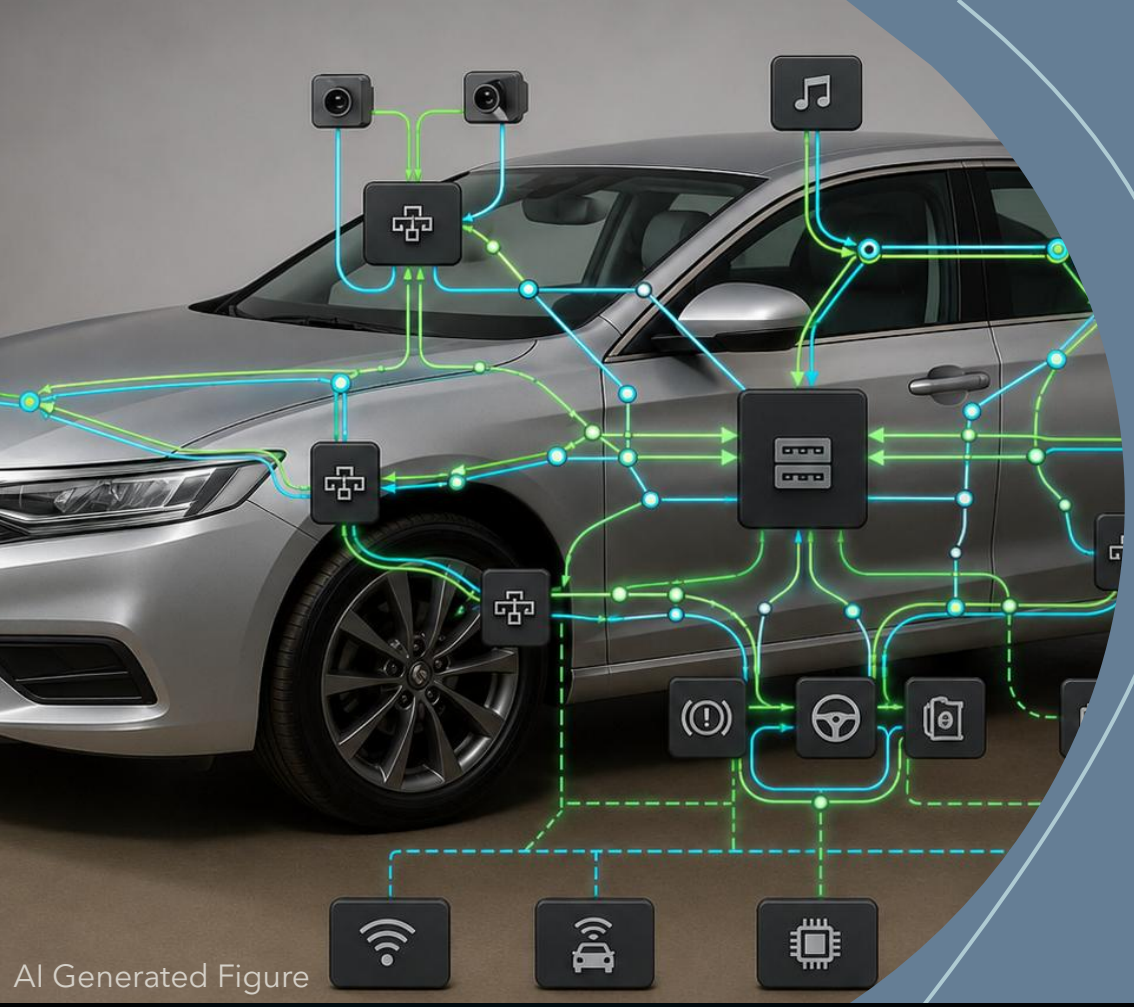

AI Generated Figure

Getting FRER Right

- Configuration Challenges for Reliable TSN Deployments

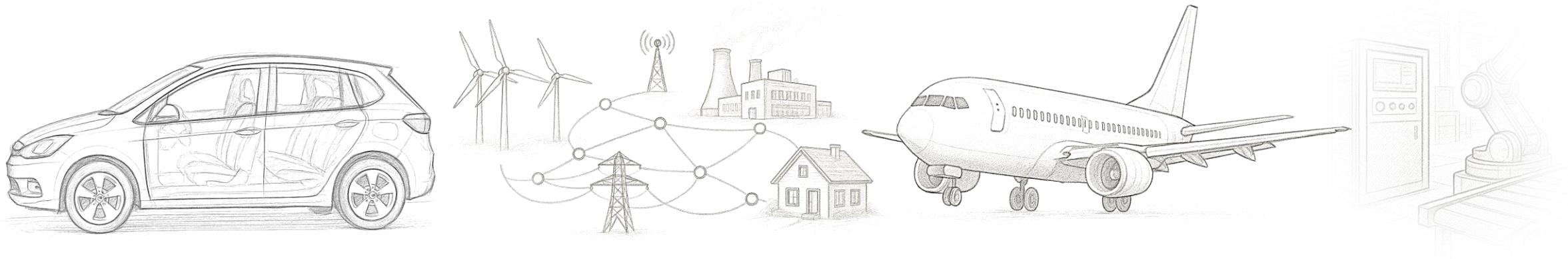
Prof. Dr. Lisa Maile, TU Eindhoven (Speaker)
Dr. Marc Boyer, ONERA
Prof. Dr. Nicolas Navet, University of Luxembourg
Leo Séguin, RealTime-at-Work

2026 ETHERNET & IP @ AUTOMOTIVE TECHNOLOGY DAY

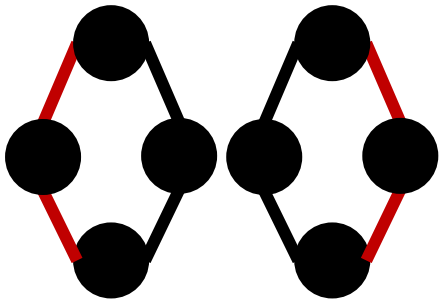
14-15 October, 2026 | Gothia Towers | Gothenburg, Sweden

Introduction

Why Network Redundancy?



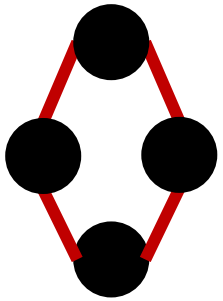
Recovery-based Redundancy



One active path

- Downtime:
  Failure Detection + Switchover

Seamless Redundancy



Continuous Replication

- Zero Downtime and No Information Loss

FRER in Standardization

[1] Balázs Varga, János Farkas, July 2019

[2] Balázs, Farkas, March 2020

[3] Maintenance 257, March 2020

[4] Balázs, Farkas, March 2020

[5] Maintenance 265, April 2020

[6] Balázs, Farkas, Sept 2020

[7] Balázs, Farkas, Fejes, Hoeftberger et al., May 2023

[8] Maile et al., Jun 2023

[9] Maile, June 2024

[10] IEEE Std. P802.1CBec, Feb 2025 – now

[11] Maintenance 378, March 2025

[12] Balázs, Farkas, May 2025

[13] McCall May 2025

[14] Balázs, Farkas, July 2025

[15] Steindl, Proell, July 2025

[16] Balázs, Farkas, September 2025

[17] Extending PAR & CSD for P802.1CBec, Nov 2025

[18] Maile (Discussion: McCall, Mangin, Turner, Varga), May 2026

[19] McCall et al., June 2026

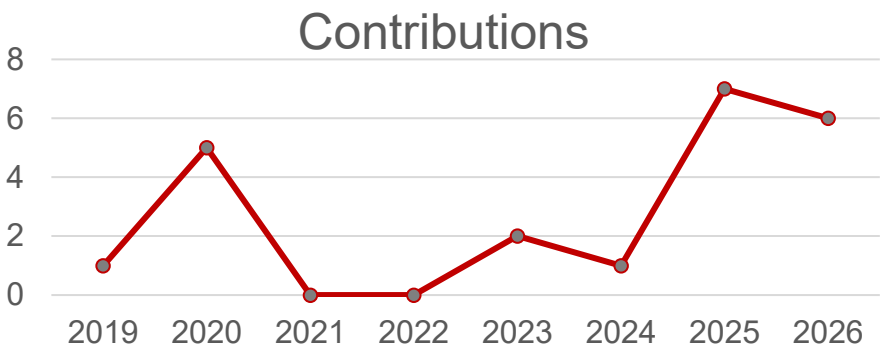
[20] Balázs, July 2026

[21] Balázs, Fejes, July 2026

[22] Maile, July 2026

[23] CBec Discussions (opcoming), September 2026

FRER receives more and more attention…

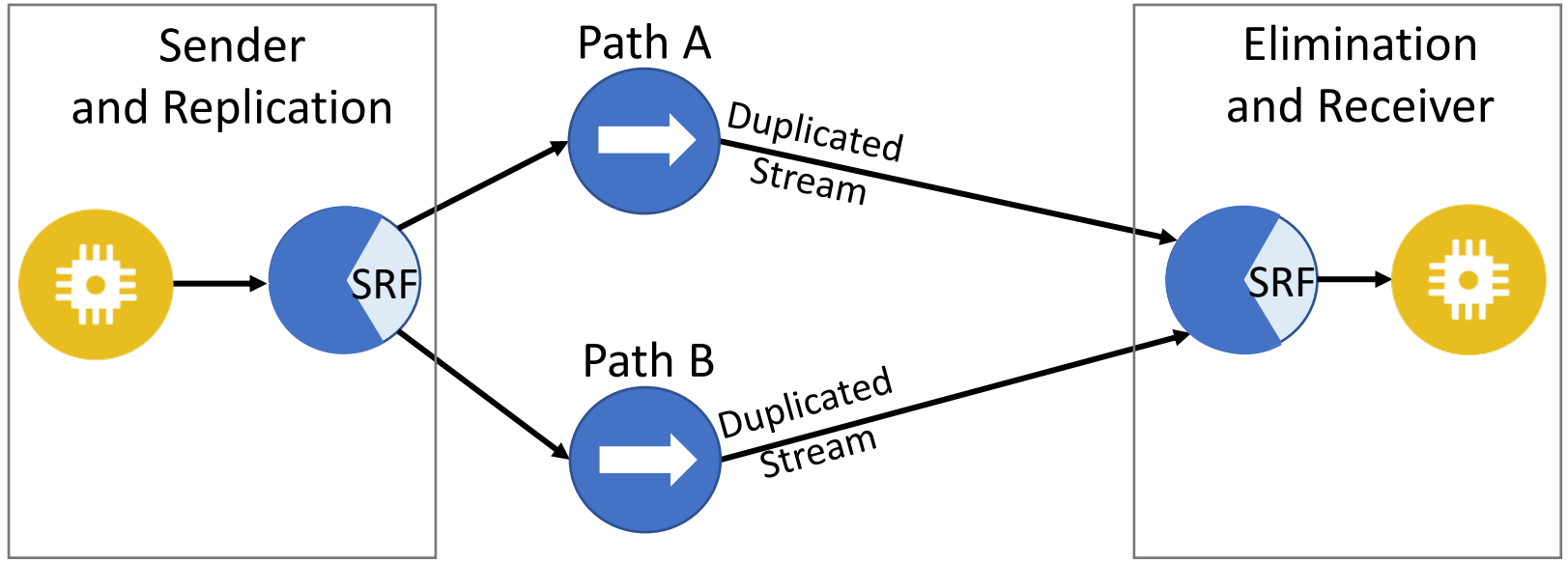


Introduction

FRER Principles

IEEE 802.1CB-2017 (Frame Replication and Elimination for Reliability - FRER):

Sending duplicate packet copies over multiple disjoint paths:



The Sequence Recovery Function (SRF)

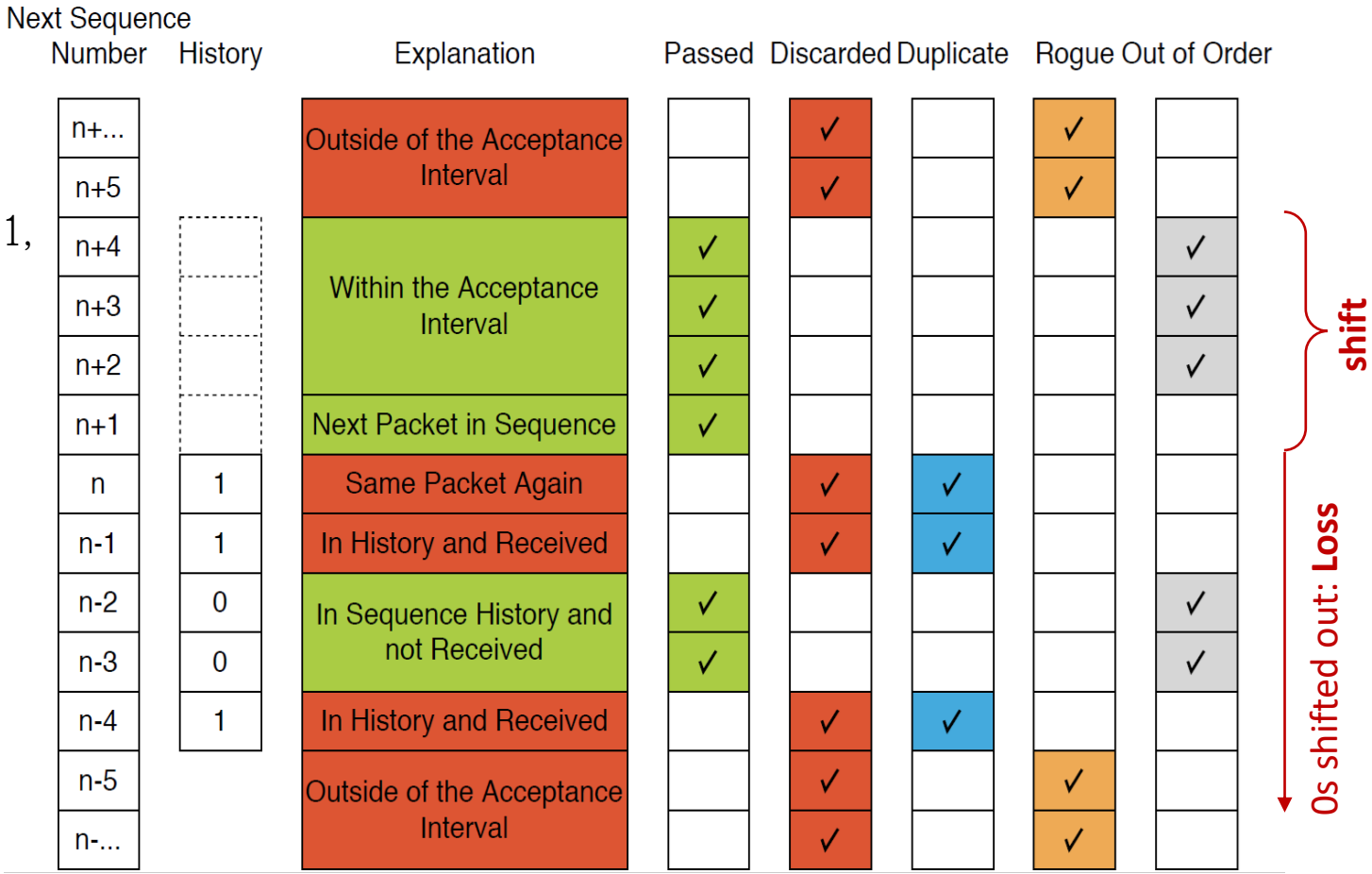
- eliminates duplicates,
- forwards new packets,
- . . .

Vector Recovery Algorithm (VRA)

- defines an interval of sequence numbers

  [RecovSeqNum - frerSeqRcvyHistoryLength + 1, RecovSeqNum + frerSeqRcvyHistoryLength]

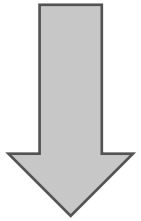
- within this interval:
  - new packets are accepted
  - duplicates are eliminated
  - higher sequence numbers than *RecovSeqNum* lead to an update of *RecovSeqNum*
- outside this interval
  - all packets are discarded



Identified Challenges since 2019

Nominal Behaviour / No Failure	Management Reset
	Member Stream Path Jitter (e.g., inference or wireless)
	Talker Pause
	Network Function Virtualization
Failure	Failure before Duplication (or: Failure on all links)
	Failure on one link
Other	Vector Recovery Algorithm with short HistoryLength
	Match Recovery Algorithm w/o intermittent streams

Many issues occur even under normal operation!



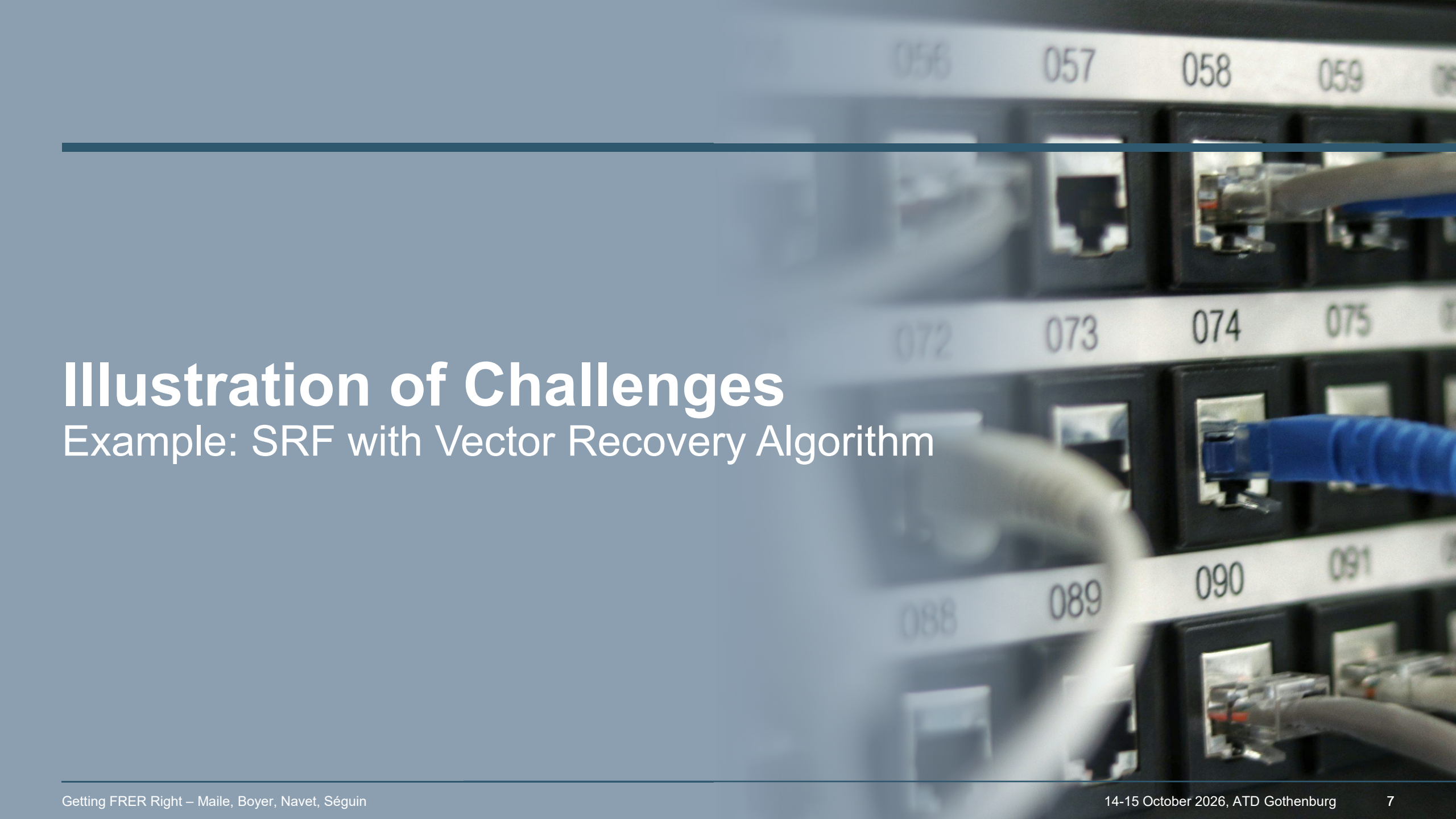
Resulting Effects

- Wrong Counter Values
- Forwarding of Replicates
- Increased Rate of Merged Stream
- Elimination of Valid Packets

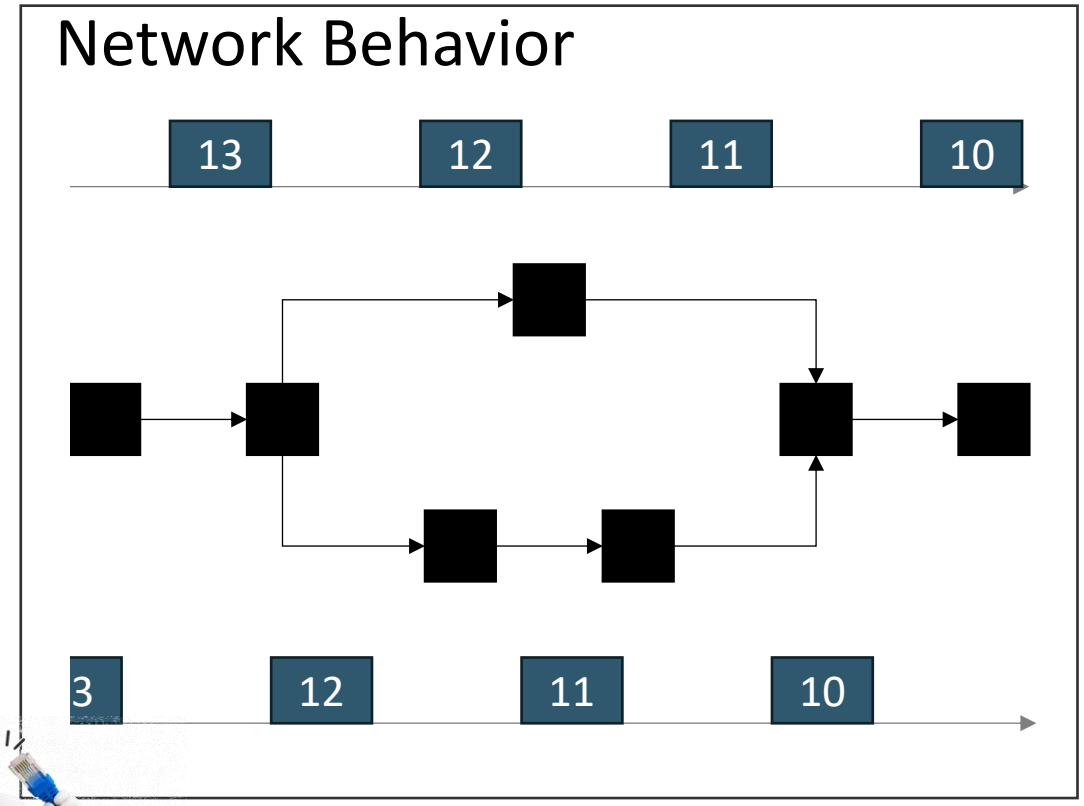
Only illustration of subset here. For full overview, see:
https://www.ieee802.org/1/files/public/docs2025/ec-maile-FRER-issues-overview-1125-v03.pdf

Illustration of Challenges

Example: SRF with Vector Recovery Algorithm

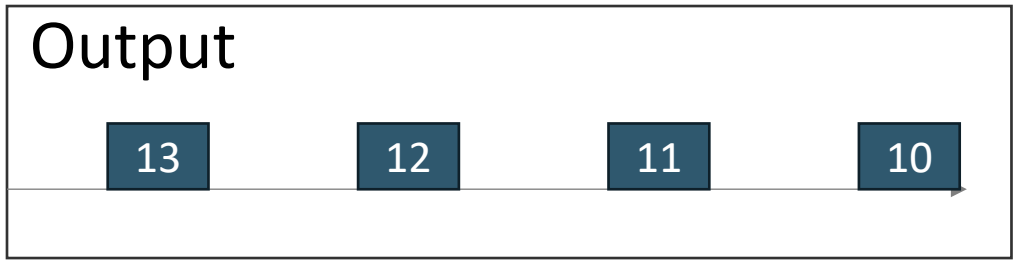


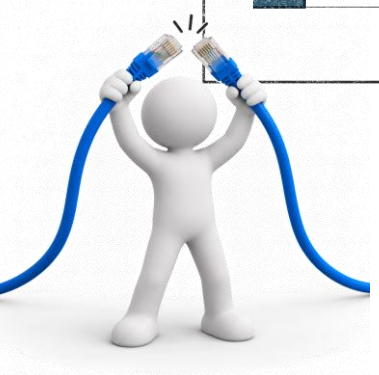
Ideal Operation



Under ideal operation (i.e., periodic, no/low jitter)

- All SeqNums within Sequence Window
- Replicates → eliminated
- Valid packets → forwarded





Wrong Counter Values

Forwarding of Replicates

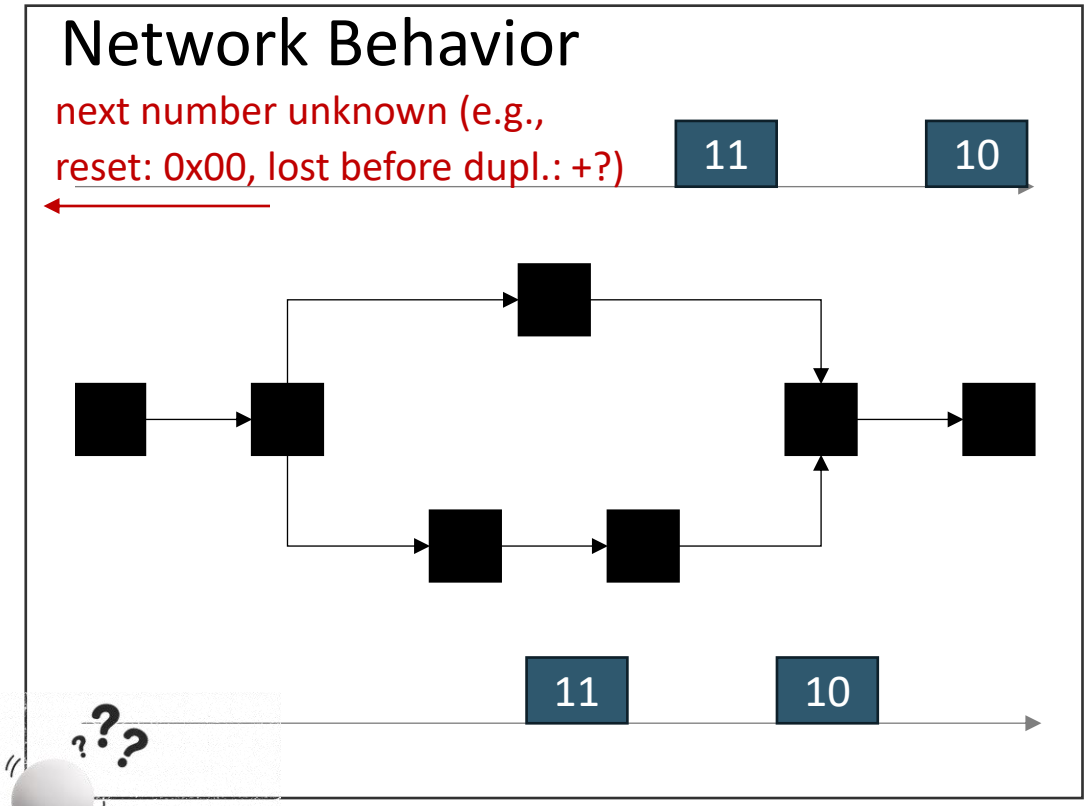
Increased Rate of Merged Stream

Elimination of Valid Packets

Grey boxes = "no issue"
Red boxes = "issue"

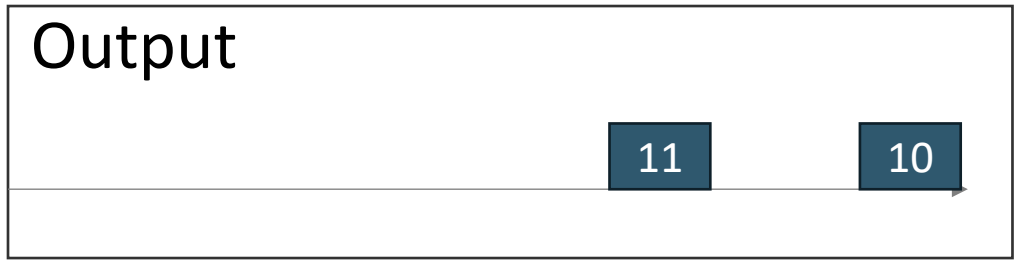
Nominal Behavior

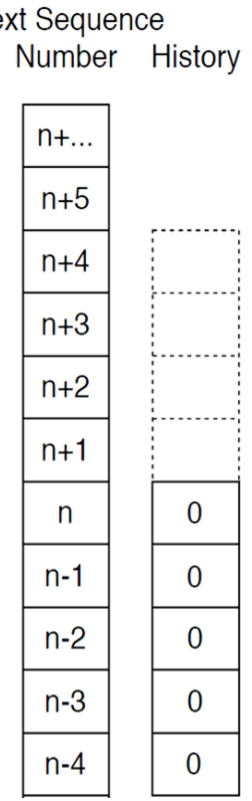
Reset



SequenceRecoveryReset

- if no packet is accepted and forwarded for the duration of frerSeqRcvyResetMSec
- All entries in Seq. History set to 0
- TakeAny = True, means that RecovSeqNum takes the value of the next packet received







Wrong Counter Values

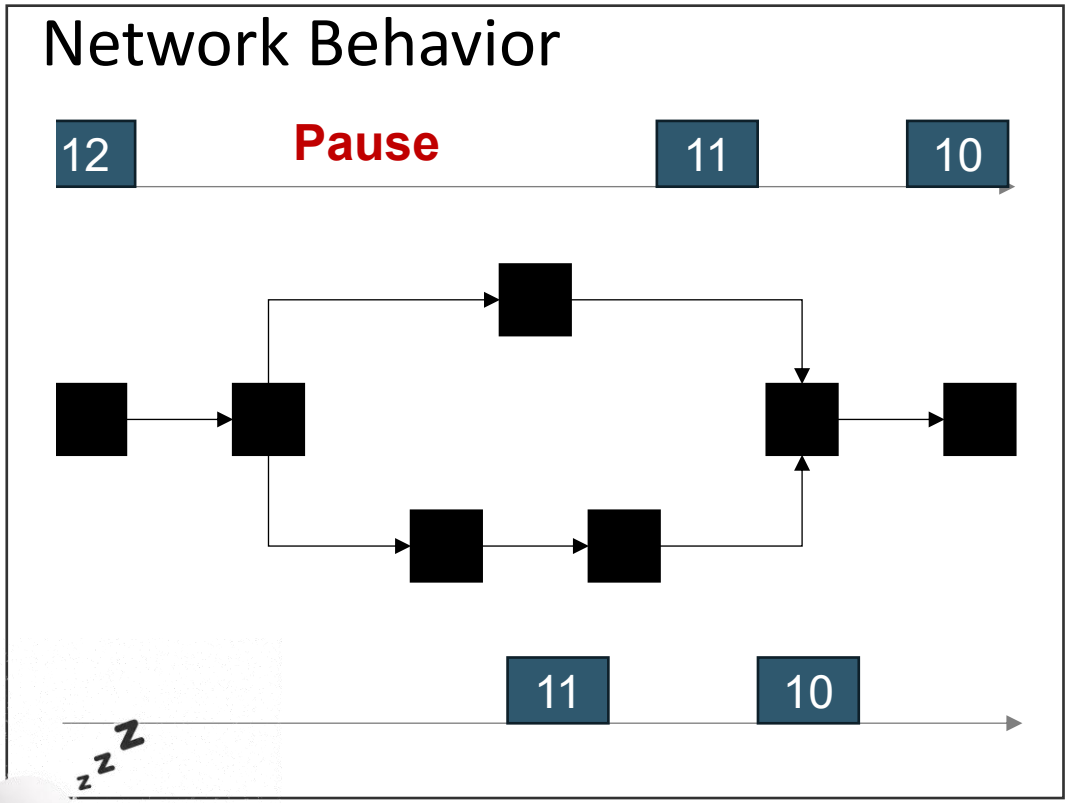
Forwarding of Replicates

Increased Rate of Merged Stream

Elimination of Valid Packets

Nominal Behavior

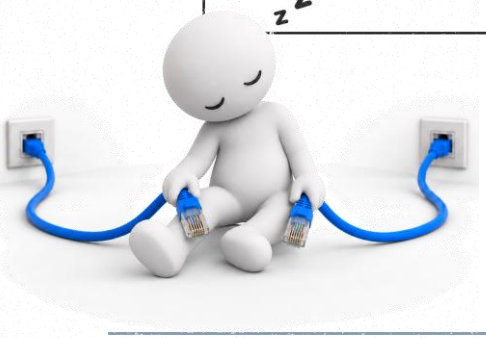
Talker Pause



Talkers are allowed to pause or send less

- Pauses can be arbitrarily long and arbitrarily often
- Will trigger SequenceRecoveryReset
- Each time loss counter increases by #HistoryLength





Wrong Counter Values

Forwarding of Replicates

Increased Rate of Merged Stream

Elimination of Valid Packets

Nominal Behavior

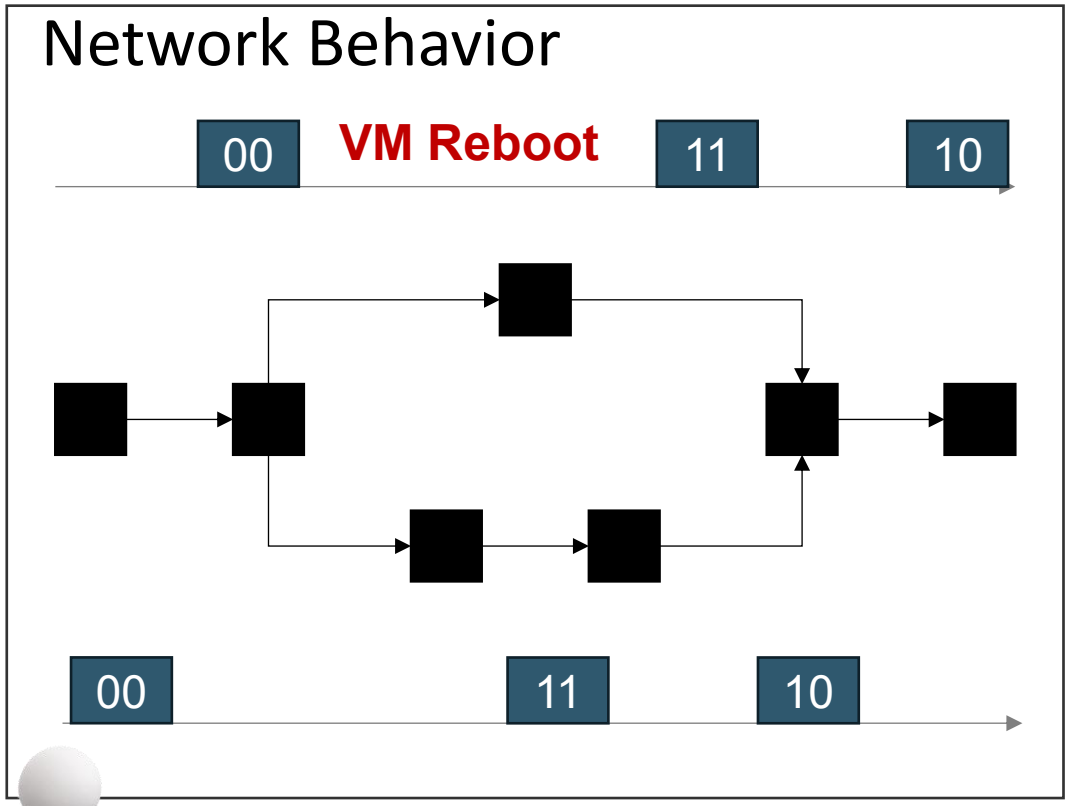
Network Function Virtualization (NFV)



Information To-Go

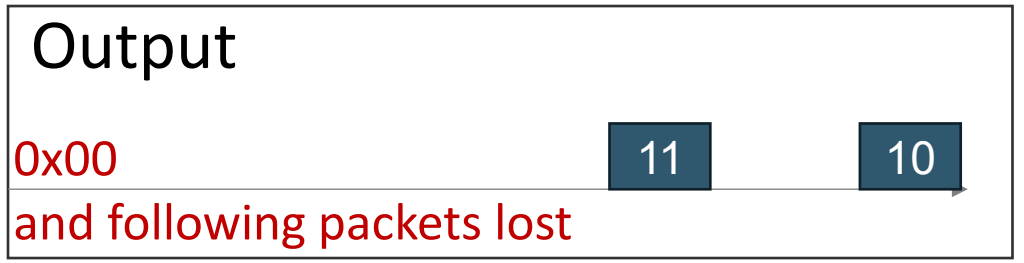
FRER is standardized,
but practice shows
unsolved challenges.

Discussed in [1,2,4,6,7,12,16]



Virtualization (e.g., containers, virtual machines)

- FRER functionality might be part of the cloud
- Virtual instances can restart fast (no timeout)
- Valid packets discarded (0x00 and following)
  → outside current Seq. Window
- Will trigger SequenceRecoveryReset after timeout, then same issues as for Talker Pause (loss counter)





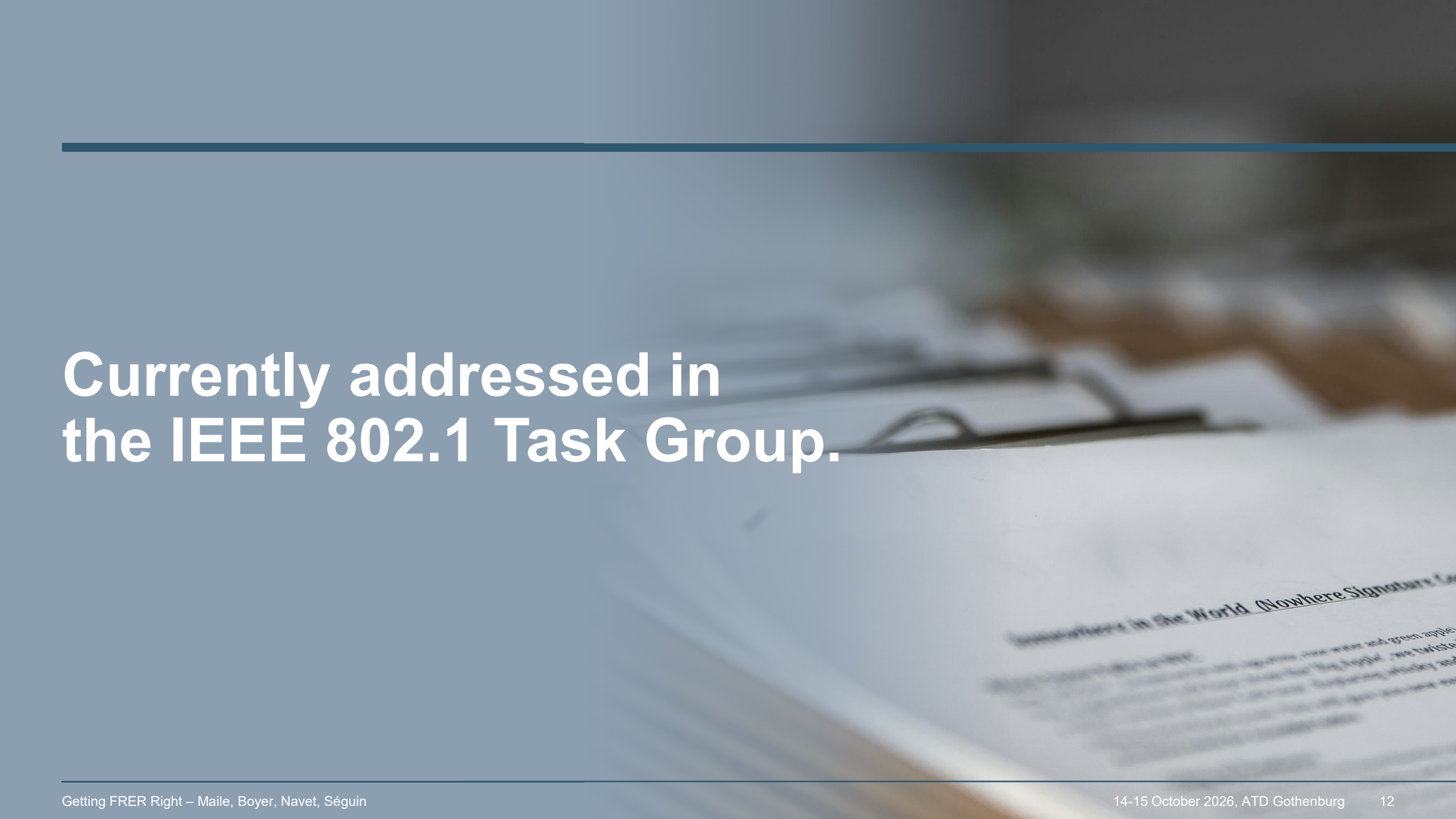
Wrong Counter Values

Forwarding of Replicates

Increased Rate of Merged Stream

Elimination of Valid Packets

Currently addressed in the IEEE 802.1 Task Group.



Current Standardization Discussions

Split the problem: Which number is next?

Disclaimer:
The following solutions are from the **CBec task force**, consisting among others of:

Balázs Varga (Ericsson, balazs.a.varga@ericsson.com)

David McCall (Intel, david.mccall@intel.com)

Lisa Maile (Technische Universiteit Eindhoven, l.t.maile@tue.nl)

Christophe Mangin (Mitsubishi Electric, c.mangin@fr.merce.mee.com)

Max Turner (Ethernovia, max.turner@ethernovia.com)

Stephan Keher (Belden, stephan.kehrer.committees@gmail.com)

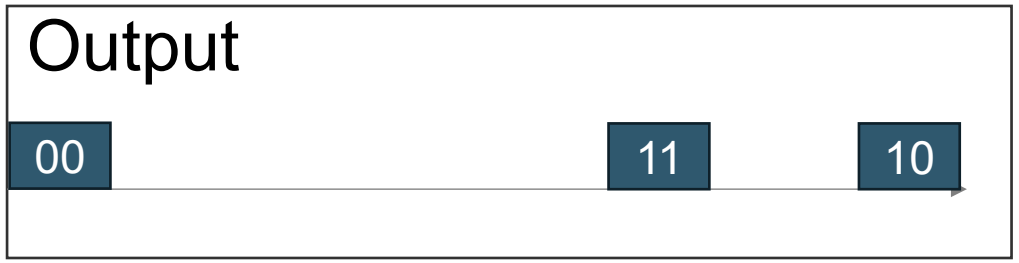
Venkat Anruthi (Broadcom, venkat.arunarthi@broadcom.com)

Two Situations

We want to distinguish **Timeout**



from **Reset**



Current Standardization Discussions

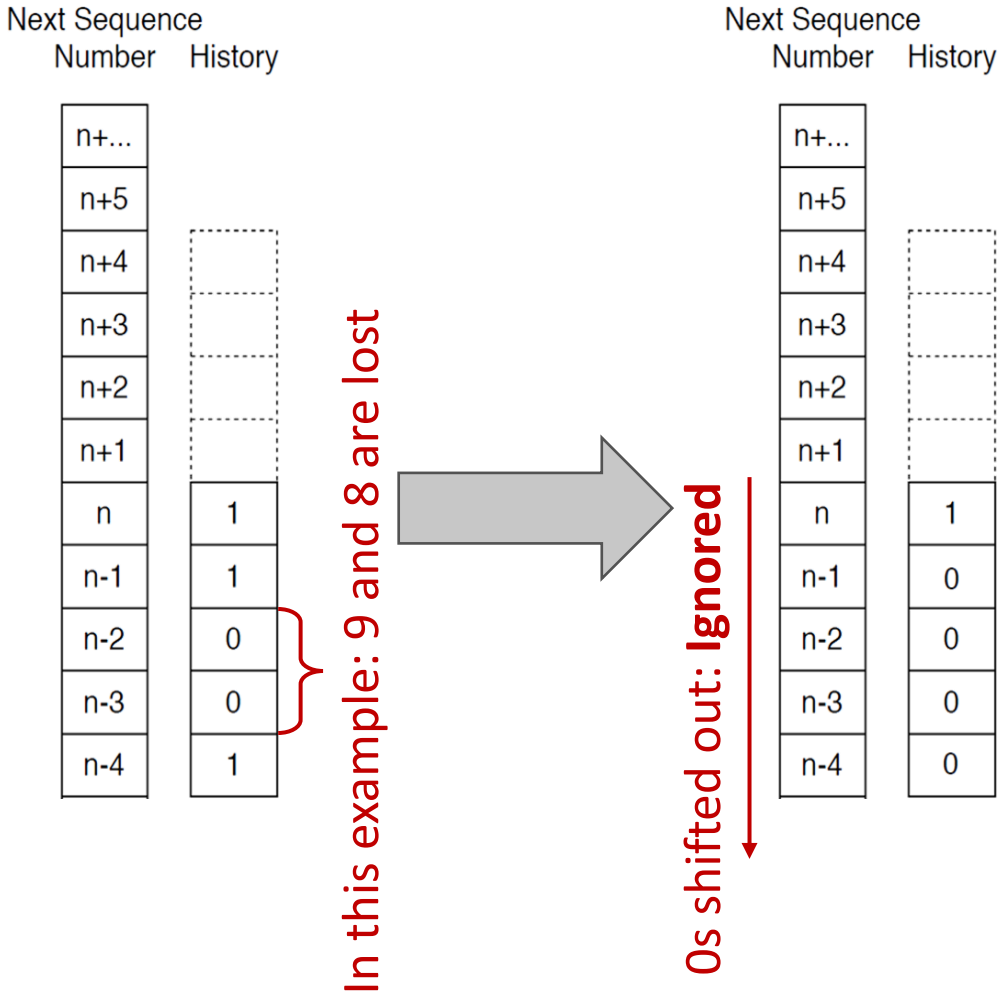
Timeout

1. Timeout



New state SupressLostCount

1. Report all zeros in current history
2. TakeAny = True, Set SupressLostCount = 1
3. Do not count 0s as lost
   until first 1 is shifted out
   → then SupressLostCount = 0



Current Standardization Discussions

Reset

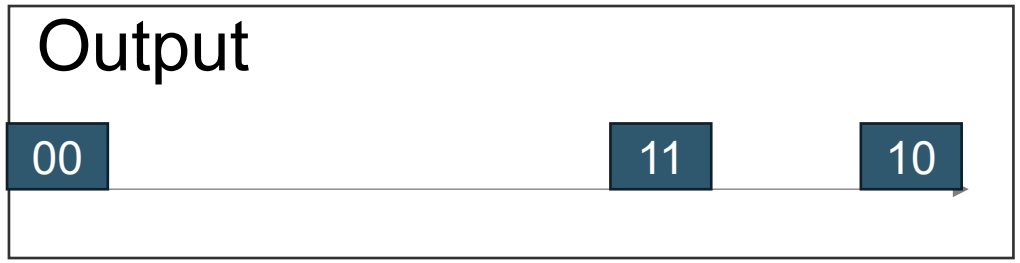


Information To-Go

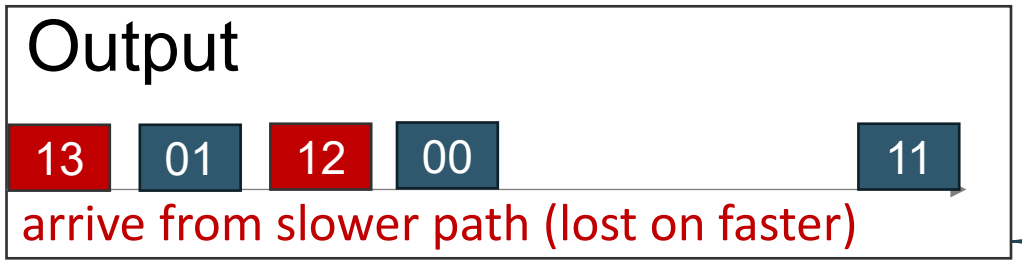
Standardization currently addresses FRER to make it behave „as expected“.

Discussed in [18-22]

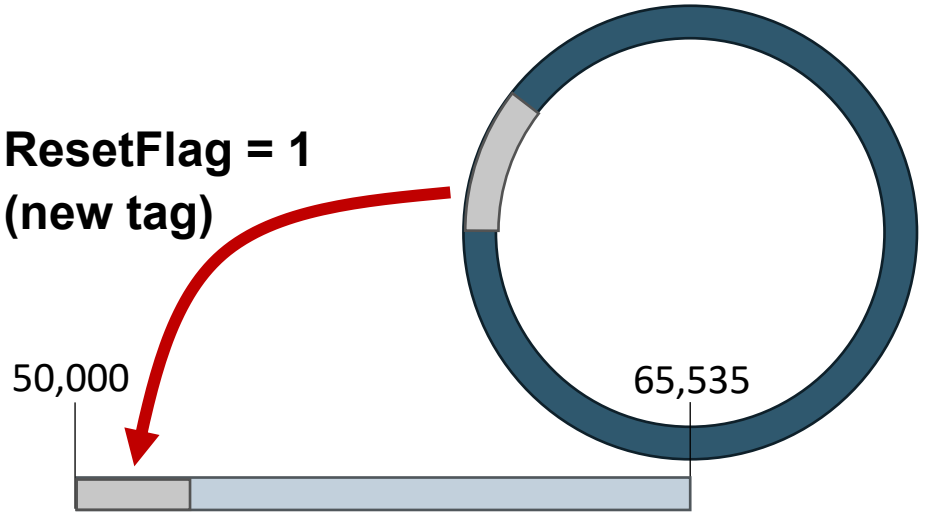
2. Reset



1. **New reset tag in packet for signaling**



2. **New sequence number space**
    1. Option between:
       Only report zeros or keep parallel spaces
    2. Process new packets in new space
    3. Spaces will merge once exhausted



Old and new sequence space distinguishable

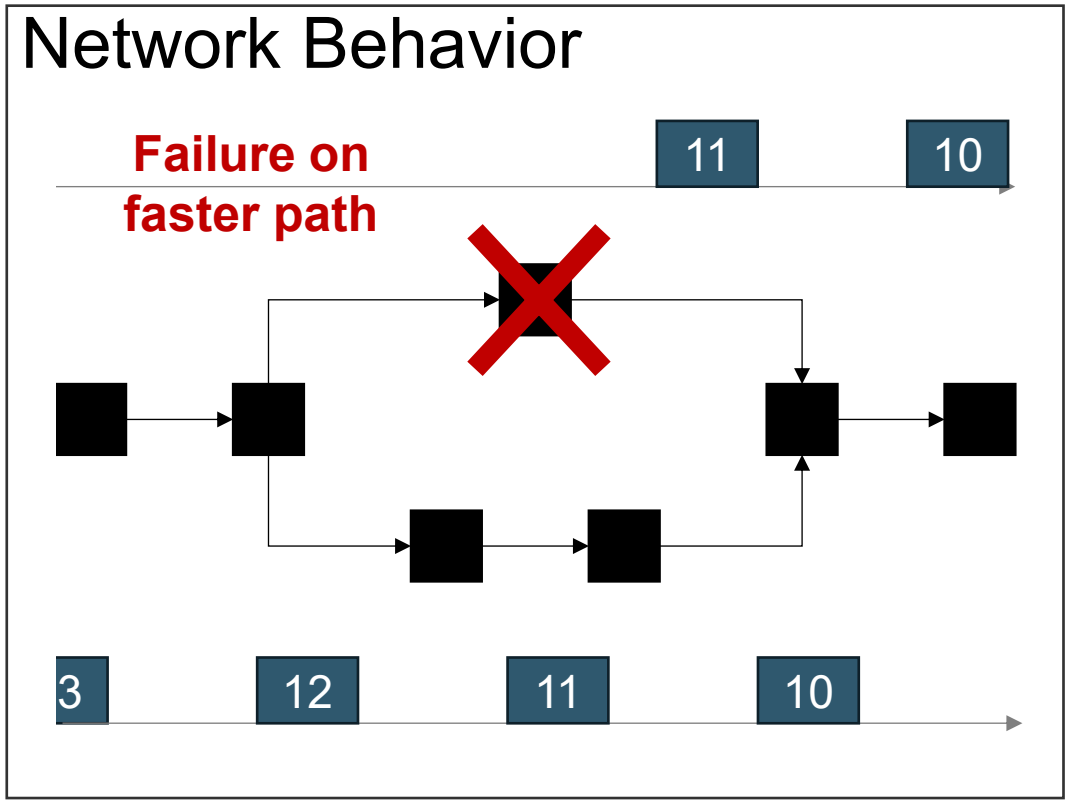
… and more in 802.1CBec

…but there is more…



Failure Behavior

Failure on one Link



Faster Link Failure & Recovery

- Main Use Case of FRER
- Exhibits three phases:
  1) Small delay
  2) Reception by slower path
  3) After recovery, doubled rate of streams



Wrong Counter Values

Forwarding of Replicates

Increased Rate of Merged Stream

Elimination of Valid Packets

Failure Behavior

Failure on one Link

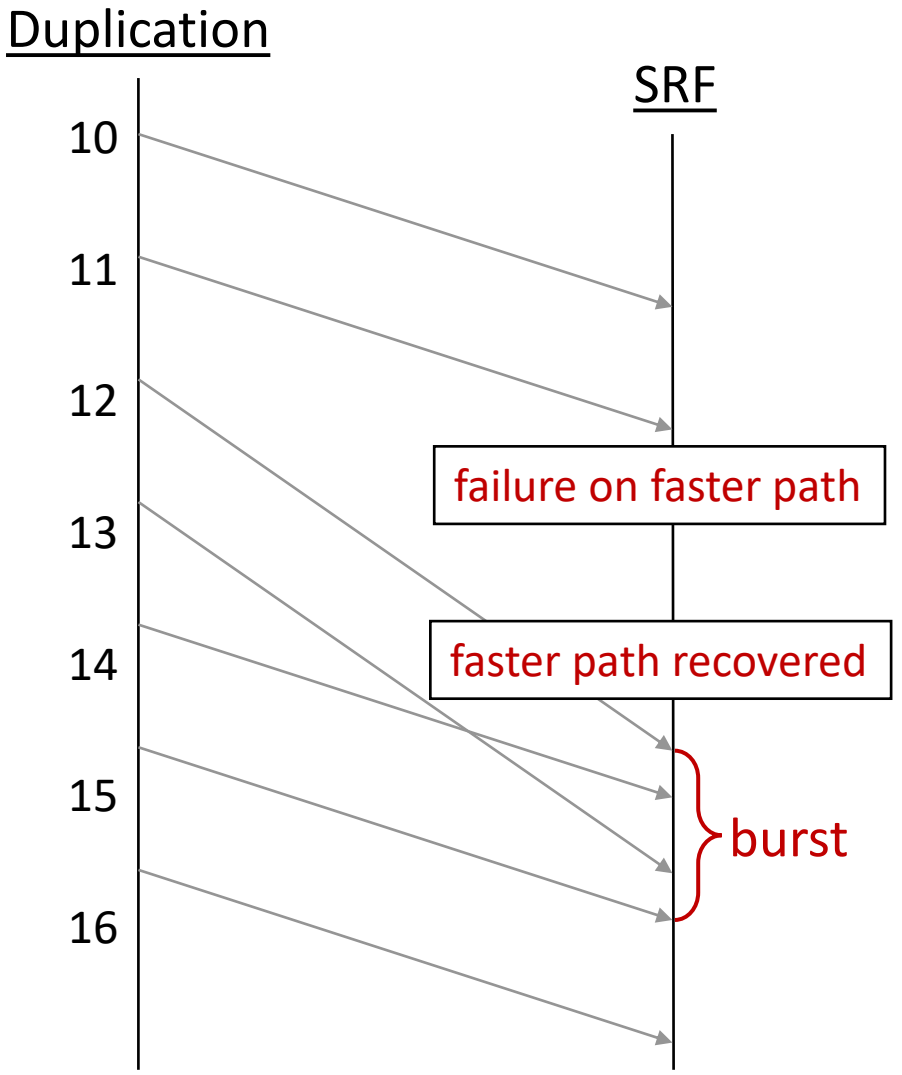


Information To-Go

FRER still requires awareness and configuration from network operators.

Discussed in [8,9,10]

- Failure transparent (no timeout, no loss counter, …)
- Burst of packets forwarded (doubled the reserved rate)*
- We don’t re-shape the flows
  → has to be considered in subsequent nodes
- **Careful!**
  1) Changes the end-to-end latency
     of the same and lower priorities
  2) Changes the latency, jitter, and memory requirement
     for all schedulers
  3) Changes required parameters
     for Per Stream Filtering and Policing



This requires network engineering.
Some thoughts…



Experiments: Failure and Recovery Behavior

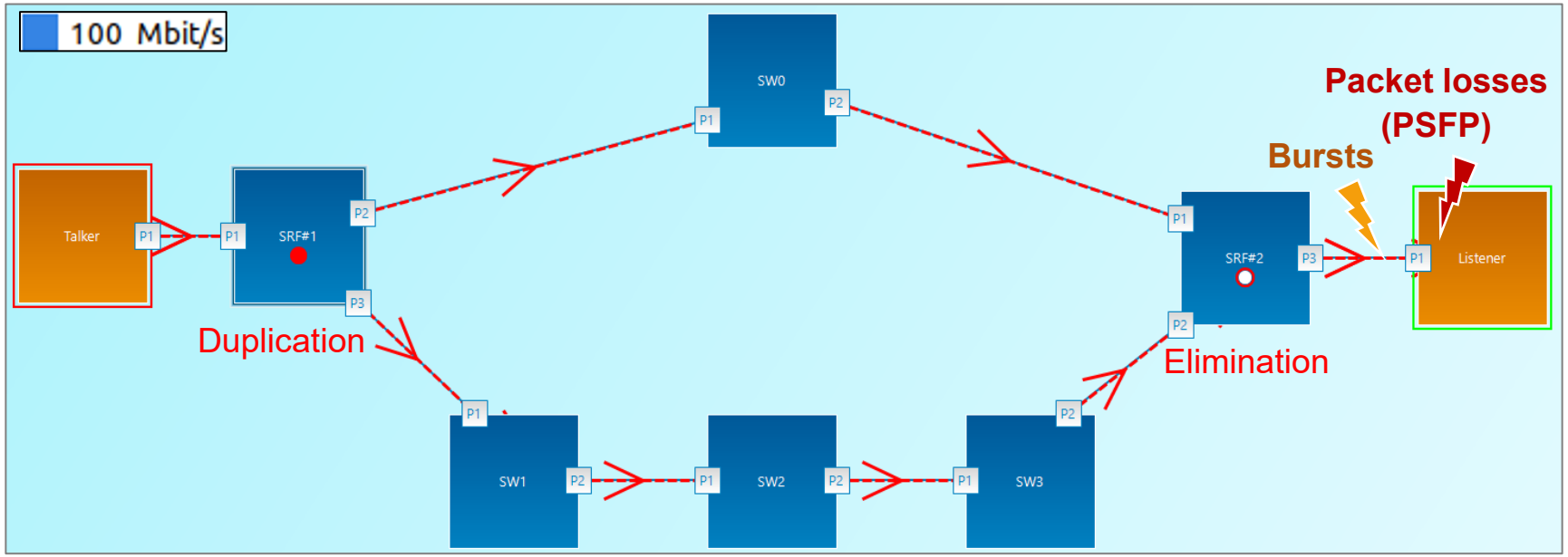
Simulation setup

Objectives:

- Show that, after a link failure, FRER with variable-delay paths creates a burst after the elimination
- Observe packet losses at a downstream PSFP policer that is not configured for the post-failure burst (i.e., the filter discards frames during the burst)

Experimental platform: RTaW-Pegase® for modeling, simulation and trace analysis

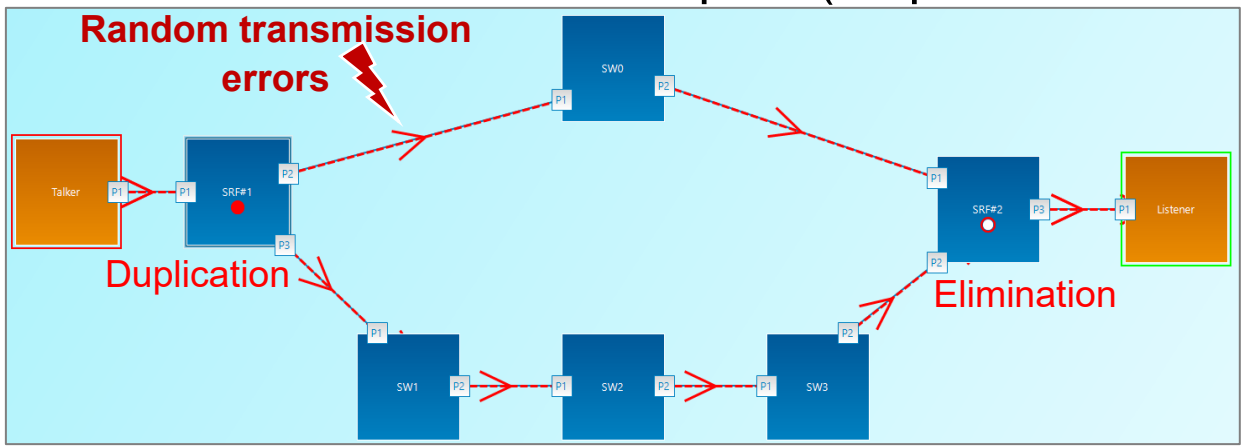
Flow	Arrival model
F1 Talker → Listener	750 B every 125 µs



Simulation Results: Failure and Recovery Behavior

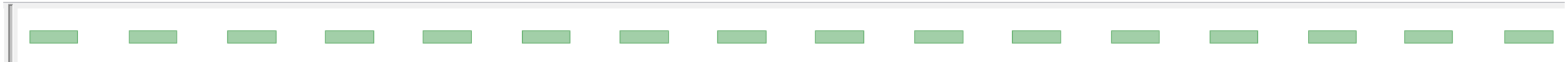
First experiment: burst after the elimination

Scenario: intermittent transmission errors on the short path (no permanent link failure)

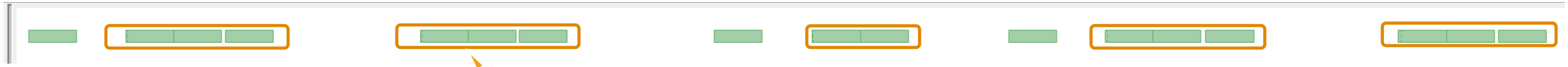


RTaW-Pegase simulation traces (link to the Listener)

Without transmission errors



With transmission errors



Bursts

No frame is lost — but frames arrive in bursts, beyond the specified 1 frame every 125 µs

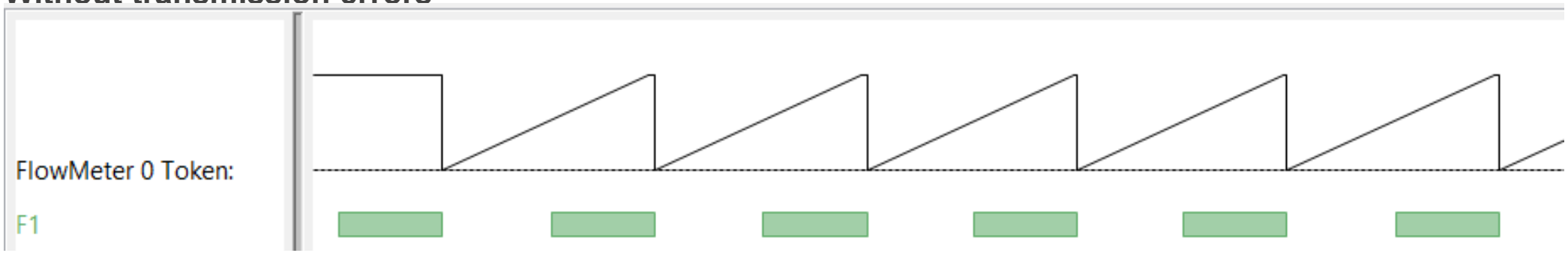
Simulation Results: Failure and Recovery Behavior

Second experiment: frames discarded by a mis-dimensioned PSFP flow meter (CBS)

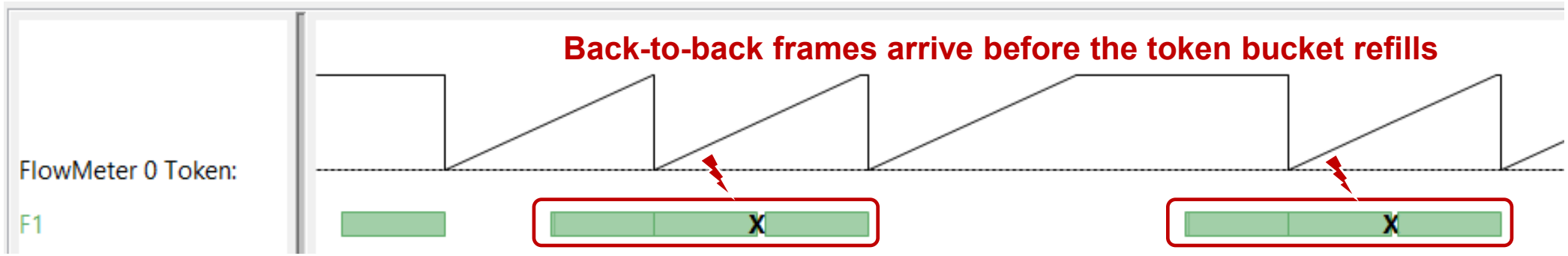
Scenario: same transmission errors. Flow meter Committed Burst Size set for the fault-free traffic (*i.e.*, 1 frame)

RTaW-Pegase simulation traces (PSFP flow meter at the listener)

Without transmission errors



With transmission errors



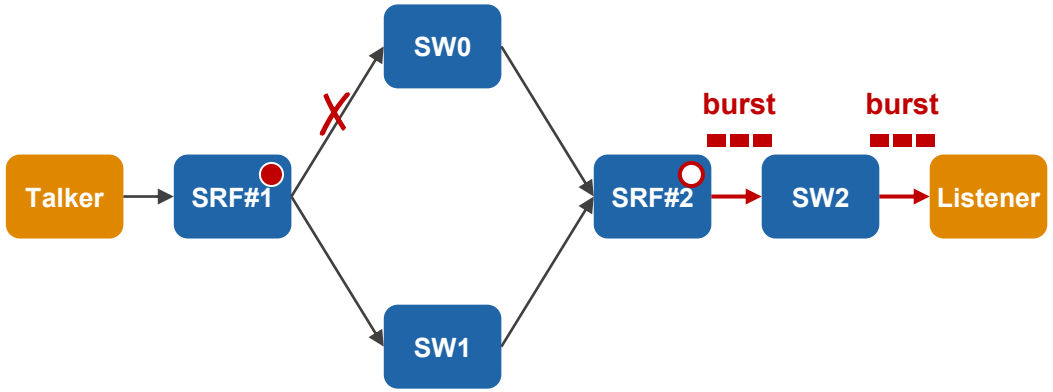
The burst exhausts the fault-free flow meter CBS budget — each discarded frame is the only remaining

FRER Network Engineering

Solution 1: FRER only in end-stations with end-to-end disjoint paths

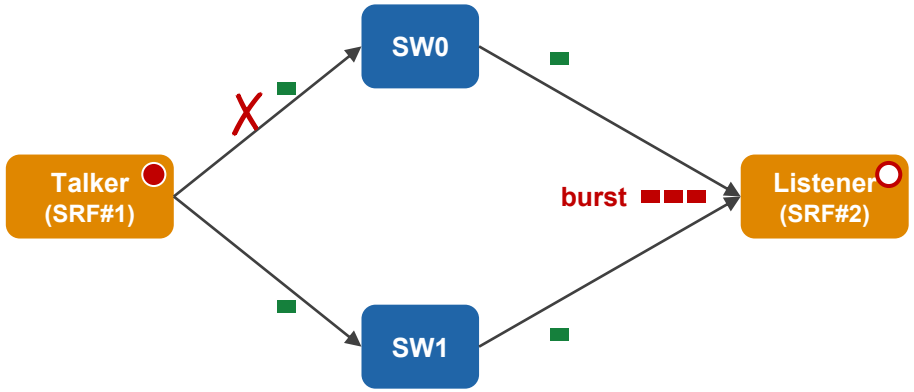
- Replication in the talker, elimination in the listener → **the post-failure burst never crosses a switch**
- **Member streams remain conformant on every link**: other streams unaffected, switch memory and PSFP keep their fault-free dimensioning
- **End-to-end protection**: a single unprotected link sharply reduces the robustness to transient losses [24]

(a) SRF in a relay bridge (our experiments)



After failure & recovery, the burst crosses every downstream hop

(b) FRER in the end-stations



Member streams stay conformant on every link — no burst within the network

No free lunch: requires 802.1CB support in the end-stations and two disjoint paths talker-to-listener

[24] Pannell, Navet, "Practical Use Cases for Ethernet Redundancy", IEEE-SA Ethernet & IP @ Automotive Technology Day, 2020.

FRER Network Engineering

Solution 2: Traffic Analysis and Network Configuration



Information To-Go

Solutions for FRER configuration are currently actively developed in academia (and industry?)

If the SRF must sit inside the network, the effects just shown are predictable and can be accounted for with worst-case analysis:

1) End-to-end latencies and jitters may change (for same and lower priorities, whatever the policy) → Use a **FRER-aware worst-case traversal time analysis**, e.g. [25]

2) Memory requirements may increase → **Size egress buffers** of every hop downstream of the SRF **considering the post-failure bursts**, e.g. using [25,26] — merged rate at most doubled, whatever the number of paths

3) PSFP parameters for the fault-free case are no longer valid → **Recompute stream gates and flow meters** (CIR/CBS) for the worst-case accumulated jitter at each hop — no published method yet!

Complementary: re-shape after the SRF (e.g., CBS) to eliminate the burst as, e.g., in [27]
(nb: re-shaping with ATS under FRER is still an open problem)

Failure scenarios must be accounted for in the timing analysis and the network configuration

[25] Thomas, Mifdaoui, Le Boudec, “Worst-Case Delay Bounds in Time-Sensitive Networks With Packet Replication and Elimination”, IEEE/ACM Transactions on Networking, 2022.
[26] Maile, Voitlein, Hielscher, German, "Ensuring Reliable and Predictable Behavior of IEEE 802.1CB Frame Replication and Elimination," ICC 2022.
[27] https://github.com/Kathess/DYRECTsn (includes automated FRER configurations and CBS re-shaping)

* L. Maile's participation is supported by the TREASURY project (Chips JU).

Overview

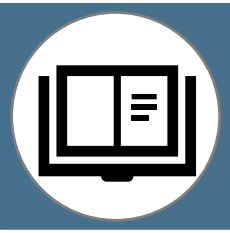
Getting FRER Right



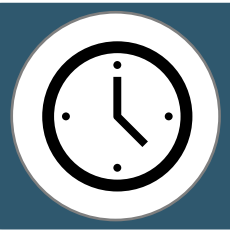
FRER offers real benefits for ultra-critical systems



Receives significant attention,
in academia, industry, and standardization



Current standardization efforts aim to solve main weaknesses



Some features continue to require network engineering

Questions?

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Marc Boyer
- marc.boyer@onera.fr

Nicolas Navet
- nicolas.navet@realtimeatwork.com

Leo Séguin
- leo.seguin@realtimeatwork.com

Thank you!

References Used (Detailed)

[1] Balázs Varga, János Farkas, July 2019
https://www.ieee802.org/1/files/public/docs2019/new-varga-FRER-improvements-0719-v01.pdf

[2] Balázs, Farkas, March 2020
https://www.ieee802.org/1/files/public/docs2020/new-varga-FRER-seamless-reset-0320-v02.pdf

[3] Maintenance 257, March 2020
https://www.ieee802.org/1/files/public/docs2020/maint-varga-257-FRER-recovery-window-0320-v01.pdf
https://www.802-1.org/items/370

[4] Balázs, Farkas, March 2020
https://www.ieee802.org/1/files/public/docs2020/maint-varga-FRER-sequence-recovery-reset-0320-v02.pdf

[5] Maintenance 265, April 2020
https://www.802-1.org/items/379

[6] Balázs, Farkas, Sept 2020
https://www.ieee802.org/1/files/public/docs2020/new-varga-FRER-RTag-0920-v02.pdf

[7] Balázs, Farkas, Fejes, Hoeftberger et al., May 2023
https://www.ieee802.org/1/files/public/docs2023/new-varga-FRER-extensions-to-support-cloudification-0523-v01.pdf

[8] Maile et al., Jun 2023
https://www.ieee802.org/1/files/public/docs2023/new-maile-ensuring-reliable-and-predictable-behavior-of-FRER-0623-v02.pdf

[9] Maile, June 2024
https://www.ieee802.org/1/files/public/docs2024/new-maile-FRER-sequence-recovery-configuration-0624-v01.pdf

[10] IEEE Std. P802.1CBec, Feb 2025 - now
https://www.ieee802.org/1/files/private/ec-drafts/d0/802-1CBec-d0-2.pdf

[11] Maintenance 378, March 2025
https://www.ieee802.org/1/files/public/docs2025/maint-arunarthi-CB-2017-item-378-0310-v02.pdf

[12] Balázs, Farkas, May 2025
https://www.ieee802.org/1/files/public/docs2025/maint-varga-CB-2017-item-378-FRER-seqrecreset-0525-v00.pdf

[13] McCall May 2025
https://www.ieee802.org/1/files/public/docs2025/maint-mccall-cb-2017-item-378-seq-recovery-options-v01.pdf

[14] Balázs, Farkas, July 2025
https://www.ieee802.org/1/files/public/docs2025/maint-varga-CB-2017-item-378-FRER-reset-analysis-0725-v01.pdf

[15] Steindl, Proell, July 2025
https://www.ieee802.org/1/files/public/docs2025/60802-Steindl-Proell-IA-Controller-ConfDomain-Cloud-0725-v01.pdf

[16] Balázs, Farkas, September 2025
https://www.ieee802.org/1/files/public/docs2025/ec-varga-FRER-improvements-0925-v00.pdf

[17] Extending PAR&CSD for P802.1CBec, Nov 2025
https://www.ieee802.org/1/files/public/docs2025/ec-draft-PAR-modification-0925-v01.pdf
https://www.ieee802.org/1/files/public/docs2025/ec-draft-CSD-modification-0925-v01.pdf

[18] Maile (Discussion: McCall, Mangin, Turner, Varga), May 2026
https://www.ieee802.org/1/files/public/docs2026/ec-maile-FRER-analysis-discussions-solutions-0526-v00.pdf

[19] McCall et al., June 2026
https://www.ieee802.org/1/files/public/docs2026/ec-mccall-et-al-FRER-combined-proposal-details-draft-0626-v02.pdf

[20] Balázs, July 2026
https://www.ieee802.org/1/files/public/docs2026/ec-varga-RESET-of-SeqRcvy-0726-v00.pdf

[21] Balázs, Fejes, July 2026
https://www.ieee802.org/1/files/public/docs2026/ec-varga-fejes-StateMachine-of-SeqGen-SeqRcvy-0726-v00.pdf

[22] Maile, July 2026 https://www.ieee802.org/1/files/public/docs2026/ec-maile-cbec-pseudocode-0726-v00.pdf

[23] Upcomming discussions in September 2026:
https://1.ieee802.org/2026-09-interim-tsn-agenda/

[24] Pannell, Navet, "Practical Use Cases for Ethernet Redundancy", IEEE-SA Ethernet & IP @ Automotive Technology Day, 2020.

[25] Thomas, Mifdaoui, Le Boudec, "Worst-Case Delay Bounds in Time-Sensitive Networks With Packet Replication and Elimination", IEEE/ACM Transactions on Networking, 2022.

[26] Maile, Voitlein, Hielscher, German, "Ensuring Reliable and Predictable Behavior of IEEE 802.1CB Frame Replication and Elimination," *ICC 2022,* doi: 10.1109/ICC45855.2022.9838905.