Ensuring Reliable and Predictable Behavior of IEEE 802.1CB Frame Replication and Elimination

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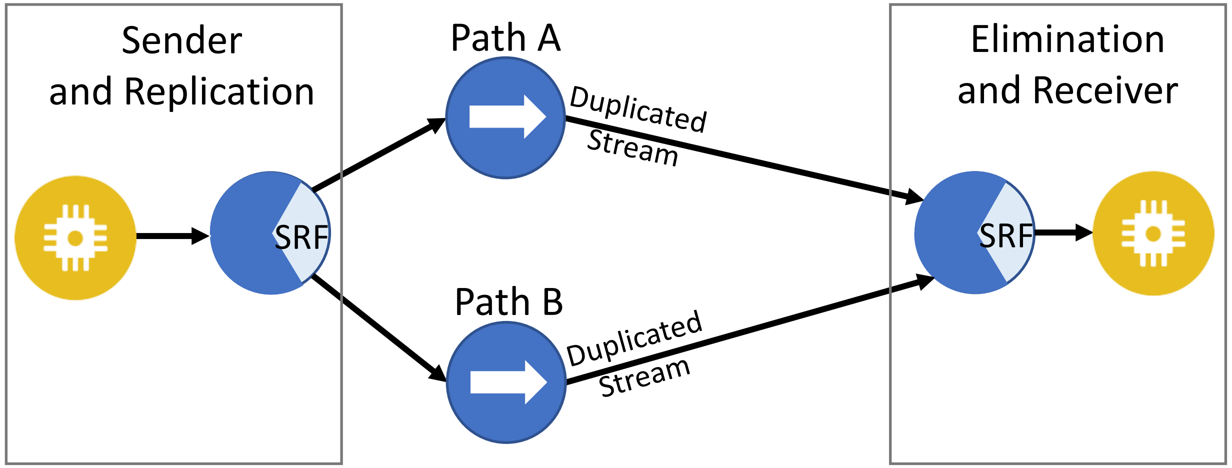
Introduction

Scope

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

Sending duplicate packet copies over multiple disjoint paths.



Configuration parameters not defined by the standard:

1) Choosing match vs. vector recovery algorithm,
2) defining the length of the sequence history,
3) setting a timer to reset the sequence history,

} Configuration of Sequence Recovery Function (SRF)

4) dimensioning burst size in case of transmission failures. → Dimensioning of the network

Introduction

Goal

Problem: Incorrect configuration can result in

- valid frames to be discarded entirely,
- passing of duplicates,
- unexpected bursts.

→ Result: IEEE 802.1CB standard named “Frame Replication and Elimination for Reliability” performs unreliable.

Solution: Formulas for guidance of users of IEEE 802.1CB. Can be provided by only using the best- and worst-case path delays of the network → often known in TSN networks.

Based on conference publication (copyright by IEEE):

L. Maile, D. Voitlein, K. -S. Hielscher and R. German, "Ensuring Reliable and Predictable Behavior of IEEE 802.1CB Frame Replication and Elimination," ICC 2022 - IEEE International Conference on Communications, Seoul, Korea, Republic of, 2022, pp. 2706-2712, doi: 10.1109/ICC45855.2022.9838905.

Notation / Terms

Stream Characteristics (from IEEE Std 802.1Qat):

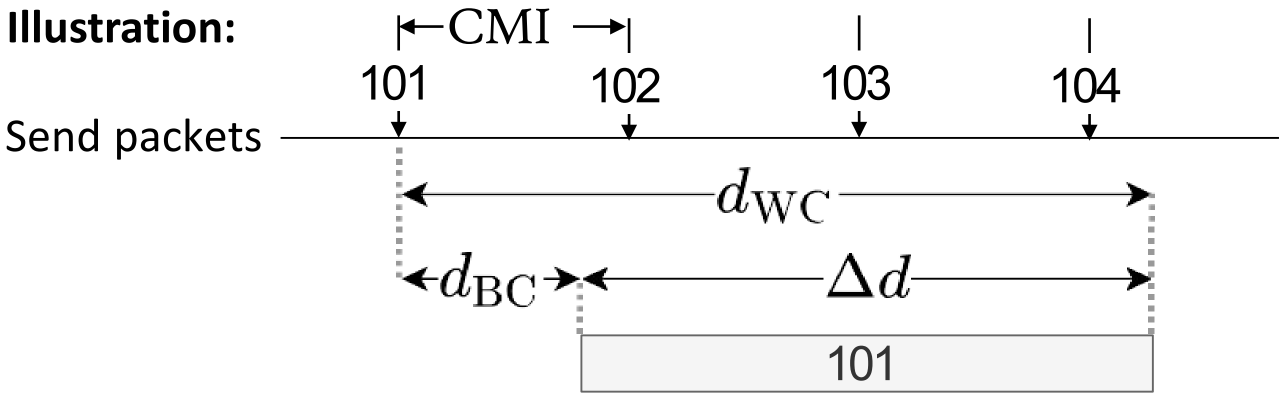
- Class Measurement Interval (CMI)
- Maximum Interval Frames (MIF)
- Maximum Frame Size (MFS)

*A stream sends at most **MIF** packets during an interval of length **CMI**. Each packet is smaller or equal to **MFS**.*

Network Characteristics:

- lowest delay of fastest path d_{BC} (best-case)
- highest delay of slowest path d_{WC} (worst-case)
- reception window: $\Delta d = d_{WC} - d_{BC}$

Illustration:



Choosing Match Recovery Algorithm

Match Recovery Algorithm

Problem Description and Challenge

For the identification of duplicates, the user must choose one of two recovery algorithms.

Match Recovery Algorithm (MRA)

- stores only highest sequence number received
- only eliminates duplicates with this sequence number
- forwards all other packets → potentially passing duplicates
- requires intermittent streams: the difference between arriving sequence numbers may not exceed one

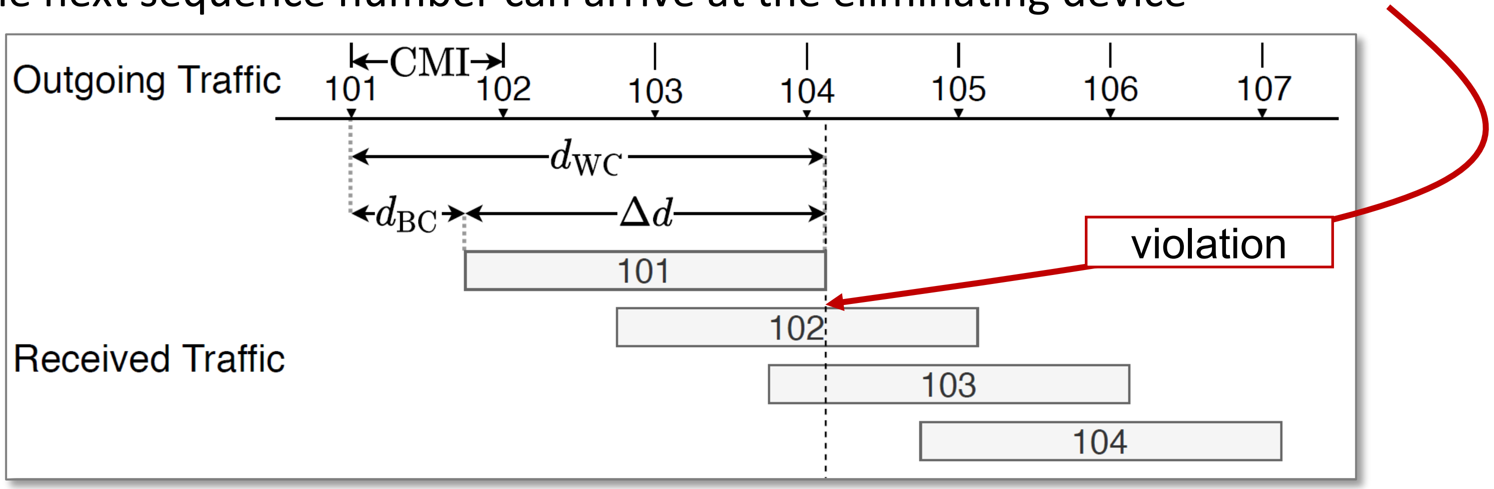
Challenge: How to identify intermittent streams?

Match Recovery Algorithm

Solution

Identify intermittent streams

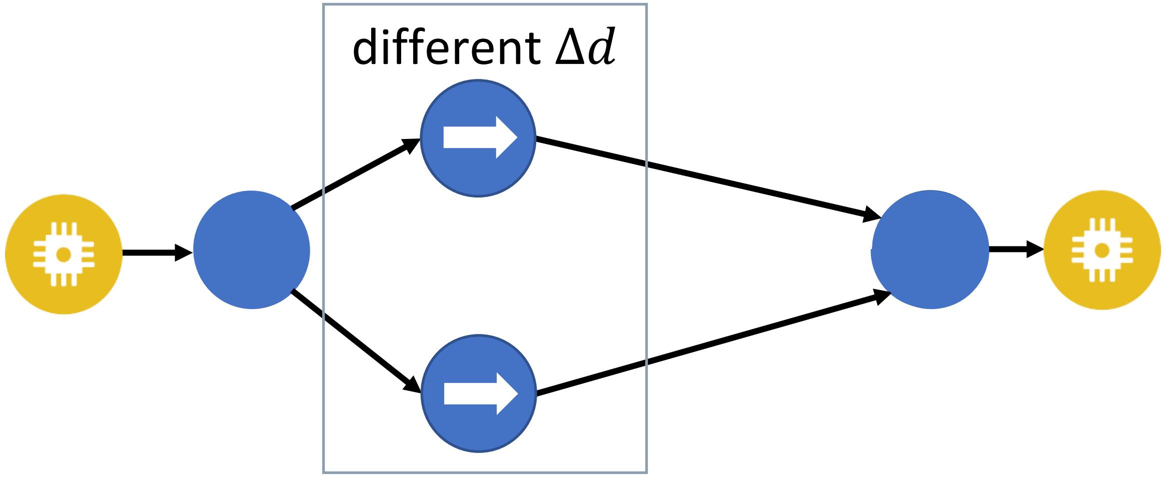
- all copies of a packet must arrive before the next sequence number can arrive at the eliminating device

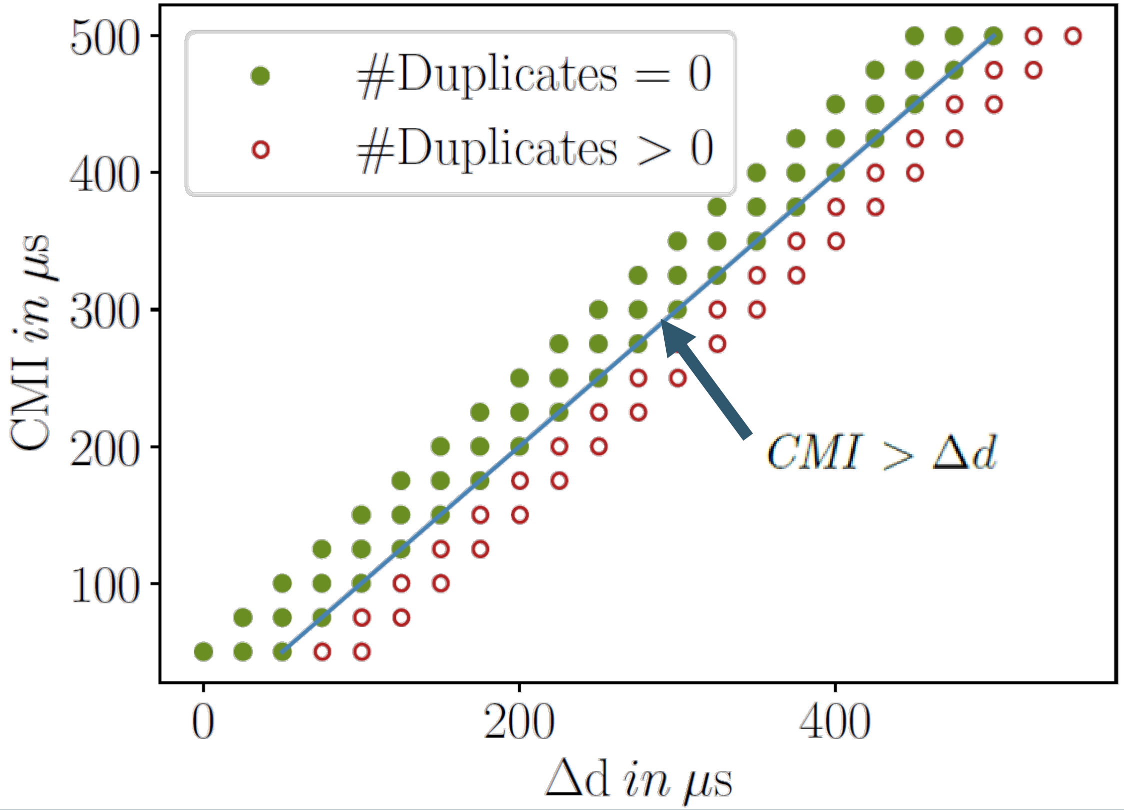


- **Solution**: Intermittent streams are present if and only if we have no overlapping reception windows, meaning:
  - Periodic Traffic: $CMI > \Delta d$
  - Aperiodic Traffic / Jitter: in the worst-case, packet i is delayed by j_1 and packet $i+1$ is sent by j_2 time units ealier, with $j_1 + j_2 = J \leq CMI$ (otherwise, packet $i+1$ is sent before packet i), resulting in: $CMI > \Delta d + J$
  - MIF > 1: Not possible in intermittent streams (in the worst-case, packets could be sent right one after another)

Simulation Results

- using the Match Recovery Algorithm, with different Δd and CMI values and periodic traffic





Defining the sequence history length

Vector Recovery Algorithm: History Length

Problem Description

Vector Recovery Algorithm (VRA)

- defines an interval of sequence numbers

$$RecovSeqNum \pm (frerSeqRcvyHistoryLength - 1)$$

- 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

default *frerSeqRcvyHistoryLength* = 2

Next Sequence Number	History	Explanation	Passed	Discarded	Duplicate	Rogue	Out of Order
n+...		Outside of the Acceptance Interval		✓		✓	
n+5		Outside of the Acceptance Interval		✓		✓	
n+4		Within the Acceptance Interval	✓				✓
n+3		Within the Acceptance Interval	✓				✓
n+2		Within the Acceptance Interval	✓				✓
n+1		Next Packet in Sequence	✓				
n	1	Same Packet Again		✓	✓		
n-1	1	In History and Received		✓	✓		
n-2	0	In Sequence History and not Received	✓				✓
n-3	0	In Sequence History and not Received	✓				✓
n-4	1	In History and Received		✓	✓		
n-5		Outside of the Acceptance Interval		✓		✓	
n-...		Outside of the Acceptance Interval		✓		✓	

Vector Recovery Algorithm: History Length

Challenge

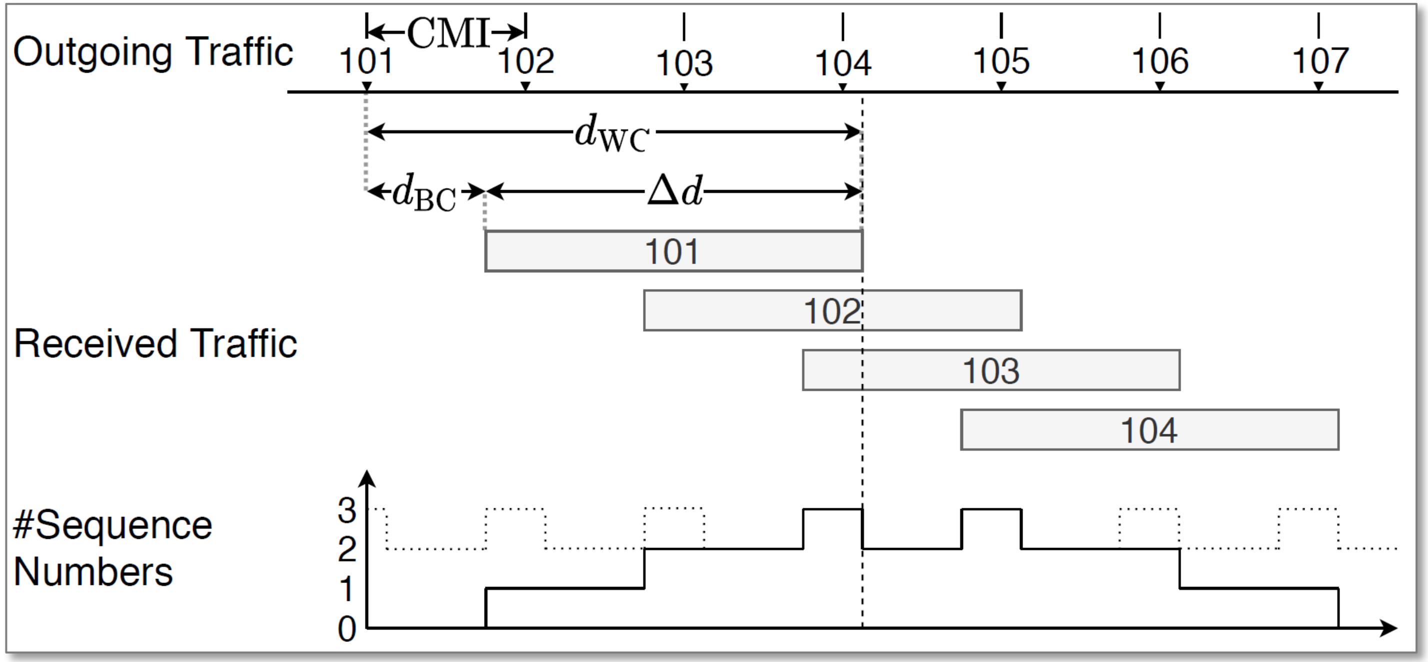
Challenge: Define *frerSeqRcvyHistoryLength* (short: L).

Too short: Valid packets can get discarded entirely. **Too long**: Unnecessary memory consumption.

Solution: The interval constantly needs an entry for each sequence number that may be received at any time.

Can be safely and tightly configured by identifying the worst integer number of overlapping sequence numbers:

$$N = \left\lfloor \frac{\Delta d}{CMI} \right\rfloor + 1$$



Vector Recovery Algorithm: History Length

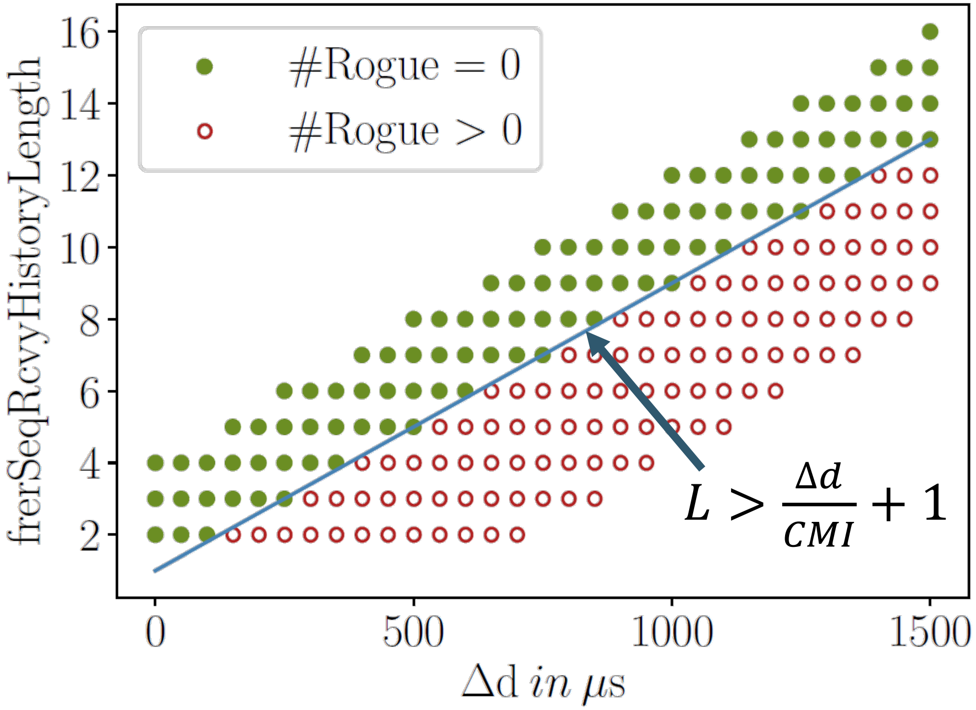
Solution and Evaluation

Solution (continued): Define *frerSeqRcvyHistoryLength* (short: L) as:

- Periodic Traffic: $L > \frac{\Delta d}{CMI} + 1$ (as only the reception of new packets triggers a shift of the sequence history)
- Aperiodic Traffic / Jitter: $L > \frac{\Delta d + J}{CMI} + 1 = \frac{\Delta d}{CMI} + 2$ with $J \leq CMI$
- MIF > 1: $\mathrm{L} > \mathrm{MIF} \cdot \left(\frac{\Delta d}{CMI} + 2 \right)$ (periodic, respectively for aperiodic)

Simulation Results

- rouge ("out of sequence interval") packets with different Δd and L values and periodic traffic and VRA



Setting timer values to reset the sequence history

Reset Timer Configuration

Problem Description and Challenge

***SequenceRecoveryReset* function**

- Reset when consecutive sequence numbers are interrupted, e.g., because a talker loses its connection
- a reset is triggered after a period (*SequenceRecoveryResetMSec*) in which no packets have been accepted
- Reason: Next sequence number is indefinitely higher than last one received.

Challenge: Define *SequenceRecoveryResetMSec (short: R)*

Too short: Duplicates forwarded. **Too long**: Valid packets can get discarded entirely.

Reset Timer Configuration

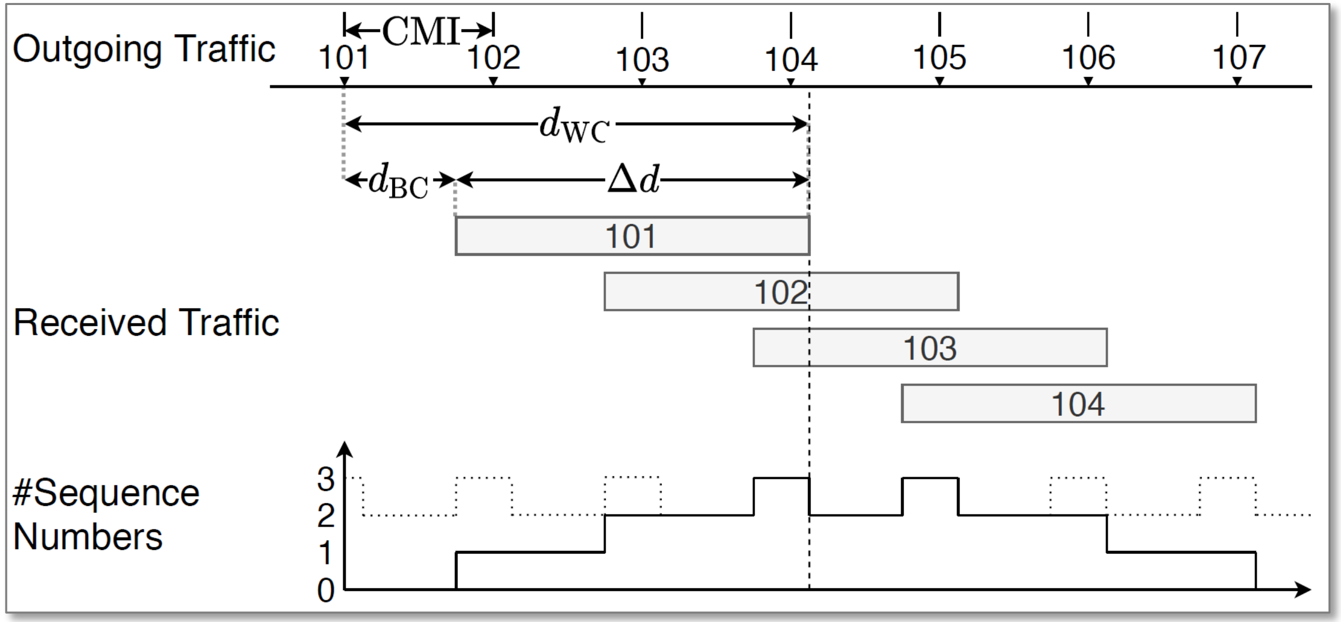
Solution

Solution:

- *SequenceRecoveryResetMSec* (short: R) is safe when no more duplicate packets can arrive: $R > \Delta d$
- However, for small Δd where the reception windows do not overlap, this configuration may result in many unnecessary resets

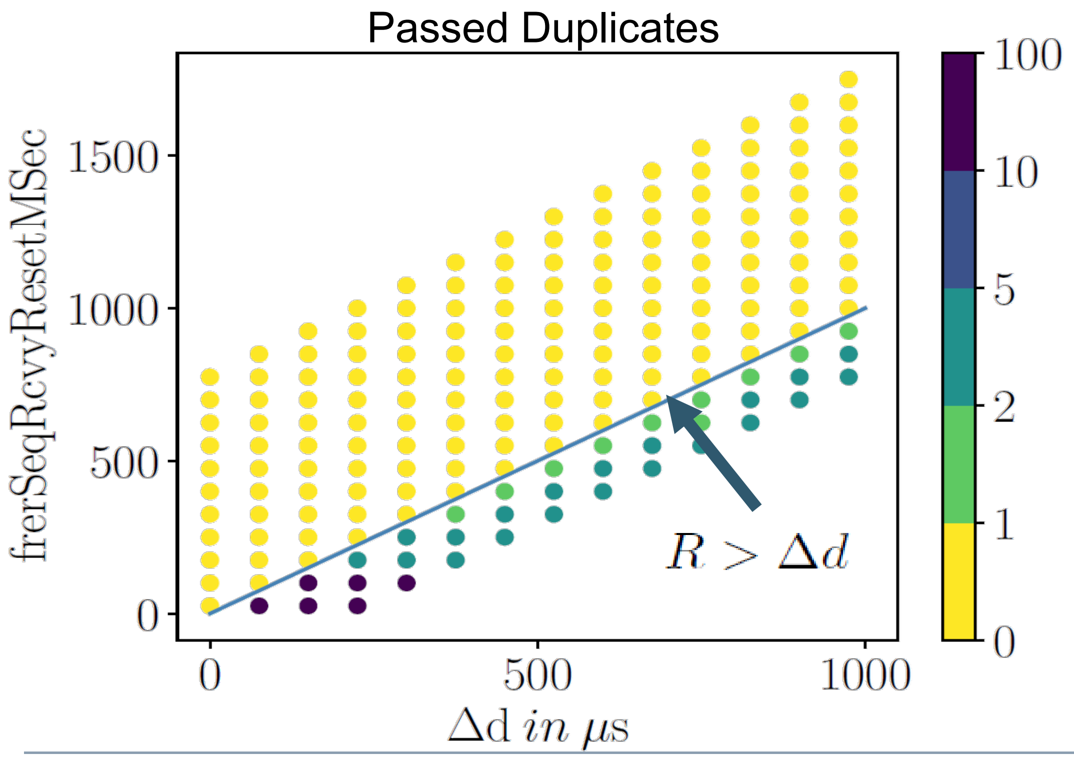
The optimal *SequenceRecoveryResetMSec* is:

- Periodic Traffic: $R = \Delta d + CMI$
- Aperiodic Traffic / Jitter:
  $R = \Delta d + J + CMI$ or $R = \Delta d + 2 \cdot CMI$
- MIF > 1: Identical



Simulation Results

- 100 packets sent with $CMI = 125\mu s$, one packet lost at talker due to interruption (max. 99 packets received) with VRA
- Optimal reset timer must be configured. Both too long and too short are unsafe.



Optimal: $R = \Delta d + CMI$

Safe: $R > \Delta d$

Timeout in µs	50	75	100	150	200	300	400	500	600
#Duplicates	99	99	0	0	0	0	0	0	0
#Passed	99	99	99	99	99	99	98	97	96
#Resets	198	101	99	2	2	2	2	2	2

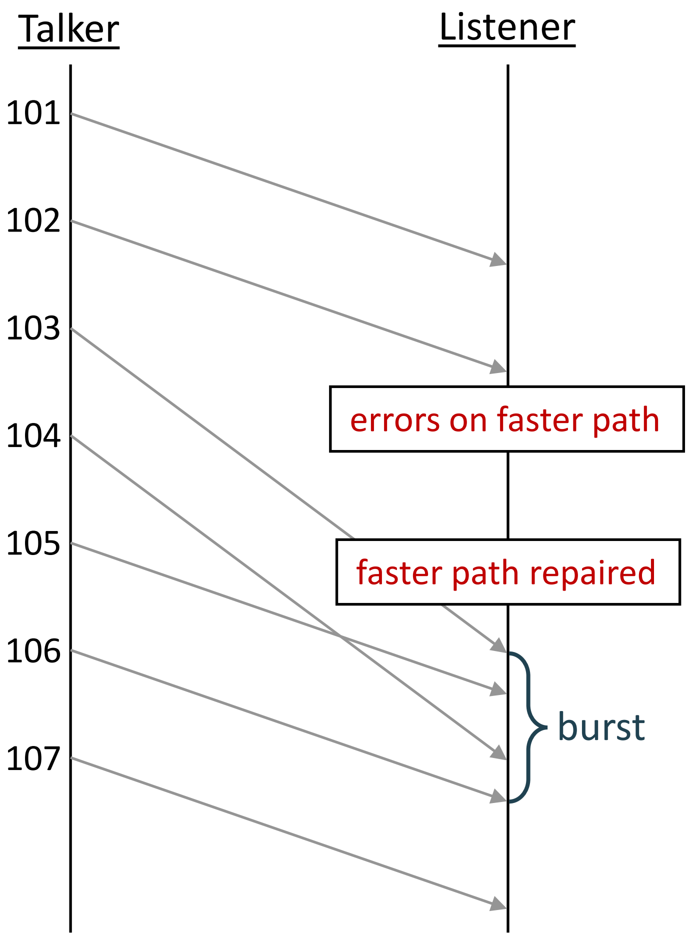
Burst in case of transmission failure

Problem

- Transmission failures can lead to bursts of traffic after repair → increase buffer requirements

Example

- transmission errors occur on the fastest path (e.g., after packet 102 is received)
- results in the following phases:
  1) only packets from the slower paths are received, but have been received before
     → no new packets
  2) new packets arrive from the slower paths with normal sending rate (e.g., 103 and 104)
     → new packets at normal rate
  3) faster path resumes transmission: slower paths continue to transmit, new packets from fast path (e.g., 105 and 106)
     → arrival rate doubles



Burst Size Prediction

Challenge and Solution

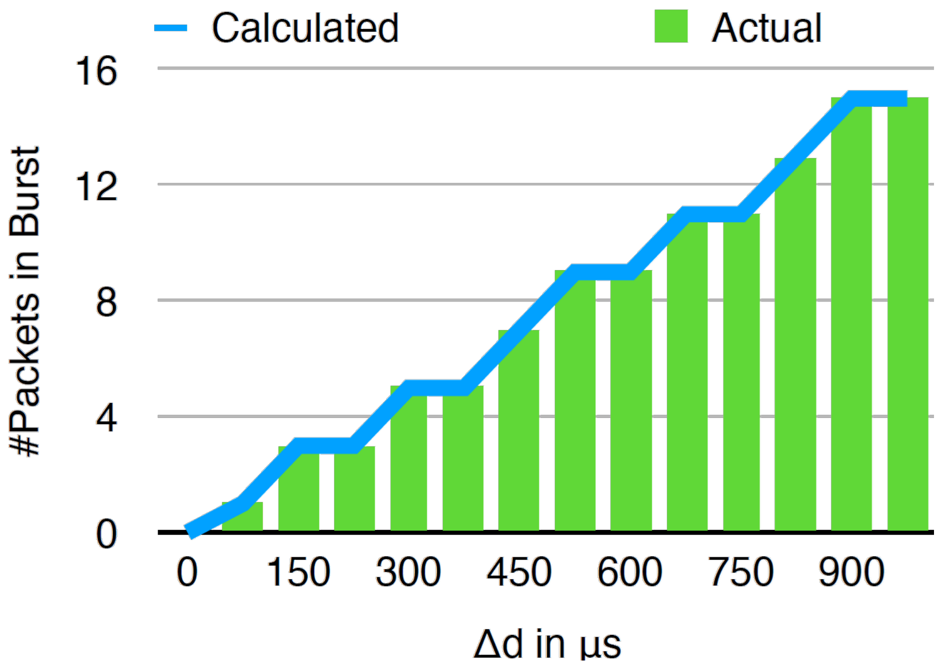
Challenge: Determine the dimension of potential packet bursts after transmission failures.

Solution:

- the duration of the burst is Δd
- the maximum number of packets that can arrive during Δd is $\left\lceil \frac{\Delta d}{CMI} \right\rceil$
- last packet not considered as part of the burst, because its successor is from the same link
- maximum number of packets arriving in a burst after transmission failure $n_{\max}$
  - Periodic Traffic: $\mathrm{n_{max}} = \max(2 \cdot \left\lceil \frac{\Delta d}{CMI} \right\rceil - 1, 0)$,
  - Aperiodic Traffic / Jitter: $\mathrm{n_{max}} = \max(2 \cdot \left\lceil \frac{\Delta d + J}{CMI} \right\rceil - 1, 0)$
  - MIF > 1: $\mathrm{n_{max}} = \max(2 \cdot MIF \cdot \left\lceil \frac{\Delta d}{CMI} \right\rceil - 1, 0)$ (periodic, respectively for aperiodic)

Simulation Results

- 100 packets sent with $CMI = 125\mu s$, 75 ms interruption of the fastest link with static path delays and VRA
- burst: packets which arrive with a spacing $< CMI$
- blue line illustrates our calculated dimensions, green bars are the simulation results



Conclusion

Conclusion

- IEEE 802.1CB-2017 seeks to add reliability to critical traffic in TSN
- Invalid configuration can result in a complete loss of reliable behavior
- Valid configurations can be easily obtained with the provided equations
- Only (best-case and) worst-case path delays required
- We hope that our solutions help the standardization processes to support the users of IEEE 802.1CB
- For further details, see also the corresponding publication:

L. Maile, D. Voitlein, K. -S. Hielscher and R. German, "Ensuring Reliable and Predictable Behavior of IEEE 802.1CB Frame Replication and Elimination," ICC 2022 - IEEE International Conference on Communications, Seoul, Republic of Korea, 2022, pp. 2706-2712, doi: 10.1109/ICC45855.2022.9838905.

References

L. Maile, D. Voitlein, K. -S. Hielscher and R. German, "Ensuring Reliable and Predictable Behavior of IEEE 802.1CB Frame Replication and Elimination," ICC 2022 - IEEE International Conference on Communications, Seoul, Korea, Republic of, 2022, pp. 2706-2712, doi: 10.1109/ICC45855.2022.9838905.

“IEEE standard for local and metropolitan area networks–frame replication and elimination for reliability,” IEEE Std 802.1CB-2017.

Related Publications

R. Hofmann, B. Nikoli´c, and R. Ernst, “Challenges and limitations of IEEE 802.1CB-2017,” IEEE Embedded Systems Letters, vol. 12, no. 4, pp. 105–108, 2020.

L. Thomas, A. Mifdaoui and J. -Y. Le Boudec, "Worst-Case Delay Bounds in Time-Sensitive Networks With Packet Replication and Elimination," in IEEE/ACM Transactions on Networking, vol. 30, no. 6, pp. 2701-2715, Dec. 2022, doi: 10.1109/TNET.2022.3180763.

E. Wandeler, L. Thiele, M. Verhoef, and P. Lieverse, “System architecture evaluation using modular performance analysis: A case study,” International Journal on Software Tools for Technology Transfer, vol. 8, pp. 649–667, 01 2006.

Thank you!