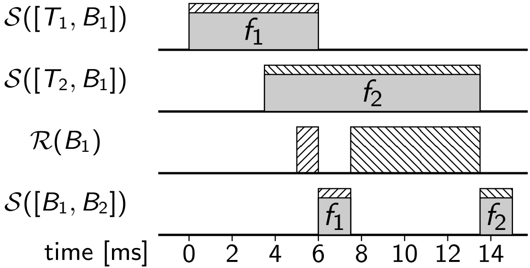

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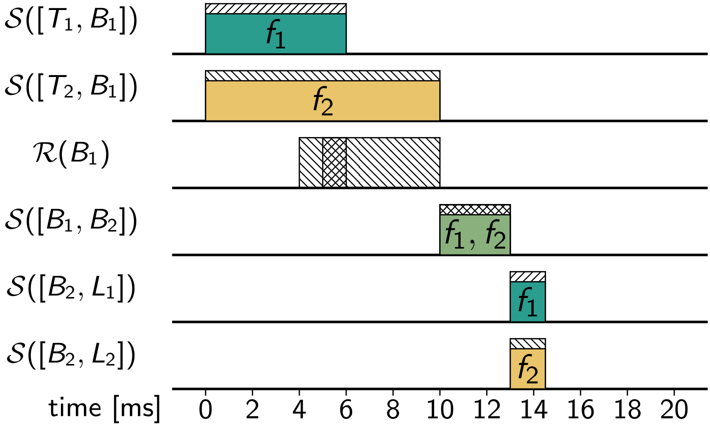
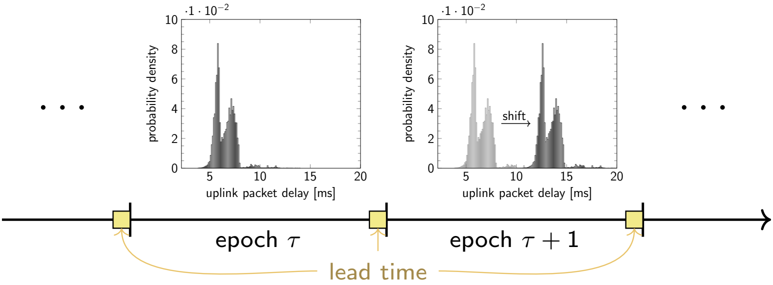
Full Interleaving Packet Scheduling (FIPS)

Controlled Frame Interleaving:



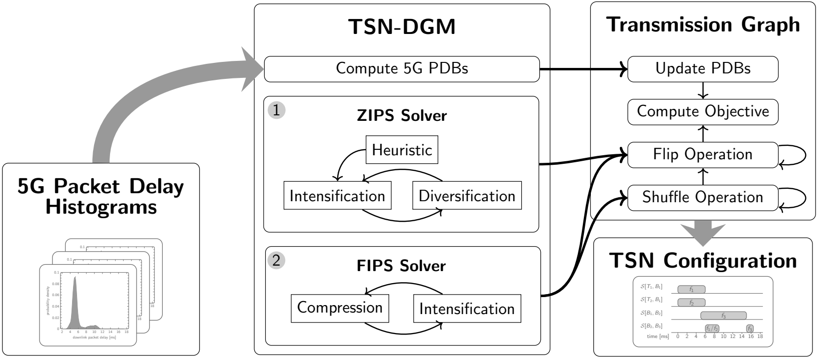
Timeline of 5G Histogram Updates



For reference, we will later consider a lead time of

- Epoch 1: 5 minutes
- Epoch τ ($\tau > 1$): 5 seconds

Overview of TSN-DGM



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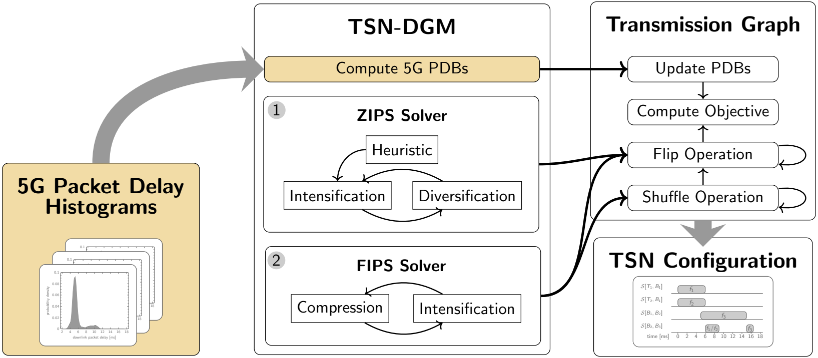
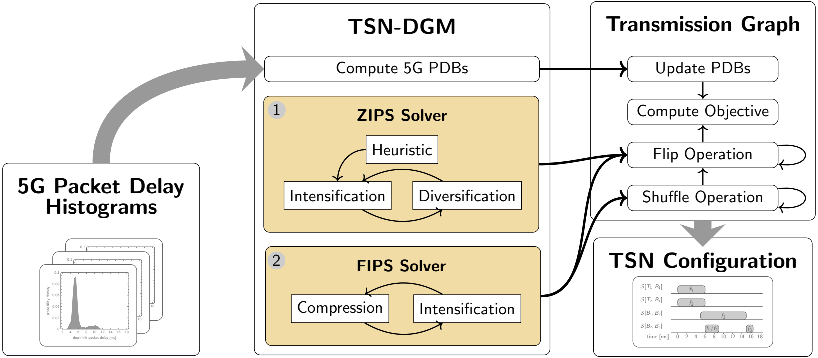


Overview of TSN-DGM



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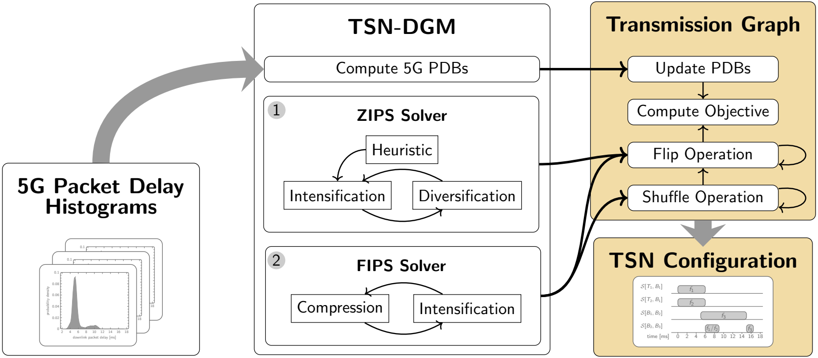
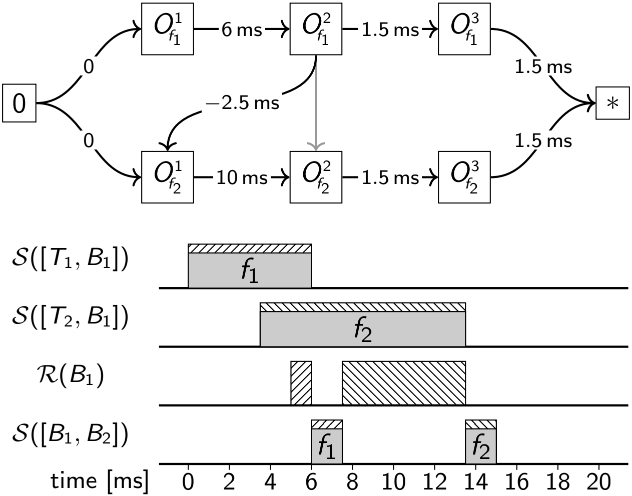
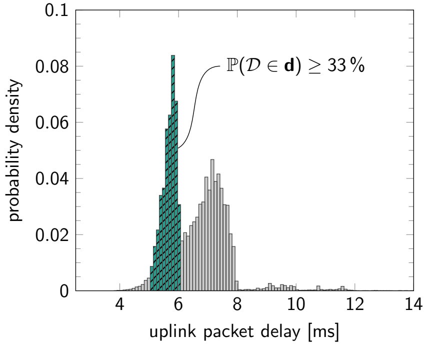


Transmission Graphs

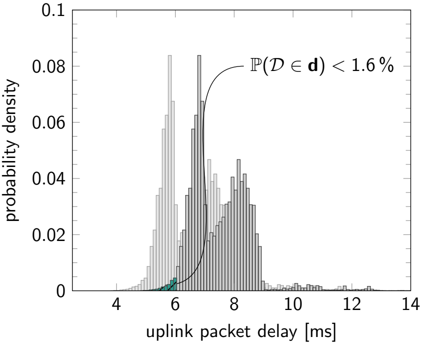


Transition to the Next Epoch

Problem Without Adaptation:



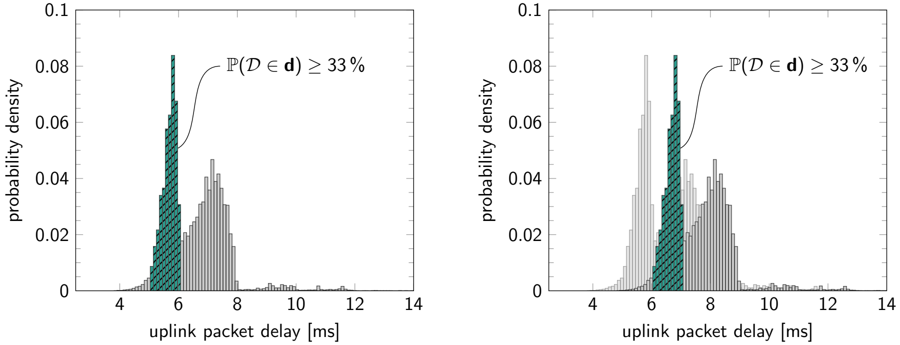
(a) Before Degradation



(b) After Degradation.

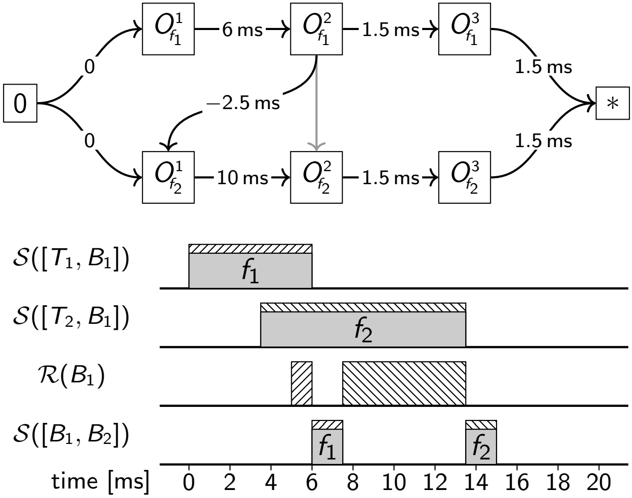
Transition to the Next Epoch

Updating the 5G Packet Delay Budgets:



(a) Before Degradation (b) After Adaptation.

Step 1: Adapting the Transmission Graph



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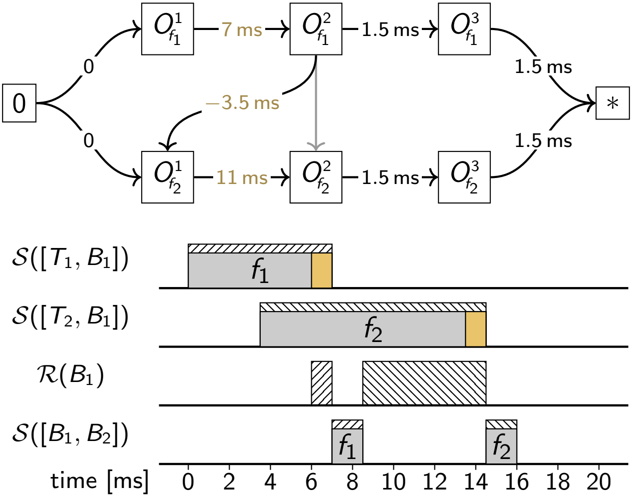
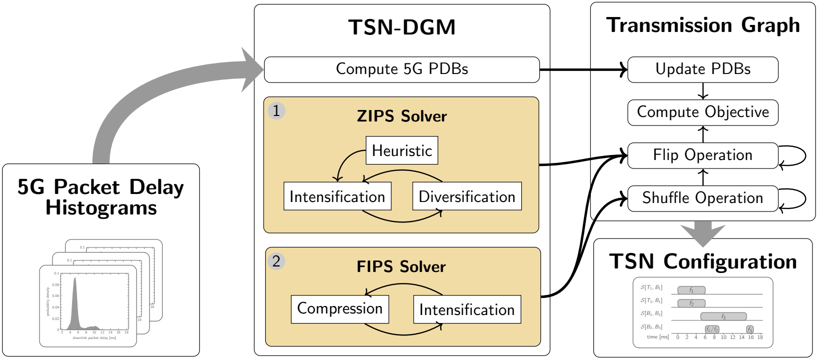


Step 2: Rescheduling & Graceful Degradation

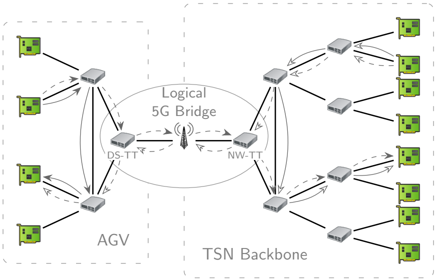


Graceful Degradation: If no optimal solution is found in time

$\rightsquigarrow$ iteratively shorten 5G PDBs until reaching zero tardiness

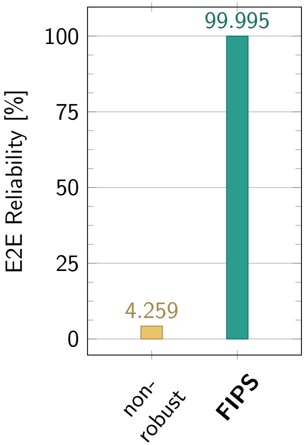
Methodology:

- Real 5G PD histograms
- 100 Mbps Ethernet links
- Frames per 20 ms hypercycle: 60 wireless + 50 wired
- Simulation: 100k hypercycles



type	*f.size*	*f.period*	*f.latency*	*f.jitter*
wireless	100	20 ms	20 ms	5 ms
wired	100	4 ms	500 µs	0

The Importance of Robust End-to-End Scheduling



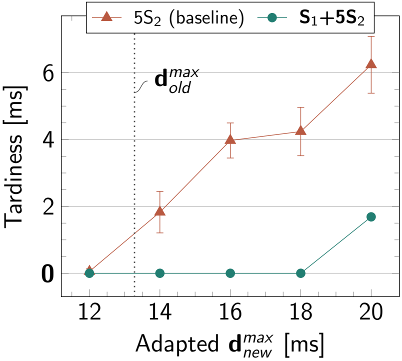
Setting:

- Non-robust TSN schedule violates robustness in a single GCL entry

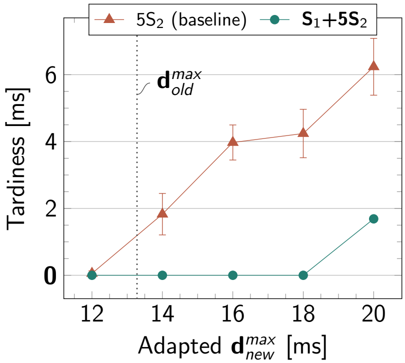
Implication:

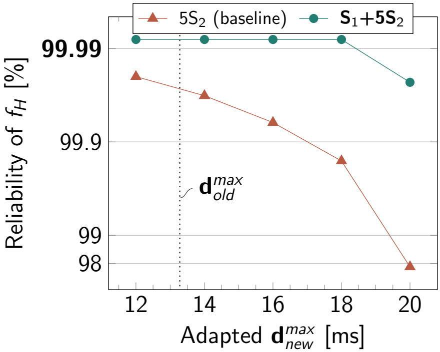
- Stationary 5G channel assumptions cannot provide formal guarantees!

Adaptation Strategy

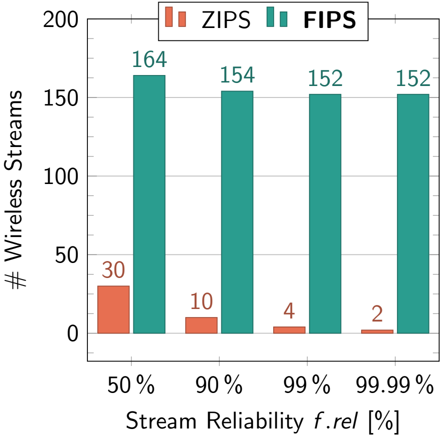


Adaptation Strategy





The Price of End-to-End Reliability



Simulation Framework Converged 6G/TSN networks

Existing simulation frameworks:

- Wired TSN networks:
  - e.g. NeSTiNg from USTUTT and INET

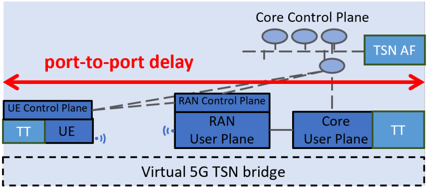
  ⇒ No 5G/6G features
- Wireless 5G/6G networks
  - e.g. Simu5G

  ⇒ No TSN functionality

Problem: There is no existing simulation framework to simulate converged 6G/TSN networks.

Simulation Framework Converged 6G/TSN networks

Goal: Evaluation platform for analysis of end-to-end deterministic communication (TSN/DetNet) in converged 6G/TSN networks.



Important aspect of 6G network: Port-to-port delay within wireless TSN bridge

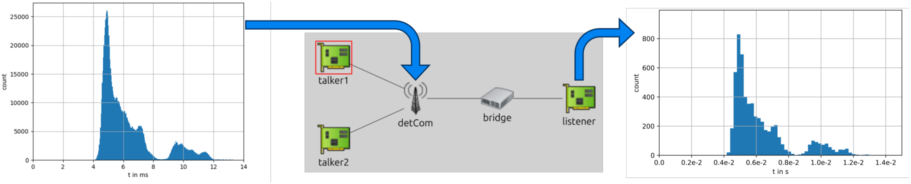
Simulation Framework Converged 6G/TSN networks

- Novel **data-driven** simulation approach:
  - Integrating real 5G measurements into TSN simulator
  - Only possibly through joint (contributions of various project partners)
  - Validation at very early stage of 6G development possible

- Based **OMNeT++/INET simulator** (open-source release of extensions)
  - Most popular platform for TSN simulations

$\Rightarrow$ Enables **realistic quantitative** validation of DETERMINISTIC6G concepts.

Simulation Framework Converged 6G/TSN networks



Simulation Input:
Delay measurements from real 5G systems[6]

Simulation:
All TSN features of INET, e.g. TAS

Simulation Result:
End-to-end delay matches input distribution

[6] Available on GitHub:
https://github.com/DETERMINISTIC6G/deterministic6g_data

Takeaway Points

Wireless-Friendly Scheduling in TSN:

- Achieves provable end-to-end reliability for each TSN stream
- Requires care to ensure both robustness and scalability

Transmission Graphs:

- Enable usage of fast Job-Shop Scheduling techniques
- Provide an efficient adaptation strategy with Graceful Degradation

Deterministic6G Simulation Framework:

- Data-driven simulation framework for converged 5G/TSN networks
- Publicly available on GitHub[7]

[7] `https://github.com/DETERMINISTIC6G/deterministic6g`

References / Contact

[1] DETERMINISTIC6G Deliverable 1.1: Use Cases and Architecture Principle.
https://deterministic6g.eu/images/deliverables/DETERMINISTIC6G-D1.1-v1.0.pdf

[2] DETERMINISTIC6G Deliverable 2.1: First report on 6G centric enablers.
https://deterministic6g.eu/images/deliverables/DETERMINISTIC6G-D2.1-v2.0.pdf

DETERMINISTIC6G Grant Agreement No. 101096504

The DETERMINISTIC6G project has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement No. 101096504.

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