# TSN performance assessment in brownfield PROFINET implementations

CINI4.0 - Converging Industrial Networks for Industry 4.0

16 June 2022, RodeBol Events, Ghent

**Arne Verhoeven (lecturer)**
Philippe Saey
Dimitri De Schuyter
Mathieu Troch

## Outline

- Introduction
- Brownfield PROFINET RT over TSN – principles
- Test network: topology and configuration
- Performance evaluation
  - PROFINET RT
  - Brownfield PROFINET RT over TSN
- Conclusion

# Introduction

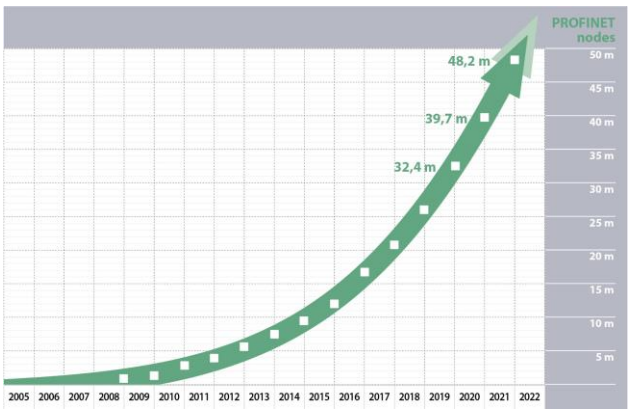
- **Introduction**
- Brownfield PROFINET RT over TSN – principles
- Test network: topology and configuration
- Performance evaluation
  - PROFINET RT
  - Brownfield PROFINET RT over TSN
- Conclusion



# Introduction

- TSN is being adopted in Industrial Ethernet networks e.g.,
  - PROFINET (PN) V2.4
  - IEC 60802 TSN profile for Industrial automation
  - …
- TSN allows for
  - Deterministic message exchange
  - Convergent Operational Technology (OT) and Information Technology (IT) networks
- … Millions of PN nodes already in the field!
- Can we implement TSN features on current PN networks?

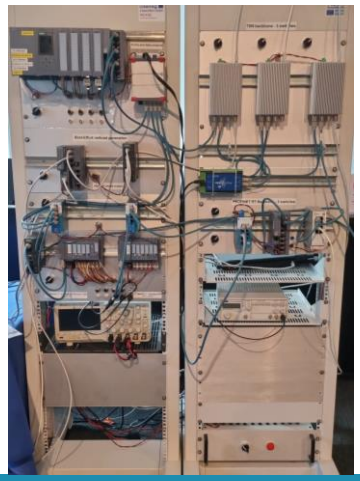
  → **Brownfield PN over TSN network**



# Introduction

*Not discussed here

- This research is focused on **PROFINET RT**
  - However, results also valid for other types of Real-Time traffic!
  - E.g., OPC UA pubsub
- Brownfield PN over TSN demonstrator with…
  - Industry-relevant PN network
  - TSN backbone
  - 100BASE-TX (100 Mbit/s) and 1000BASE-T (Gbit/s)
- TSN Backbone supports
  - 802.P - Quality of Service (= PROFINET RT)
  - 802.1AS – Synchronization
  - 802.1Qbv – Time Aware Shaper
  - 802.1Qbu + 802.3Qbr – Frame preemption
  - (802.1CB – Seamless redundancy)*





# Research Questions

**“Which TSN mechanisms ensure that PN traffic is protected against Best-Effort (BE) netload (bursts)?”**

**“What are the advantages of upgrading to Gbit/s?”**

**“How do TSN features such as Time Aware Shaper and preemption influence the end-to-end delay of PN frames?”**

**“What is the optimal TSN domain configuration for a brownfield PN over TSN network using Time Aware Shaping and preemption?”**

# Introduction – Use Case

- Tunneling PROFINET Traffic over a TSN domain NOT configured by a PROFINET network manager

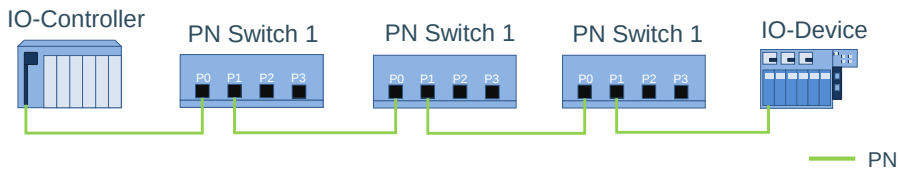


# Brownfield PROFINET RT over TSN – principles

- Introduction
- **Brownfield PROFINET RT over TSN – principles**
- Test network: topology and configuration
- Performance evaluation
  - PROFINET RT
  - Brownfield PROFINET RT over TSN
- Conclusion

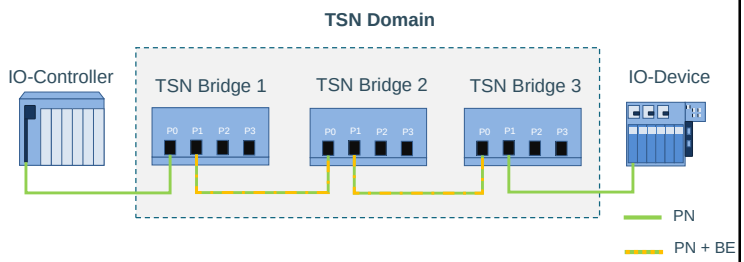
# PROFINET RT Network

- **Real-Time** behaviour
  - **802.1P Quality of Service (QoS)** (Strict prioritization)
  - Absence of other traffic types
- **No OT/IT Convergence**
- Unsynchronized
- 100 Mbit/s
- Configured in IO-Controller




# Brownfield PROFINET over TSN network

- PN application “pipelined” over TSN domain
- **Real-Time** behaviour
  - **QoS + TSN Features**
    - Time Aware Shaper
    - Preemption
- TSN Domain
  - Synchronized
  - Independent configuration
  - **OT/IT Convergence**
  - 10/100/1000 Mbit/s




→ **PN and TSN Clock unsynchronized!**

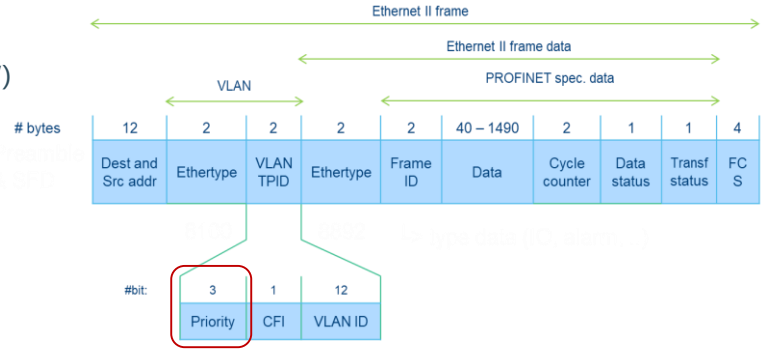
→ **TSN domain invisible to PN application**

# PN RT – QoS mechanism

- Priorities
  - 0 → 7
  - PN RT = priority 6
  - Best-Effort (BE) = priority 0 (this demonstrator)
  - Highest priority transmitted first
  - Doesn't solve everything
    - No guaranteed bandwidth (BW)
    - Congestion?
    - Equal priorities?

→ **No other traffic types allowed**

→ **Restrict total netload!**

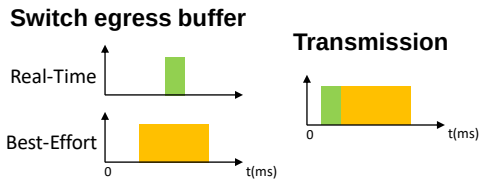




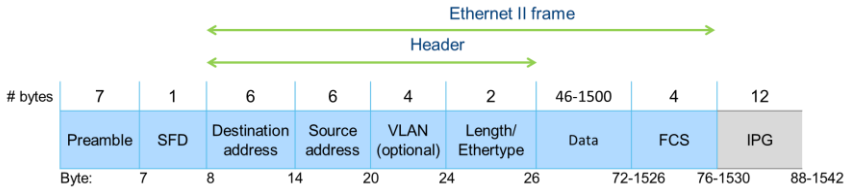

# PN RT – how are PN frames delayed?

- PN frames get stuck in egress buffer while Best-Effort (BE) frame is transmitting
  - Delay dependent on BE frame length
  - Delay can accumulate in every switch hop

- Max frame length: 1542 bytes
  - Max. delay 100BASE-TX ~ 123,360 µs
  - Max. delay 1000BASE-T ~ 12,336 µs




- All frame lengths include PRE, SFD, FCS, IPG



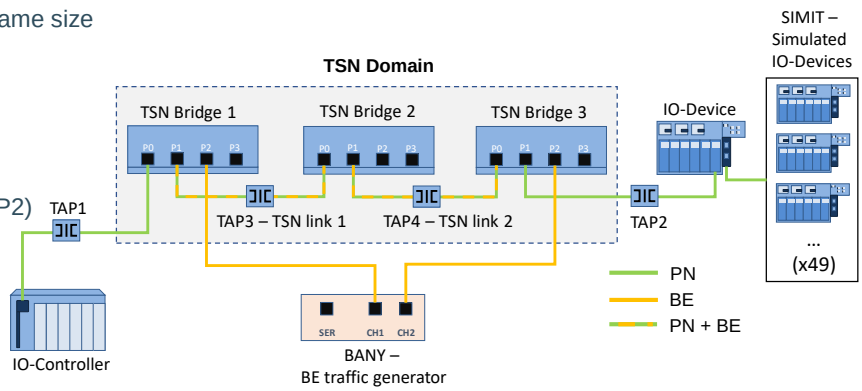
# Test network: topology and configuration

- Introduction
- Brownfield PROFINET RT over TSN – principles
- **Test network: topology and configuration**
- Performance evaluation
  - PROFINET RT
  - Brownfield PROFINET RT over TSN
- Conclusion



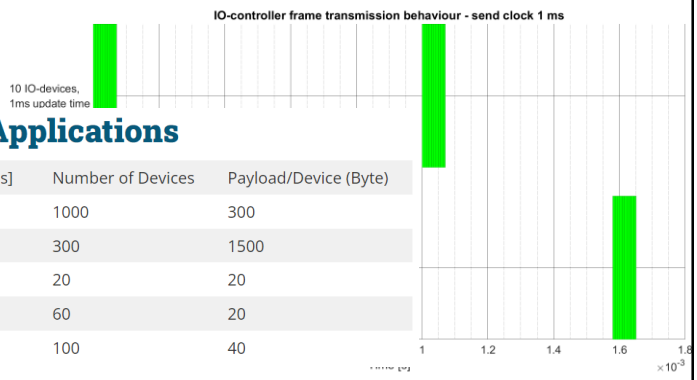
# Performance evaluation of brownfield PN over TSN

- **Industry relevant PN network**
  - 50 IO-Devices @ 1 ms → 35% PN netload
  - Relevant for all networks with update times ≥ 1 ms
- **OT/IT Convergence** → Injection of Best-Effort (BE) traffic
  - Strict control of netload and frame size
    - 35% BE Netload
    - 1538 byte frame length
  - Artificial traffic generation
- **Analysis**
  - End-to-end delay (TAP1 – TAP2)
  - TSN behaviour (TAP3, TAP4)
  - Demonstration on stand!



# IO-Controller transmission behaviour – send clock and update times

- IO-Controller spreads frame transmission over send clock
  - Send clock ≤ update time
- Identical transmission behaviour with…
  - 40 IO-Devices @ 4 ms
  - 10 IO-Devices @ 1 ms




## Typical Requirements of Industrial Applications

| Industrial Application | Cycle Time (ms) | Synchronization Accuracy [µs] | Number of Devices | Payload/Device (Byte) |
|---|---|---|---|---|
| Condition Monitoring | 100 | 1 | 1000 | 300 |
| Process Automation | 10-100 | 1000 | 300 | 1500 |
| Machine Tool | 1 | 0, 5 | 20 | 20 |
| Packaging Machines | 1 | 5 | 60 | 20 |
| Printing Machines | 2 | 0, 25 | 100 | 40 |

*https://iebmedia.com/technology/tsn/experimental-evaluation-of-tsn-timing-performance/*



# TSN Backbone

- 3x Relyum RELY-TSN-BRIDGE
- Line Topology
- **Store and Forward**
- 10/**100/1000** Mbit/s
- Currently supported TSN standards
  - 802.1AS – Synchronization
  - 802.1Qbv – **Time Aware Shaper**
  - 802.1Qbu + 802.3Qbr – **Frame preemption**
  - (802.1CB – Seamless redundancy)

*RELY_TSN_BRIDGE*

- Introduction
- Brownfield PROFINET RT over TSN – principles
- Test network: topology and configuration
- **Performance evaluation**
  - **PROFINET RT**
  - **Brownfield PROFINET RT over TSN**
- Conclusion

# Performance evaluation



# Test setup - summary

**Hilscher netANALYZER**
- End-to-end delay measurement
- ± 5 ns accuracy, 1 ns resolution
- $t_{(end-to-end)} = t_{TAP2} - t_{TAP1}$




**PROFINET load**
- 50 IO-Devices
- 1 ms update tim

= 35% PN load

**Best-Effort load**
- Long frames - 1538 bytes
- 35 Mbit/s on 100BASE-TX
- 350 Mbit/s on 1000BASE-T)

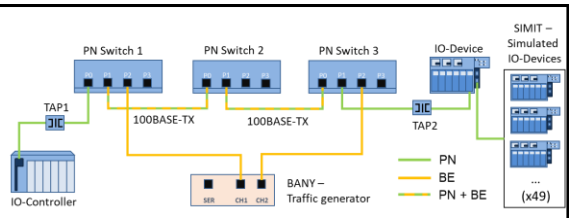
# Analysis of a brownfield PN over TSN network

- Comparison of different network configurations
  - **Standard PN network – benchmark**
  - Brownfield PN over TSN
    - Time Aware Shaper
    - Preemption
    - Time Aware Shaper + preemption

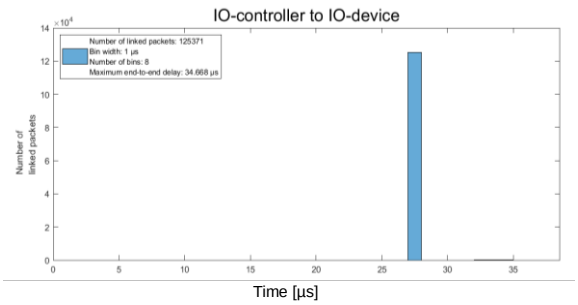


# Standard PN

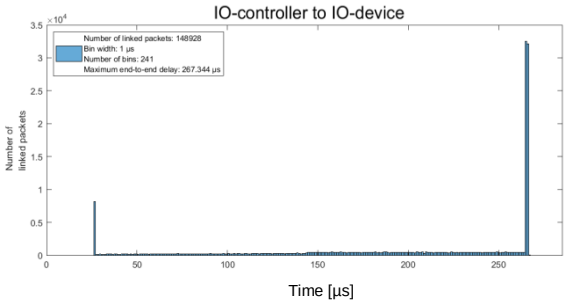
- Line topology – **3 switches**
- 100BASE-TX
- BE traffic: 35% Netload, 1538 byte frame length
- **BE traffic greatly increases delay!**




**End-to-end delay – no BE traffic**

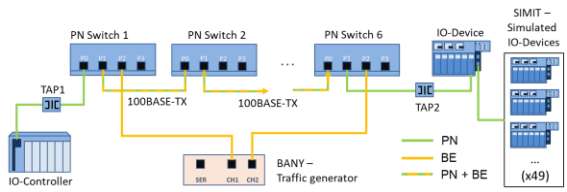



**End-to-end delay – with BE traffic**

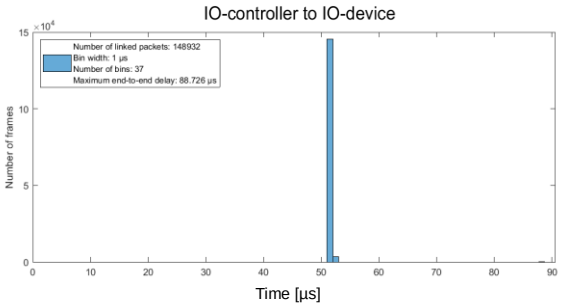


# Standard PN

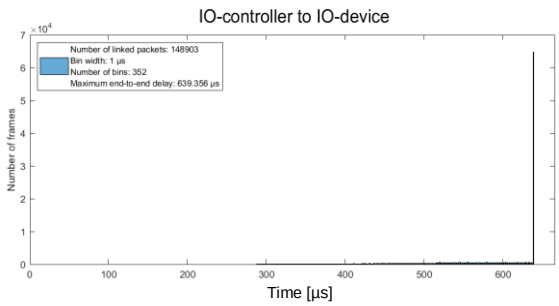
- Line topology – **6 switches**
- 100BASE-TX
- BE traffic: 35% Netload, 1538 byte frame length
- **BE traffic greatly reduces delay!**




**End-to-end delay – no BE traffic**



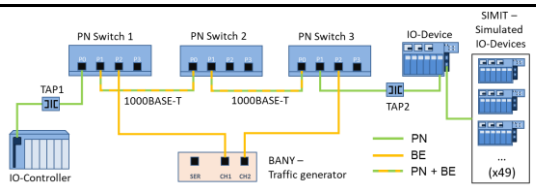

**End-to-end delay – with BE traffic**



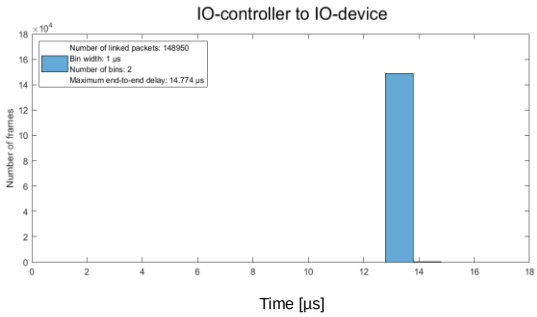



# Standard PN

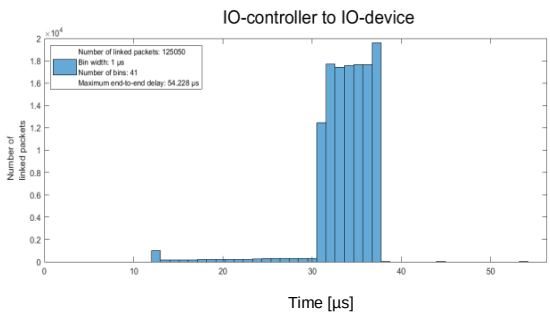
- Line topology – **3 switches**
- **1000BASE-T**
- BE traffic: 35% Netload (350 Mbit/s), 1538 byte frame length
- **BE traffic greatly reduces delay!**




**End-to-end delay – no BE traffic**

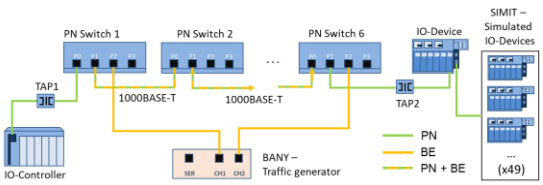



**End-to-end delay – with BE traffic**

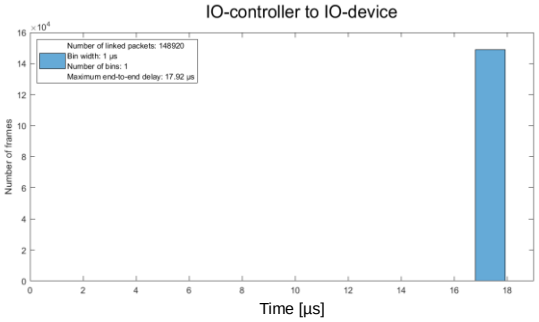


# Standard PN

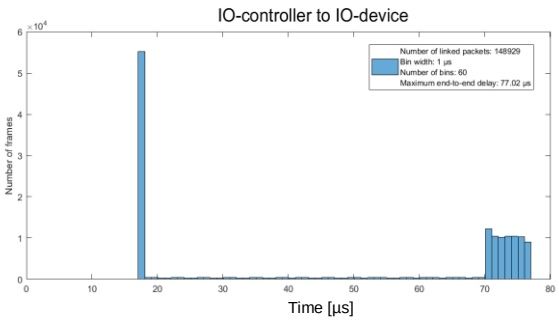
- Line topology – **6 switches**
- 1000BASE-T
- BE traffic: 35% Netload (350 Mbit/s), 1538 byte frame length
- **BE traffic greatly reduces delay!**




**End-to-end delay – no BE traffic**




**End-to-end delay – with BE traffic**






# End-to-end delay in standard PN networks

- IT load causes PN frame delay
  - …Especially in larger networks!
  - Accumulated delays can exceed update time
    - Frame gaps!
    - Line depth restrictions (PN Guideline)
- Upgrading to 1000BASE-T?
  - 10x increase in available bandwidth (BW)
    - OT BW remains identical (< 100 Mbit/s)
    - High **reserve BW** available for **IT applications**
  - Reduced forwarding and transmission delay
    - Allows increased line depth
  - Still based on PN RT
    - No guaranteed bandwidth
    - Delay accumulation

**Table 5-2: Maximum line depth with "Store and Forward" switches**

| Maximum line depth with update time of | | | |
|---|---|---|---|
| **1 ms** | **2 ms** | **4 ms** | **8 ms** |
| 7 | 14 | 28 | 58 |

*PN Commissioning Guideline*

# Analysis of a brownfield PN over TSN network

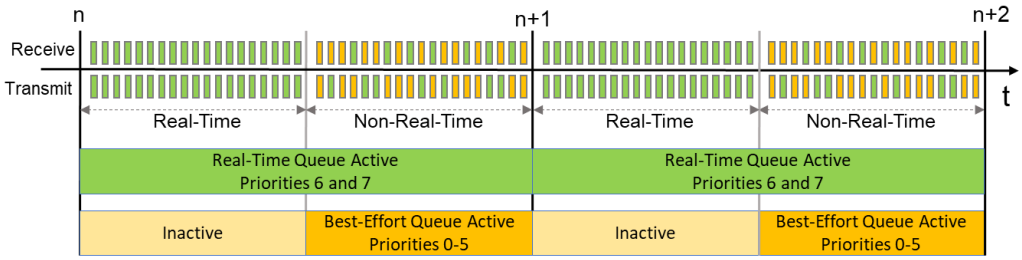
- Comparison of different network configurations
  - Standard PN network – benchmark
  - **Brownfield PN over TSN**
    - **Time Aware Shaper**
    - Preemption
    - Time Aware Shaper + preemption



# Principles of Time Aware Shaping (TAS)

- Extension to 802.1P QoS
- RT and BE traffic based on priorities
- Time windows assigned to traffic types
- **Guaranteed bandwidth** for RT

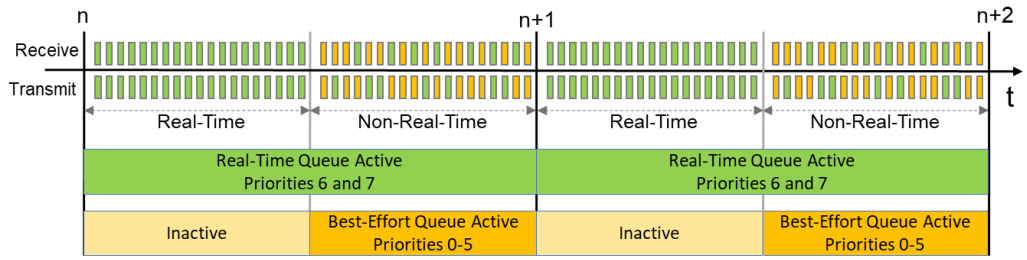
**Time Aware Shaper – example**



# Time Aware Shaper – Configuration

- Fully integrated TSN network → RT traffic scheduled in RT window
- Brownfield PN over TSN → TSN and PN unsynchronized!
  - **RT Queue always active**
    - PN frames may always be transmitted
    - PN frames not delayed when no BE traffic exist

**Time Aware Shaper – example**

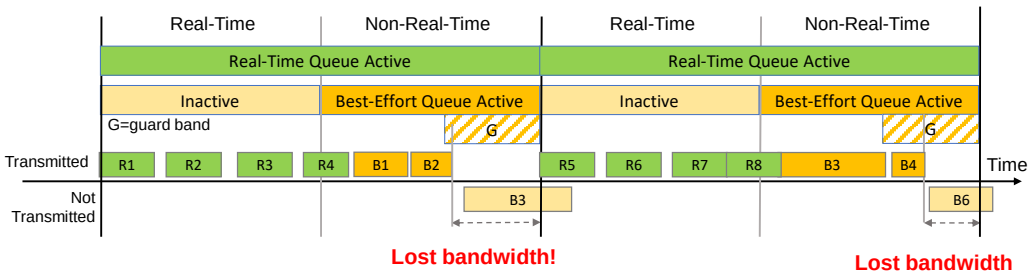





# Time Aware Shaper – guard band

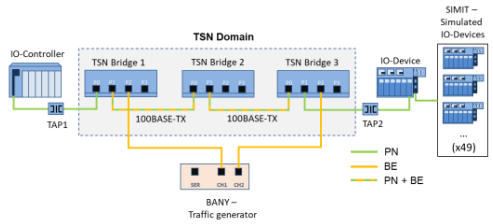
- TAS can reduce available bandwidth
- Frames can be dropped even if total netload < 100%

**Time Aware Shaper – example**

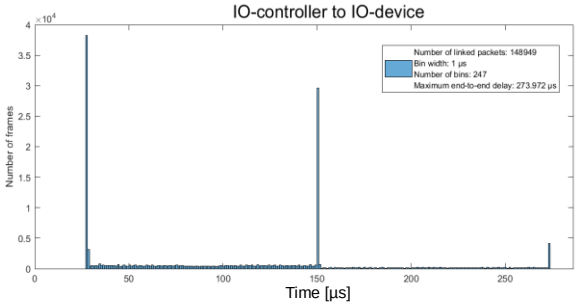


# PN over TAS - Measurements

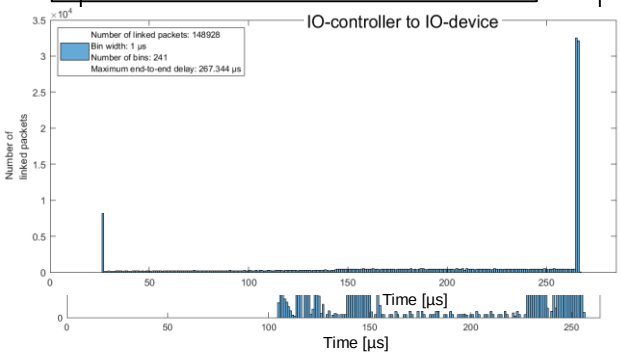
- 100BASE-TX
- TAS window size: 125 µs and 500 µs
- Max. end-to-end delay not reduced




**End-to-end delay – TAS window size 125 µs**




**End-to-end delay – PN RT with BE traffic**

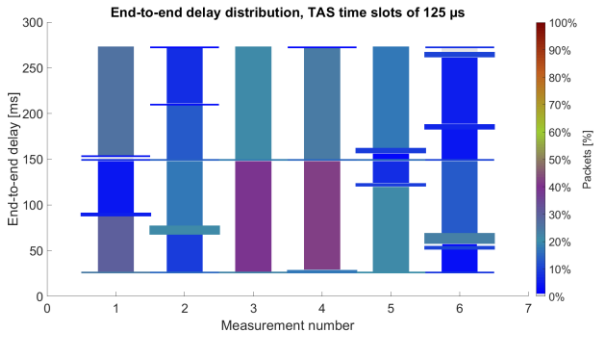




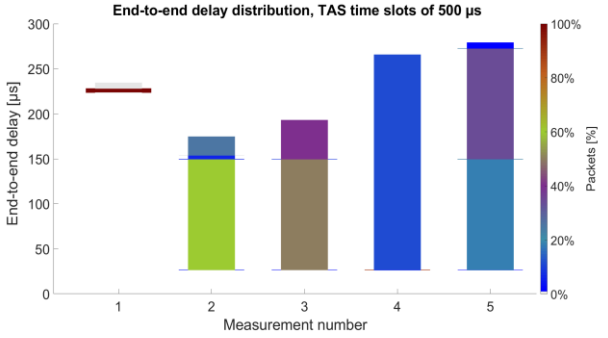

# TAS - Results

- Distribution of end-to-end delays

**End-to-end delay – TAS window size 125 µs**

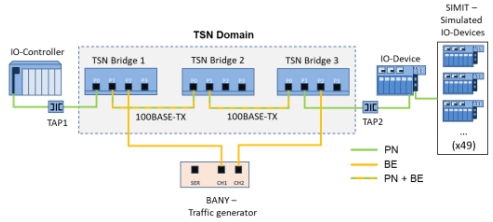



**End-to-end delay – TAS window size 500 µs**

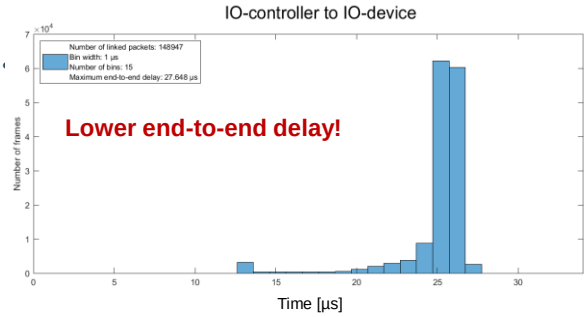


# PN over TAS - Measurements

- 1000BASE-T
- TAS window size: 15,625 µs and 125 µs
- Max. end-to-end delay reduced with small TAS window!



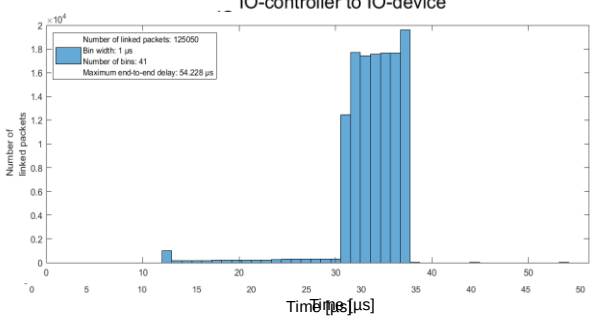

**End-to-end delay – TAS window size 15,625 µs**




**Lower end-to-end delay!**

**End-to-end delay – PN RT with BE traffic**

**End-to-end delay – TAS window size 125 µs**





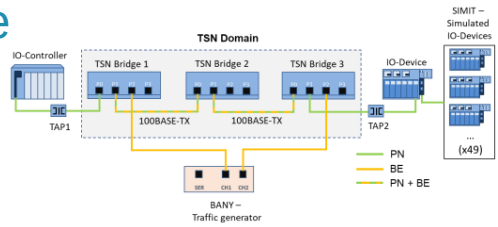

# PN over TAS – Conclusion

- TAS does **not guarantee** a lower end-to-end delay
- TAS provides PN **bandwidth reservation**
  - Protection from netload bursts!
- Bandwidth might not fully be utilized (guard bands)
- Small TAS windows are preferred
  - Improved network predictability
  - Small TAS windows **can** improve end-to-end delay
  - Determine max. end-to-end delay with
    - PN load
    - TAS Configuration
    - Topology → **Impractical**

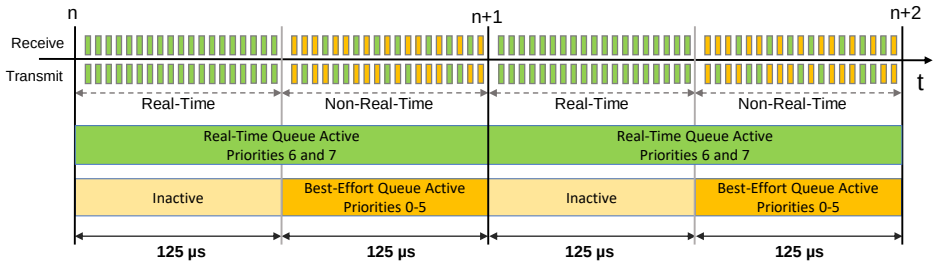
**Refer to CINI4.0 stand for further elaboration!**

# PN over TAS – Optimal window size

- Window size ≥ max. frame length
- Reserved RT bandwidth > PN netload
- E.g., 100BASE-TX optimal TAS configuration
  - 125 µs RT
  - 125 µs RT + BE




**Optimal TAS configuration for 100BASE-TX and 35% PN netload**

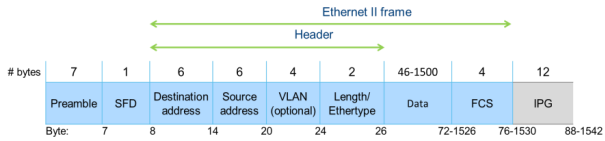




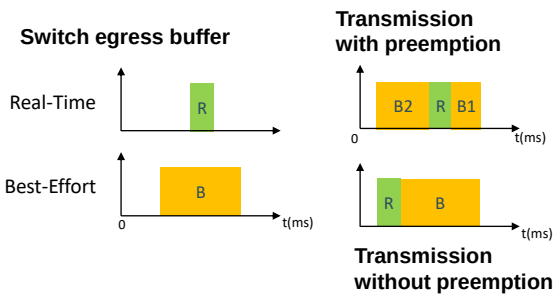

# Analysis of a brownfield PN over TSN network

- Comparison of different network configurations
  - Standard PN RT network – benchmark
  - Time Aware Shaper
  - **Preemption**
  - Time Aware Shaper + preemption

# Preemption - principles



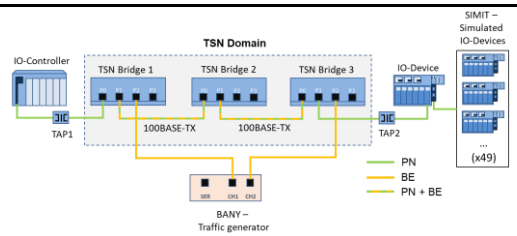

- RT Frames can interrupt BE frames
- Minimum fragment size: 84 bytes
- Max. non preemptable fragment: 143 bytes
- new PRE, SFD, CRC, IPG required!
  - 24 bytes overhead
- Preemption changes SFD field





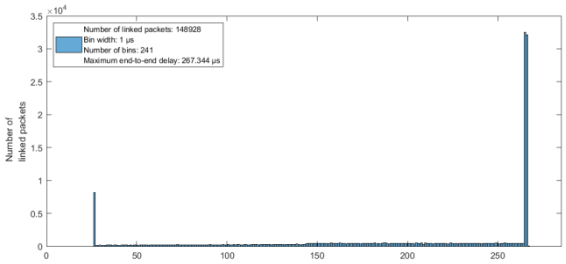

# Preemption - measurements

- 100BASE-TX
- BE traffic: 35% Netload, 1538 byte frame length
- **End-to-end delay greatly reduced**



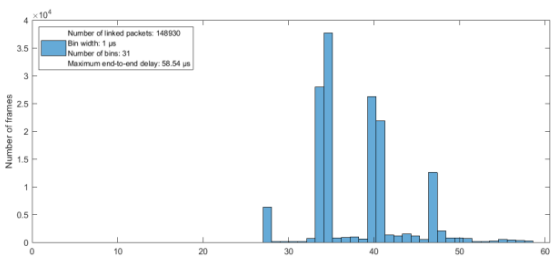

**End-to-end delay – PN RT with BE traffic**

IO-controller to IO-device



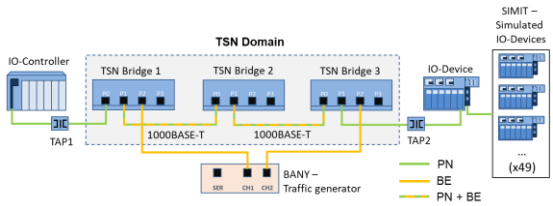

**End-to-end delay – Preemption with BE traffic**

IO-controller to IO-device



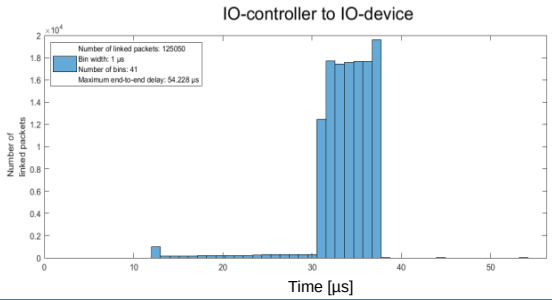
# Preemption - measurements

- 1000BASE-T
- BE traffic: 35% Netload (350 Mbit/s), 1538 byte frame length
- **End-to-end delay greatly reduced**

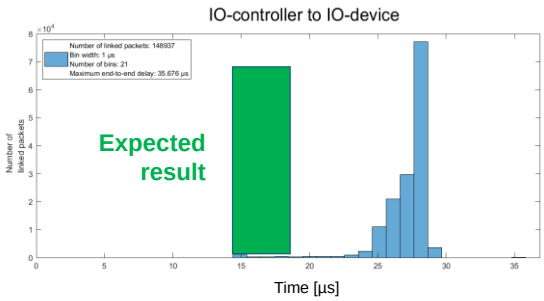



**Issues exist 1000BASE-T preemption implementation, we are in contact with vendor to clarify this!**

**End-to-end delay – PN RT with BE traffic**




**End-to-end delay – Preemption with BE traffic**






# Preemption – conclusion

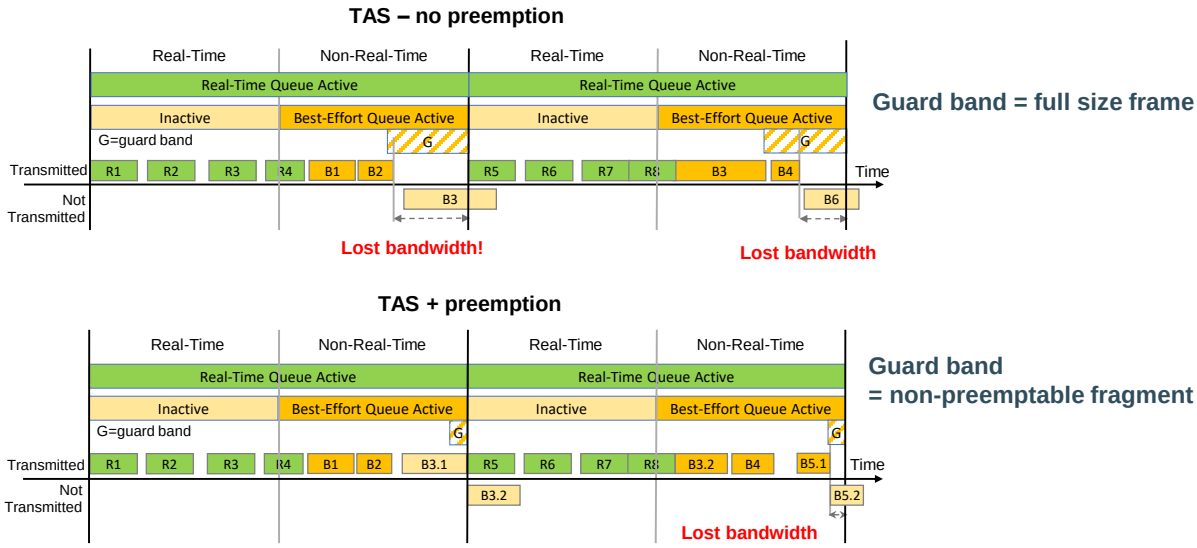
- Preemption greatly reduces end-to-end delay

# Analysis of a brownfield PN over TSN network

- Comparison of different network configurations
  - Standard PN RT network – benchmark
  - Time Aware Shaper
  - Preemption
  - **Time Aware Shaper + preemption**

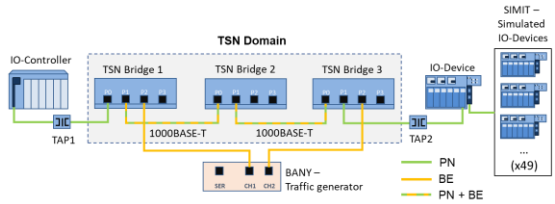


# TAS + preemption – reduced guard bands

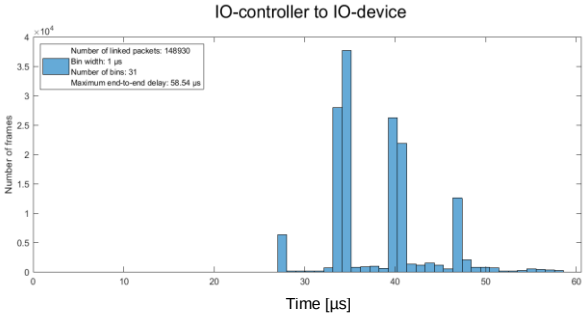


# TAS + preemption

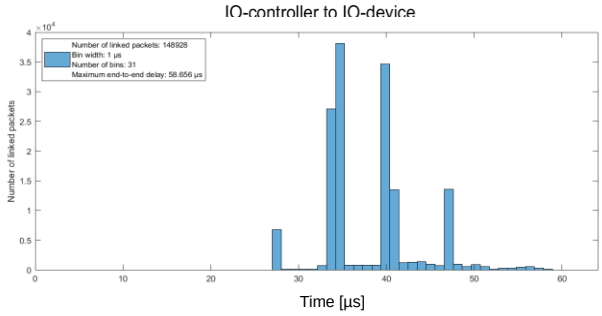
- 100BASE-TX
- BE traffic: 35% Netload, 1538 byte frame length
- **End-to-end delay identical to preemption stand alone**
- **TAS window size does not influence delay**




**End-to-end delay - Preemption stand alone – with BE**



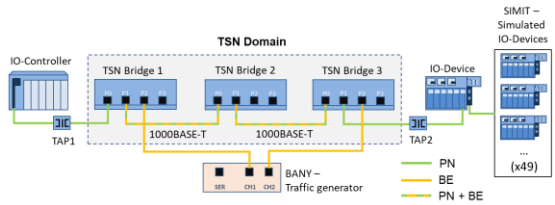

**End-to-end delay - TAS 125 µs + Preemption – with BE**



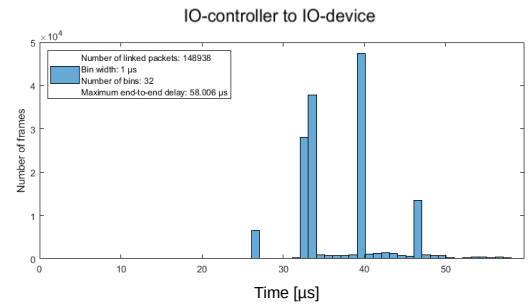



# TAS + preemption

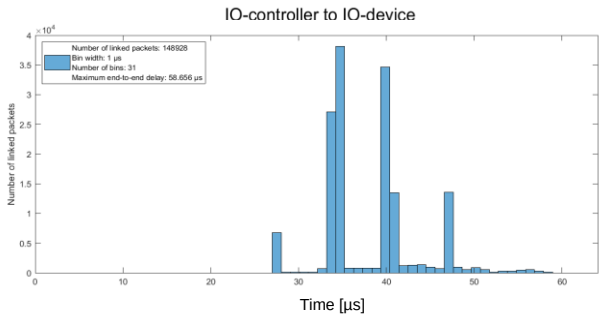
- 100BASE-TX
- BE traffic: 35% Netload, 1538 byte frame length
- **End-to-end delay identical to preemption stand alone**
- **TAS window size does not influence delay**




**End-to-end delay - TAS 15,625 µs + Preemption – with BE**

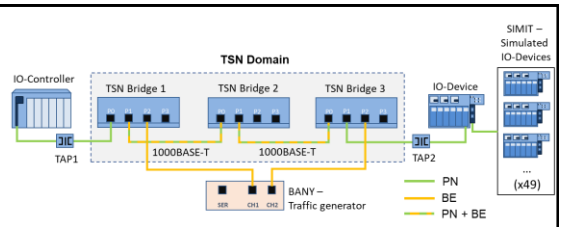



**End-to-end delay - TAS 125 µs + Preemption – with BE**



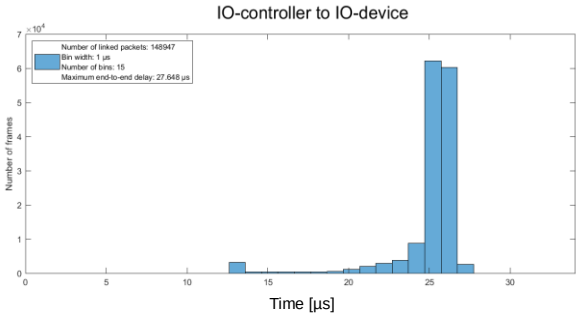
# TAS + preemption

- 1000BASE-T
- BE traffic: 35% Netload (350 Mbit/s), 1538 byte frame length
- **End-to-end delay greatly reduced**
- **TAS window size does not influence delay**

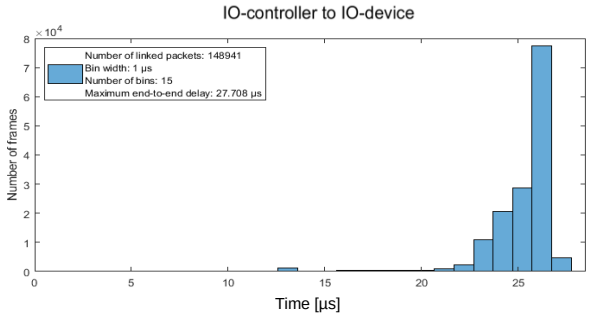



**Issues exist 1000BASE-T preemption implementation, we are in contact with vendor to clarify this!**

**Preemption stand alone – with BE**



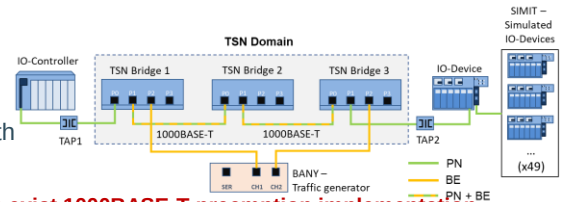

**TAS 125 µs + Preemption – with BE**





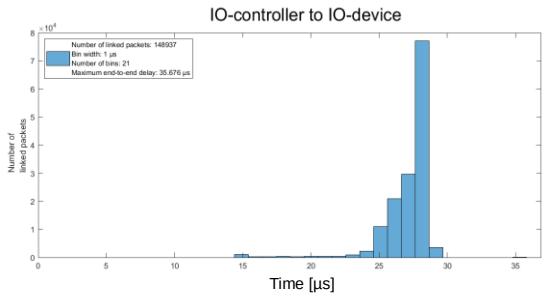

# TAS + preemption

- 1000BASE-T
- BE traffic: 35% Netload (350 Mbit/s), 1538 byte frame length
- **End-to-end delay greatly reduced**
- **TAS window size does not influence delay**

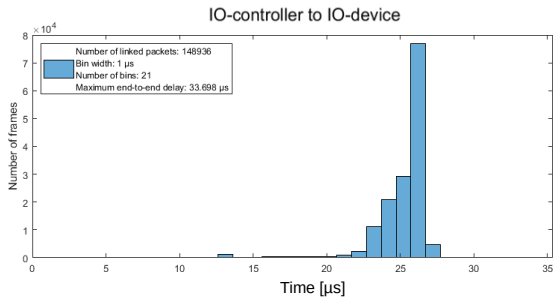



**Issues exist 1000BASE-T preemption implementation, we are in contact with vendor to clarify this!**

**Preemption stand alone – with BE**




**TAS 15,625 µs + Preemption – with BE**



# TAS + preemption - Conclusion

- TAS → bandwidth protection
  - Window size irrelevant
- Preemption → low end-to-end delay
- TAS + preemption → increased bandwidth utilization



# Conclusion

- Introduction
- Brownfield PROFINET RT over TSN – principles
- Test network: topology and configuration
- Performance evaluation
  - PROFINET RT
  - Brownfield PROFINET RT over TSN
- **Conclusion**

# Brownfield PN over TSN - Conclusion

- Optimal configuration for **this demonstrator**
  - TAS + preemption = optimal configuration
    - Preemption provides low end-to-end delay
      - Deeper line depth allowed!
    - TAS protects PN traffic
    - Small guard band provide efficient BW use

- Upgrading to **1000BASE-T**
  - Provides high BW reserve for IT applications
  - Forwarding and transmission delay greatly reduced
    - Deeper line depth allowed!
    - Delay improvements almost identical to implementing preemption on 100BASE-TX



# Remarks

- TAS is designed for scheduled synchronized traffic
  - Not for BW reservation!
- Other standards exist specifically for BW reservation
  - 802.1Qci – Ingress Protection
  - Protects TSN domain from netload bursts
  - Ensures that only PN frames have high priority!
    → **Method used in PN 2.4!**
- For brownfield PN over TSN
  - 802.1Qci Ingress protection can replace TAS
    → **Future work for CINI4.0**