TSN for critical systems:
feedback from the multi-industry EDEN project

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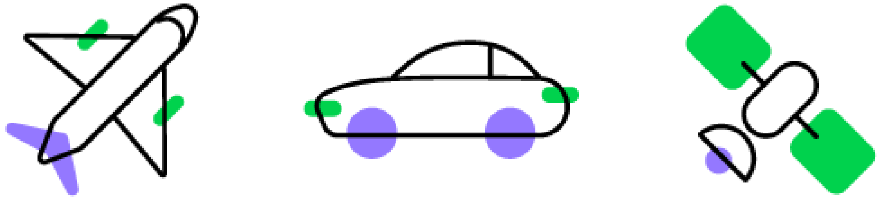
Introduction

EDEN Project

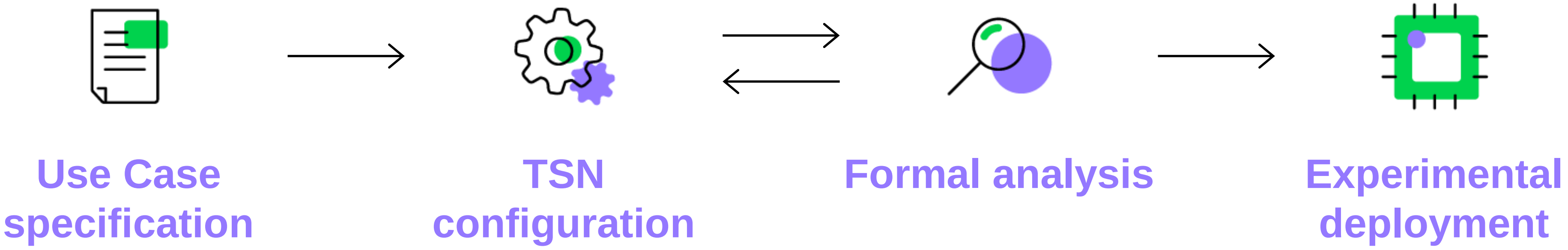
EDEN : Evaluation of a Deterministic Ethernet Network

- Get full confidence and enable deployment of Ethernet Time Sensitive Network (TSN) as embedded network for multi-domain architectures (aeronautic, automotive and spatial)
- 3 Years (2020 – 2023)



Introduction

Presentation organization



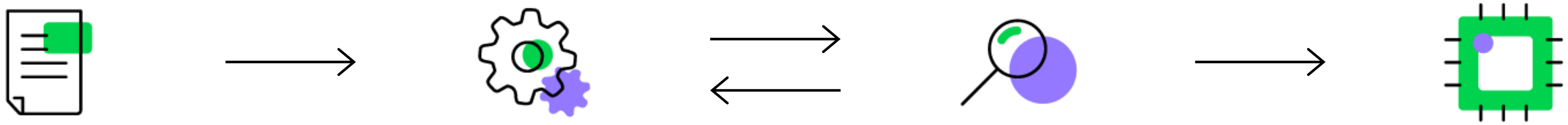
Use Case specification

TSN configuration

Formal analysis

Experimental deployment

Use Case Specification



Use Case specification

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FRENCH INSTITUTES OF TECHNOLOGY

Use Case Specification

Aircraft cockpit

Goal : Define an alternative to AFDX with a lower footprint and lower cost. More efficient with the same quality of service.

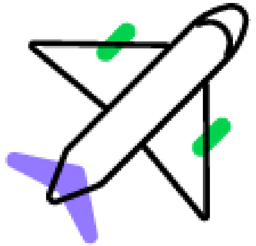
6
Switches

9
End Stations

19
Flows

Characteristics

- 1Gb/s network for cockpit audio digitalization
- Multiple paths for redundancy
- AVTP, Control, Data, Video



Use Case Specification

Automotive

Goal : New communication needs required by autonomous vehicle. Enable off-the-shelf systems in standard Ethernet with certifiable network.

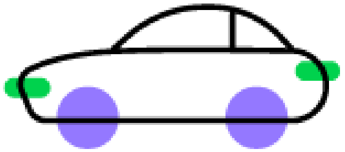
7
Switches

25
End Stations

73
Flows

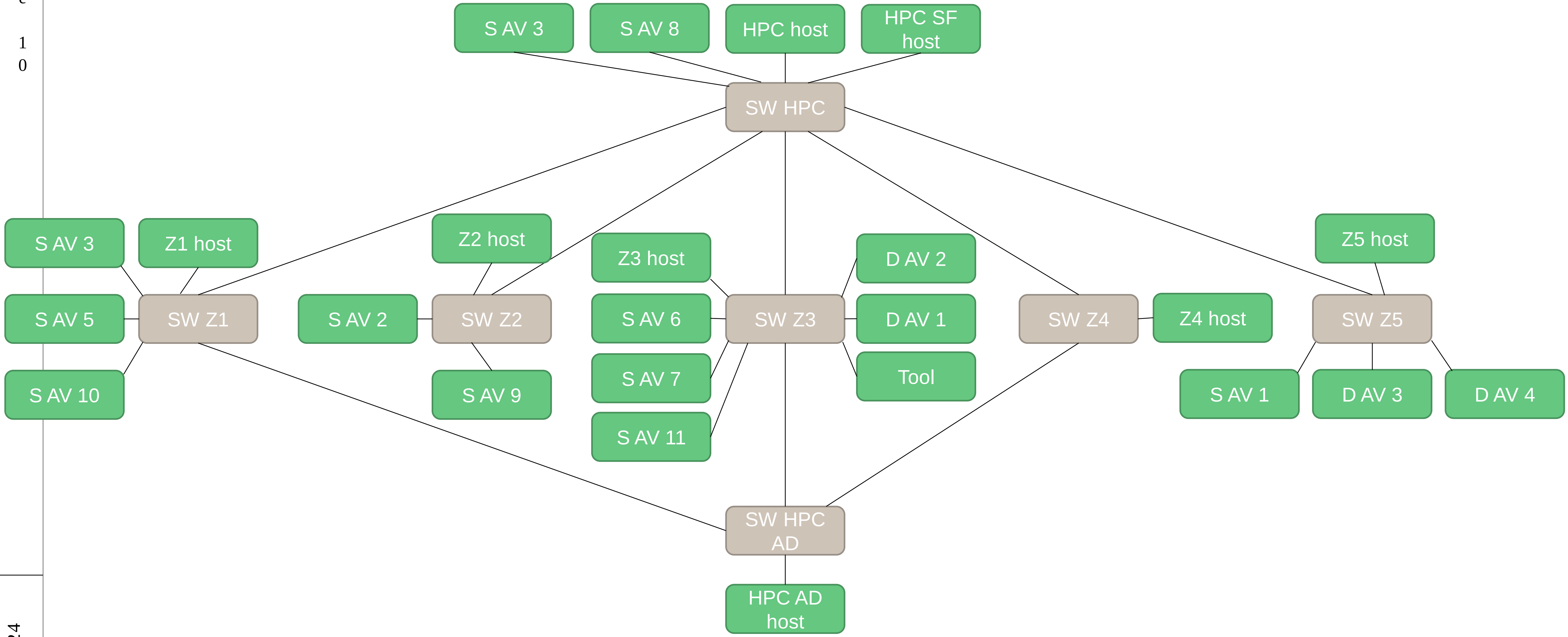
Characteristics

- 100Mb/s / 1Gb/s network for new zonal architectures
- Variable wired redundancy
- Best-effort, CAN over Ethernet, A/V and Some/IP



Use Case Specification

Automotive



Use Case Specification

Automotive

Traffic Classes	Number of flows	Burst size	Period (ms)	Payload size (Bytes)	Latency constraint (ms)	Jitter constraint (ms)
CC_LT	18	1	[4; 10]	[8; 123]	1	N/A
Env	11	[11; 29]	33,333	1500	[10; 33,33]	N/A
AV	4	[10; 22]	[1,25; 33,333]	[256; 1500]	[1,25; 33,333]	N/A
CC_MHL	36	1	[20; 1000]	[8; 105]	[2; 50]	N/A
BE	4	[1; 2860]	356	[32; 1500]	N/A	N/A

Use Case Specification

Satellite

Goal : Unified network for platform and payloads with increased performances. COTS as IP in space FPGAs (Switch and Endpoint) at low footprint, cost.

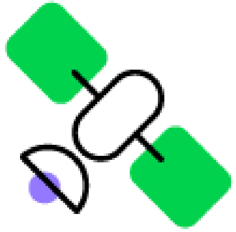
4
Switches

14
End Stations

101
Flows

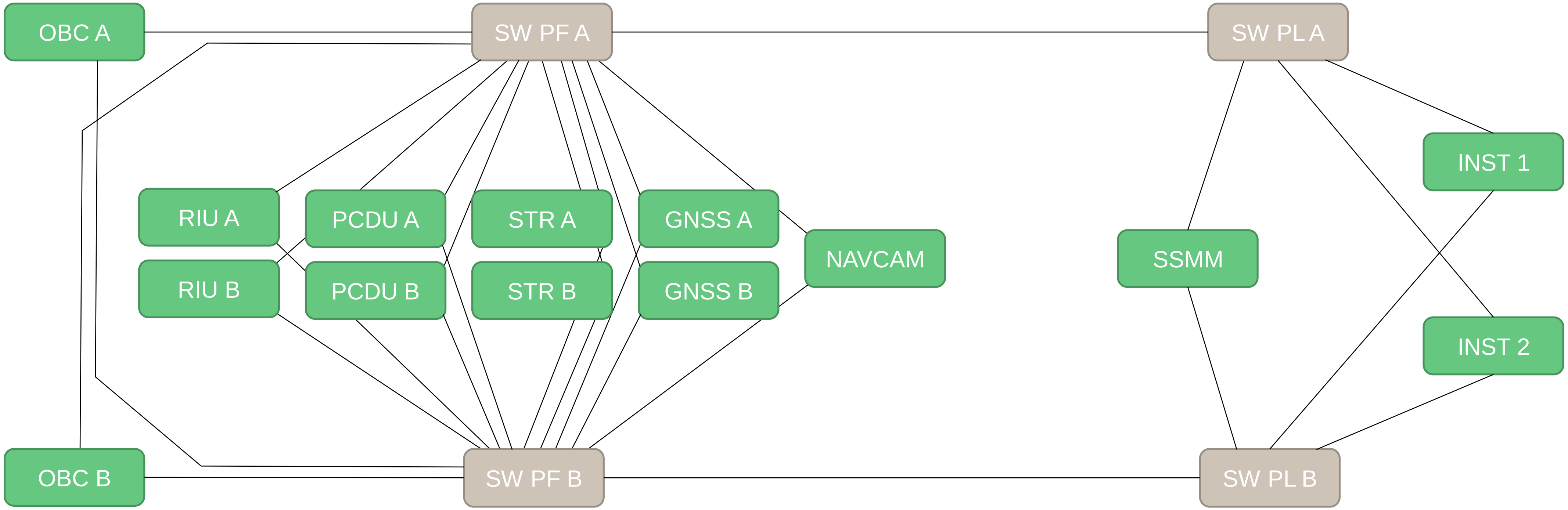
Characteristics

- 1Gb/s symetrical network
- Cold end-station redundancy
- Best-effort to Hard real-time
    - Low latency
    - Jitter control (<1µs)



Use Case Specification

Satellite

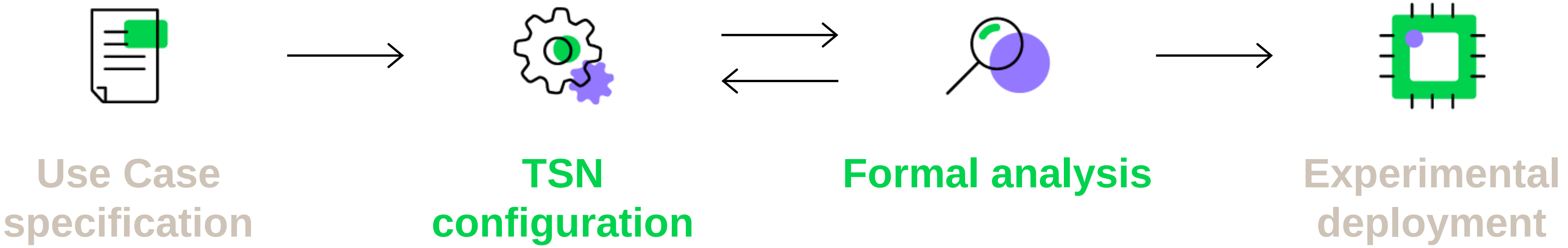


Use Case Specification

Satellite

Traffic Classes	Number of flows	Burst size	Period (ms)	Payload size (Bytes)	Latency constraint (ms)	Jitter constraint (ms)
C&C ultra low jitter	11	1	125	[32; 54]	N/A	0,001
C&C low jitter	3	1	125	[36; 508]	125	[0,5; 1]
Async urgent	1	1	1000	86	1	0,1
C&C Time window	24	1	[125; 1000]	[32; 1116]	[31,25; 1000]	N/A
Acquisition	23	1	[125; 1000]	[32; 1420]	[125; 10000]	N/A
Acquisition list	23	1	[125; 1000]	[32; 70]	[125; 1000]	N/A
VBN	1	777	33,33	1490	33,33	N/A
MEO	11	1	[125; 1000]	[2; 480]	[125; 1000]	[10; 1000]
PL high perf	1	4303	100	1490	1000	1
Instrument	3	[4; 717]	[1; 125]	[1024; 1490]	N/A	N/A

TSN configuration



Use Case specification

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Formal analysis

Experimental deployment

TSN configuration

Step 1

Make an initial mapping of a traffic class to a priority level according to their temporal constraints :

- Aircraft cockpit : 5 classes to map on 8 priority levels
- Automotive : 5 classes to map on 8 priority levels
- Satellite : 10 classes to map on 8 priority levels
  - The most constrained classes have a priority level of their own.
  - The least constrained classes are grouped together

TSN configuration / Formal analysis

Step 2 – TSN ?

Perform an initial formal analysis with vanilla Ethernet (BCTT, WCTT, backlog)

- Aircraft cockpit : all flows respect their temporal constraints
- Automotive : 8 flows fail to meet their latency constraints
  - Change one link to 1Gb/s : + 3 flows ➔ OK
  - Reroute other flows : + 5 flows ➔ OK
- Satellite : 12 flows fail to meet their jitter constraints
  - TAS on 2 ports to meet all the jitter constraints (>1µs) : + 12 flows ➔ OK

➔ Two of the use cases do not require TSN shaper

➔ Only the satellite need TSN shapers (on two ports)

➔ We also carried out evaluations with TSN shapers, even though this wasn't really necessary.

TSN configuration

Step 3 - Synchronization

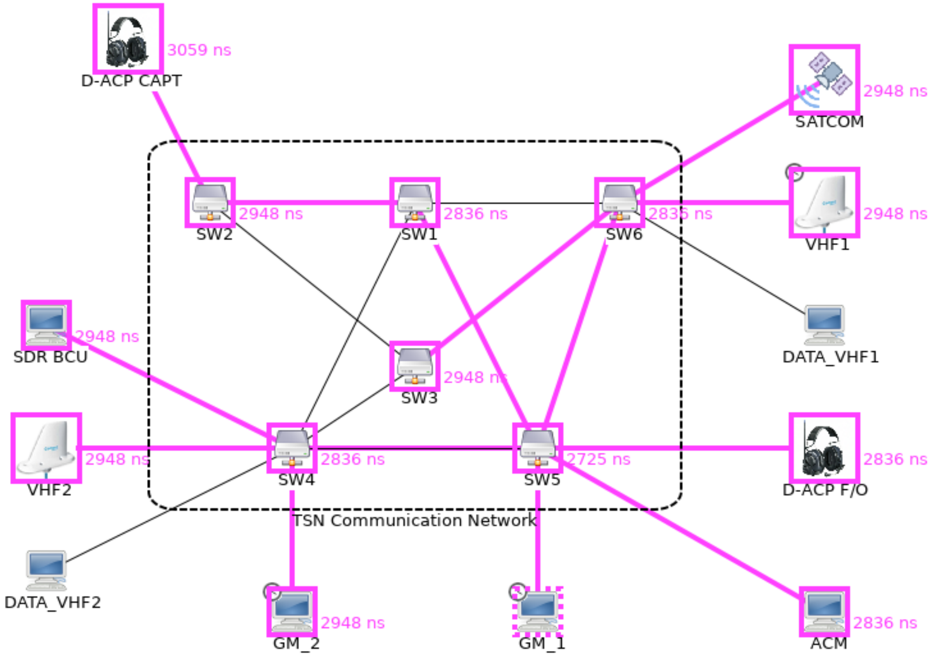
TSN isn’t just about traffic shaping ... Let's talk synchronization with gPTP :

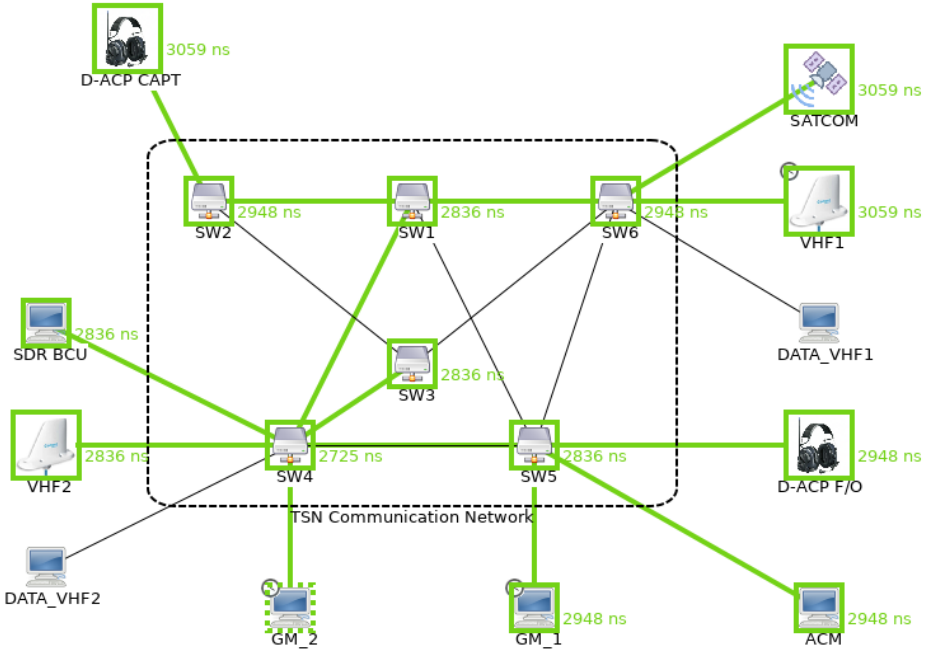
- Aircraft cockpit :
  - Need robust synchronization for synchronous audio playback(AVTP)
- Automotive :
  - Need robust synchronization for timestamping measurements
- Satellite :
  - Need robust synchronization for TAS and timestamping of measurements

TSN configuration

Step 3 - Synchronization

2 of the 4 gPTP domains for robust (multiple independent spanning trees) and precise (worst-case) synchronization on the aircraft use case.





➔ Jean-Luc Scharbarg : “On precision and robustness of IEEE802.1AS synchronization in TSN networks” in the 6th Workshop on Advanced Technologies in Industrial Vehicular Systems

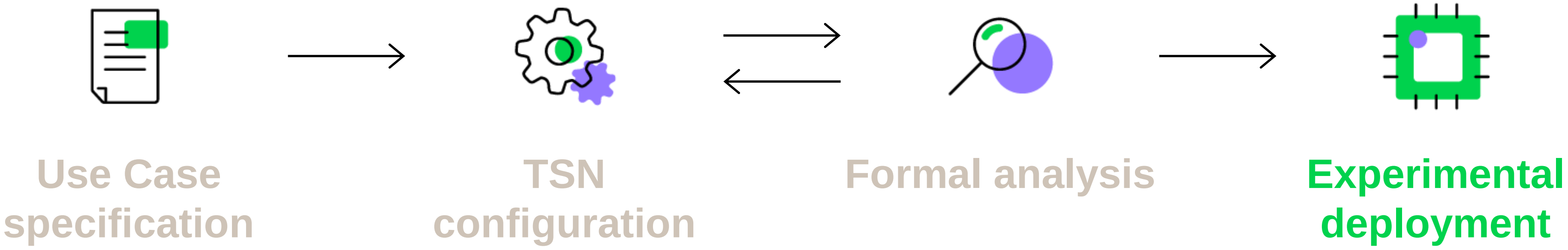
TSN configuration

Step 4 - FRER

TSN is not just about traffic shaping ... Let's talk reliability with FRER :

- Aircraft cockpit :
  - Three classes of traffic (Control_*, Audio) need FRER to withstand the failure of a single link or node.
  - Add 21 replicated paths ➔ Constraints are still respected
- Automotive :
  - Only one traffic class (ENV) needs FRER to withstand a single link or node failure
  - Add 16 replicated paths ➔ 2 latency constraints not met
  - Reroute 9 replicated paths : + 2 flows ➔ OK
- Satellite :
  - All flows are replicated
  - Nothing to change due to symmetrical topology

TSN configuration



Use Case specification

TSN configuration

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Experimental deployment

Experimental deployment

Toolchain presentation

A TSN network has a large number of configurable parameters (Forwarding table, TAS Schedule, CBS slope, Synchronization, Stream identification, Replication, Elimination, etc.)

➔ We need tools to support TSN's industrial use.

Experimental deployment

Toolchain presentation

Design Network

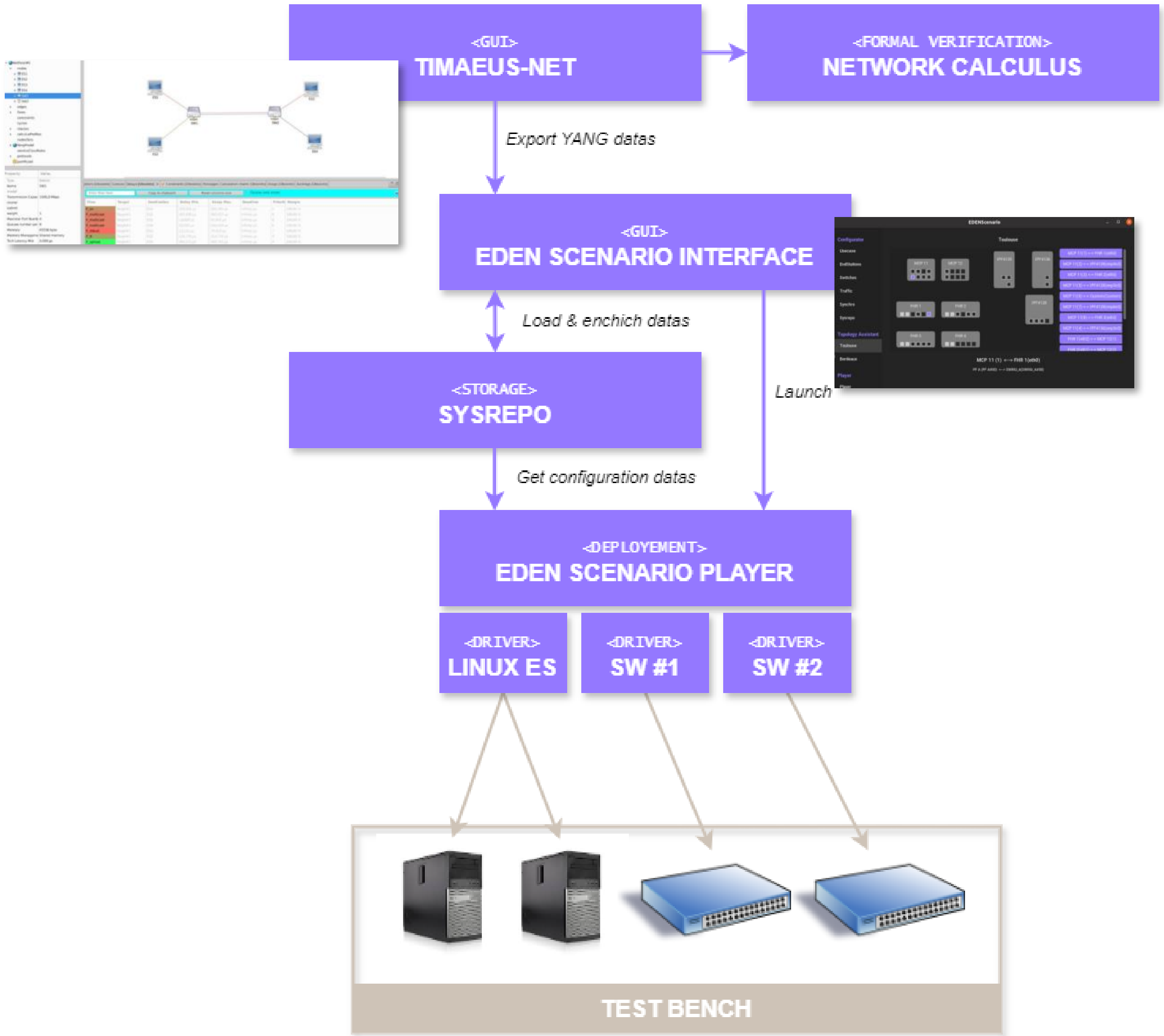
Define networks, traffic and TSN mechanism configuration

Store YANG models

Standards-compliant network definition data model

Play usecase scenario

Configure remote network hardware and run a traffic use case scenario



<GUI> TIMAEUS-NET

<FORMAL VERIFICATION> NETWORK CALCULUS

Export YANG datas

<GUI> EDEN SCENARIO INTERFACE

Load & enchich datas

<STORAGE> SYSREPO

Launch

Get configuration datas

<DEPLOYEMENT> EDEN SCENARIO PLAYER

<DRIVER> LINUX ES

<DRIVER> SW #1

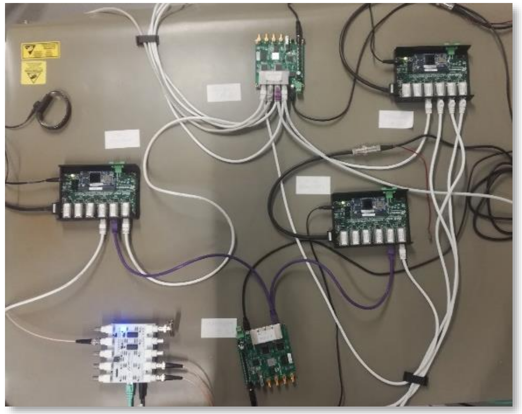
<DRIVER> SW #2

TEST BENCH

Experimental deployment

Toolchain presentation

- 2 generic test benches
  - 18 Multivendor switches
  - ~ 40 end stations
  - 100/1000Base-T + 10Base-T1S
  - GPS grandmaster clock
  - Simulated / real network traffic
  - Instruments :
    - PPS analyzer
    - Network TAPs + traffic capture on ES



Experimental deployment

Deployment feedback

Feedback on the use of the shaper on the hardware :

- CBS :
  - Works as expected
  - Can be easily used on a specific port (e,g. only on end stations or on a few switch ports)
- TAS :
  - It is possible to create highly optimized TAS schedules, but they often don't work.
    - Need to take into account the guardband, synchronization precision, application jitter, …
    - In the end, we simply oversize the windows by a factor of x
    - Schedule changes every time we add a new TAS flow. (not really ideal for a certification process)
- ATS :
  - We have not found any hardware implementation (2020/2021)

Experimental deployment

Deployment feedback

Feedback on the use of the shaper on the hardware :

- A lot of unwanted traffic (MDNS, …) due to linux ➔ cause temporal constraint violation
- Misconfigured traffic generators on CBS flows ➔ cause temporal constraint violation
- Some time trigger emission imprecision (Non RT OS, …) ➔ cause temporal constraint violation

➔ We need Per Stream Filtering and Policing (IEEE 802.1Qci)

Experimental deployment

Deployment feedback

Feedback on the use of synchronization on hardware :

- Few interoperability problems due to differences in timestamping points and clock quality :
  - Can be solved by allowing parameters such as *meanLinkDelayThresh* to be configured in the implementation.
- Static configuration and hot standby mechanism are very interesting for the critical embedded sector
  - Deterministic and faster reconfiguration time than BMCA
  - But only pre-standard test implementation
  - Deployment with BMCA

Experimental deployment

Deployment feedback

Feedback on the use of FRER on hardware:

- Seems to be a straightforward standard, but in reality offers a wide range of implementation options, leading to interoperability problems.
- Easy to misconfigure (Match vs Vector recovery, Individual recovery, …)
- Limitation when using passive stream identification function and multicast flow with static forwarding table
  - Can be bypassed by constraints on replicated paths (if there are enough paths available)

Experimental deployment

Deployment feedback

Feedback on configuration deployment and monitoring on hardware :

- SNMP is not really suited to configuration
- NETCONF/RESTCONF can configure and monitor but not implemented in the switches we use
  - Not really adapted for critical embedded networks
- A lighweight, YANG-based and standard configuration and monitoring protocol adapted to the need of critical embedded sector is required for industrial use of TSN.

Conclusion

Key takeaways :

- TSN mechanisms can help meet the needs of the critical embedded world
- Perhaps the attention given to the TSN shapers is a bit excessive (at least in our use cases).
- FRER and PSFP are the mechanisms that slow down the deployment of TSN in the critical embedded world.
- A lighweight, YANG-based configuration and monitoring protocol is needed for the critical embedded world.

Thank you for your attention!

Questions ?

References

Use cases :

- BARBERO, Massimo, LEYDIER, Thierry, CUENOT, Philippe *et al*. How to design a sage Ethernet TSN network on spacecraft application. In : DASIA 2023. 2023.

Synchronisation :

- BAILLEUL, Quentin, CUENOT, Philippe, JAFFRÈS-RUNSER, Katia, *et al.* Worst-case synchronization precision of IEEE802. 1AS. In : *2023 IEEE 28th International Conference on Emerging Technologies and Factory Automation (ETFA)*. IEEE, 2023. p. 1-8.
- BAILLEUL, Quentin, JAFFRÈS-RUNSER, Katia, SCHARBARG, Jean-Luc, *et al.* Assessing a precise gPTP simulator with IEEE802. 1AS hardware measurements. In : *11th European Congress on Embedded Real-Time Systems (ERTS 2022)*. 2022.
- BAILLEUL, Quentin. *Dimensioning TSN network synchronization in different embedded contexts*. 2023. Thèse de doctorat. Institut National Polytechnique de Toulouse-INPT.

Tool interoperability with YANG :

- CUENOT, Philippe, LEYDIER, Thierry, FRUCHARD, Damien *et al.* Yet another experience on TSN tools interoperability for critical embedded networks. In : *ERTS 2024*. 2024.
- https://sahara.irt-saintexupery.com/embedded-systems/eden-yang