Computer Networks and Communication Systems
Computer Science 7
Friedrich-Alexander-Universität
Erlangen-Nürnberg

Application of Network Calculus for Reliable and Predictable Behavior of IEEE 802.1CB Frame Replication and Elimination in Time-Sensitive Networks

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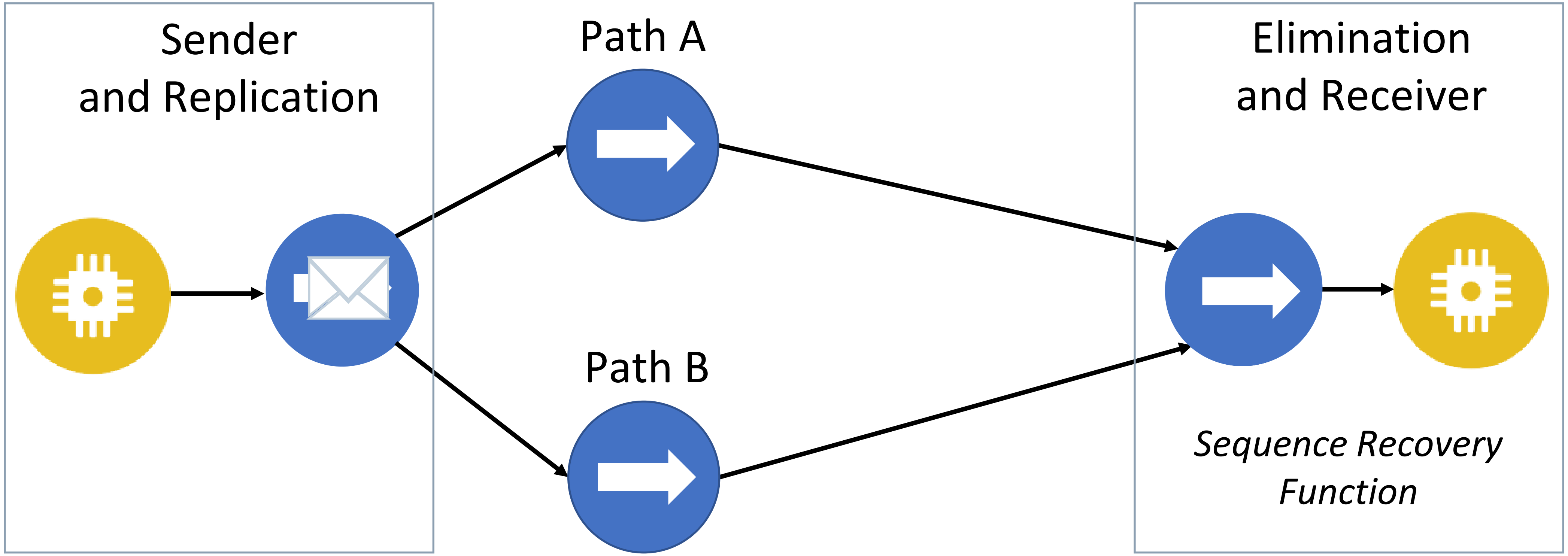
Friedrich-Alexander Universität, Erlangen-Nürnberg**

Academic Salon 2022, TUM,
Low-Latency Communication, Programmable Network Components and In-Network Computation

Applying Network Calculus?

> "It is up to the user to […] match the needs of the particular network […]"
> *IEEE 802.1CB-2017 Standard*



Sender
and Replication

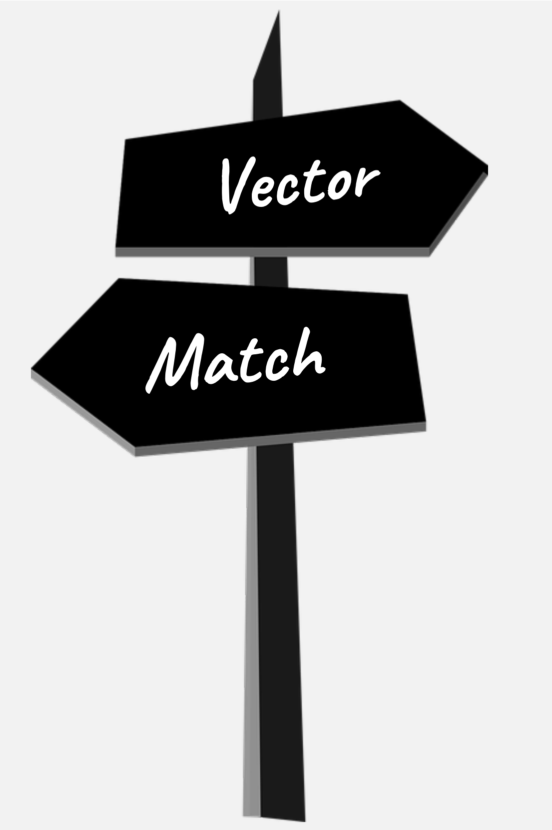
Path A

Path B

Elimination
and Receiver

*Sequence Recovery
Function*

Limitations of the IEEE 802.1CB-2017 standard



Choosing match or vector recovery algorithm

Configuring the length of the sequence history

Setting timer values to reset the sequence history

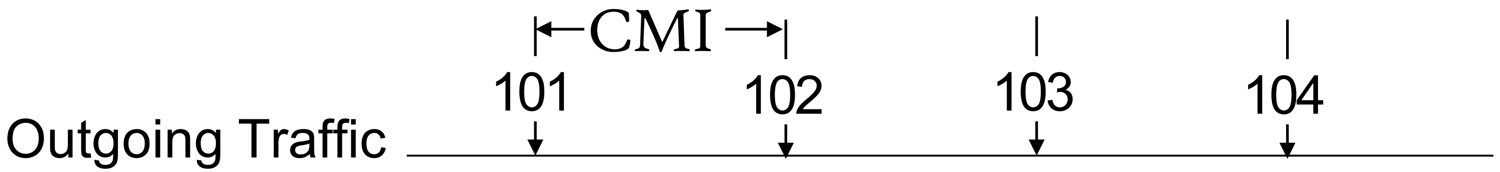
Studying the length of bursts in case of link failure

Requirements

Stream Characteristics (IEEE Std 802.1Qat):

- Class Measurement Interval (CMI)
- Maximum Interval Frames (MIF)
- and 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: $\Delta d = d_{WC} - d_{BC}$

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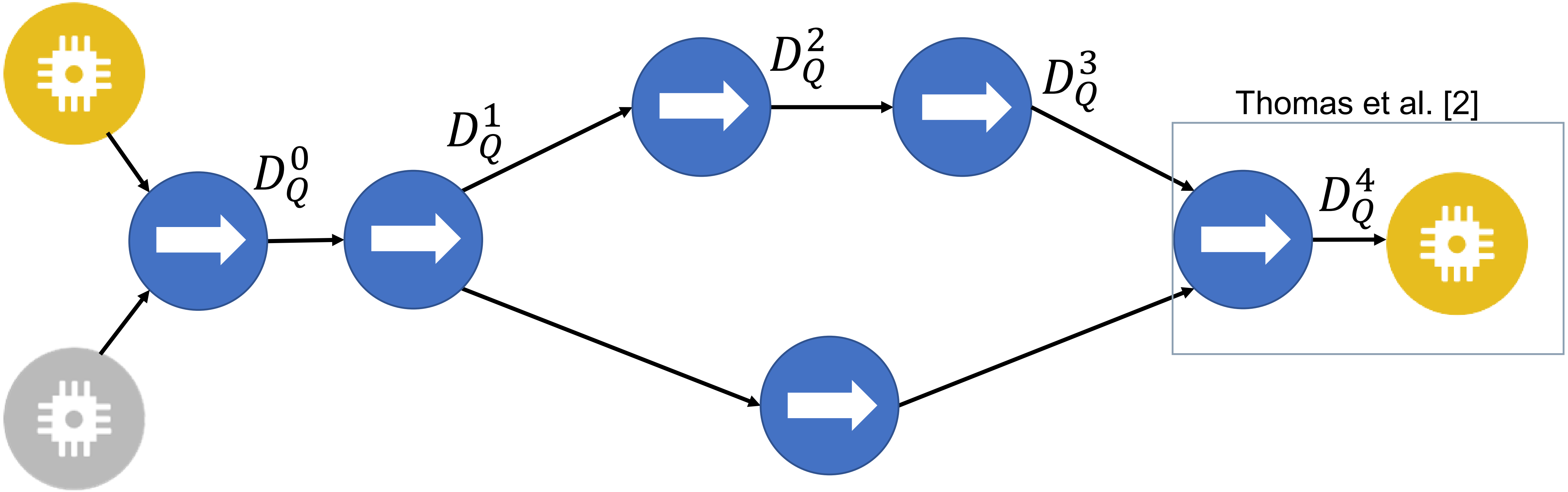
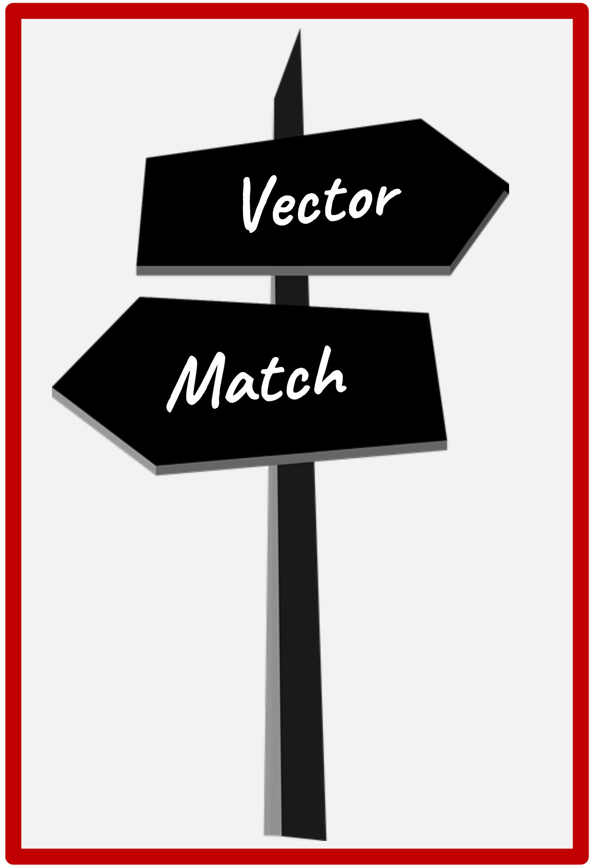
Different View on Network Delays



Thomas et al. [2]

- **Best-Case Delay:** Processing Propagation Transmission
- **Worst-Case Delay:** Processing Propagation Transmission Queuing

Limitations of the IEEE 802.1CB-2017 standard



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Match recovery algorithm

Problem Description

Match Recovery Algorithm (MRA)

- stores only highest sequence number received
- only eliminates duplicates with this sequence number
- forwards all other packets

requires intermittent streams:
the difference between arriving sequence numbers may not exceed one

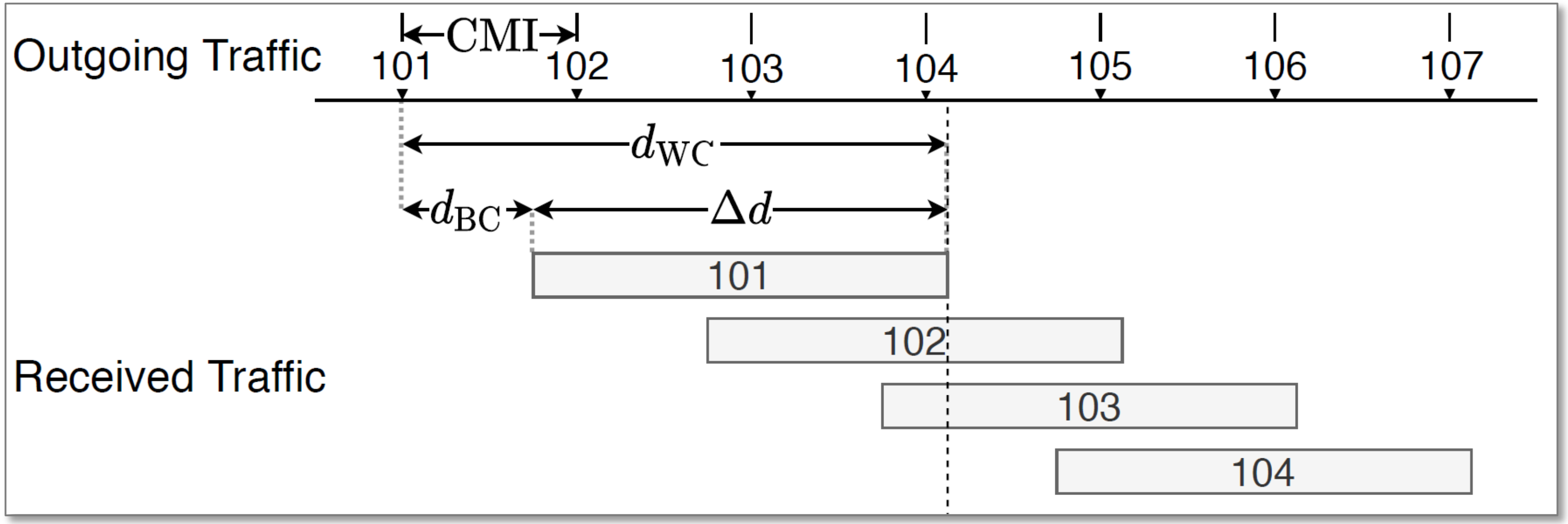
Match recovery algorithm

Solution

Identify intermittent streams

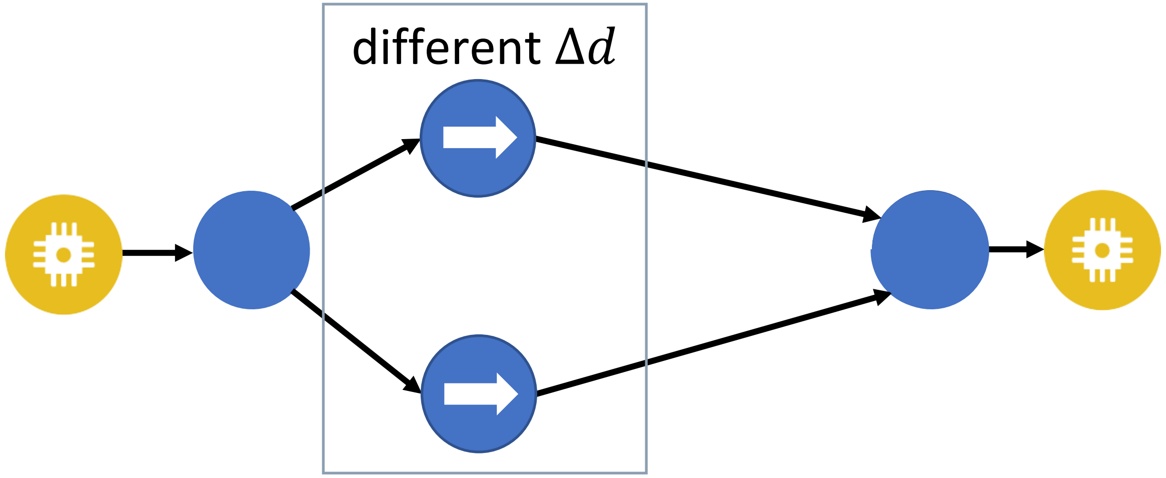
- all copies of a packet must arrive before the next sequence number can arrive at the eliminating device

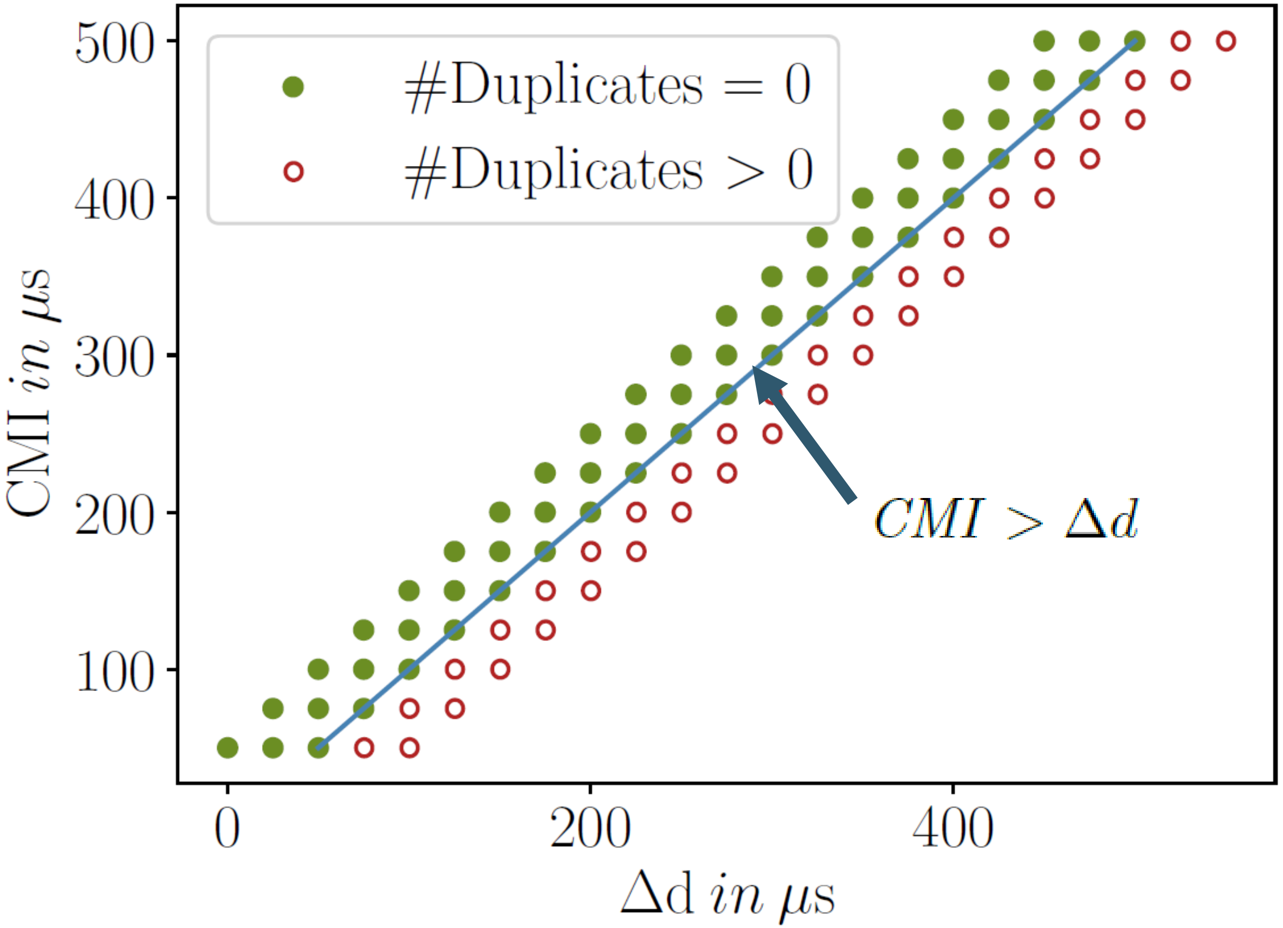
$$CMI > \Delta d = d_{WC} - d_{BC}$$



Match recovery algorithm

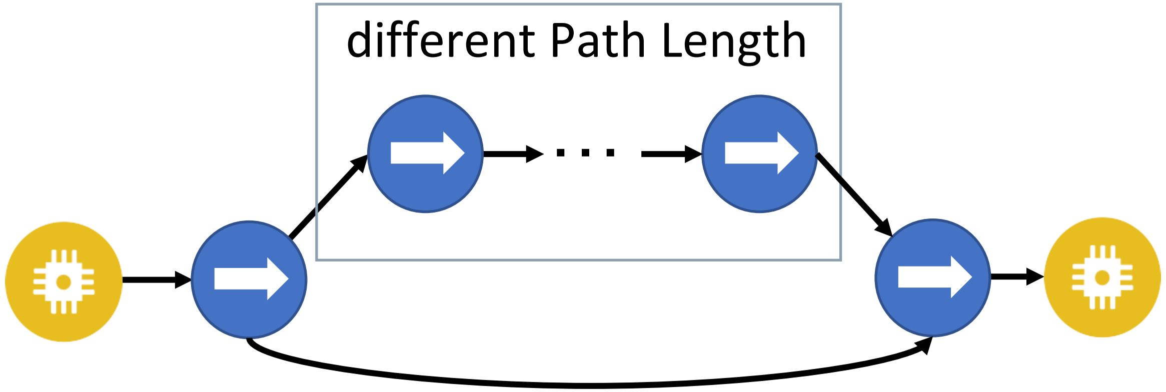
Evaluation





Match recovery algorithm

Central / NC versus Decentral / Standard

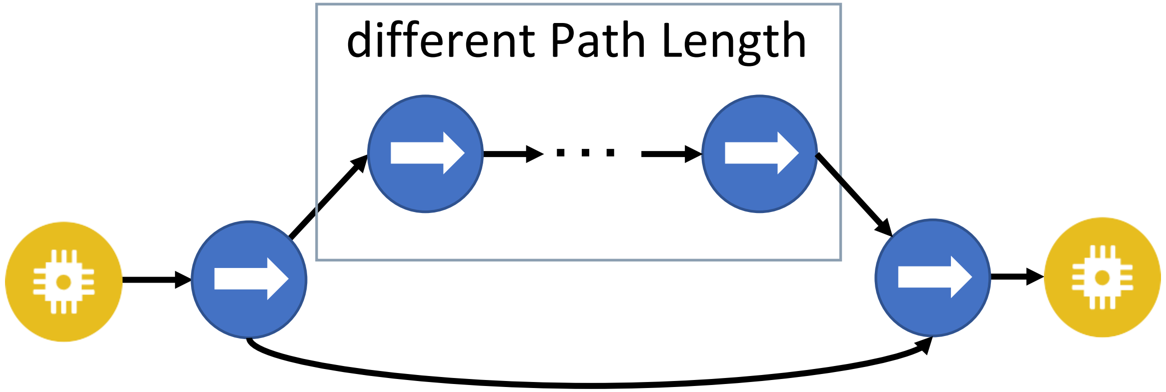


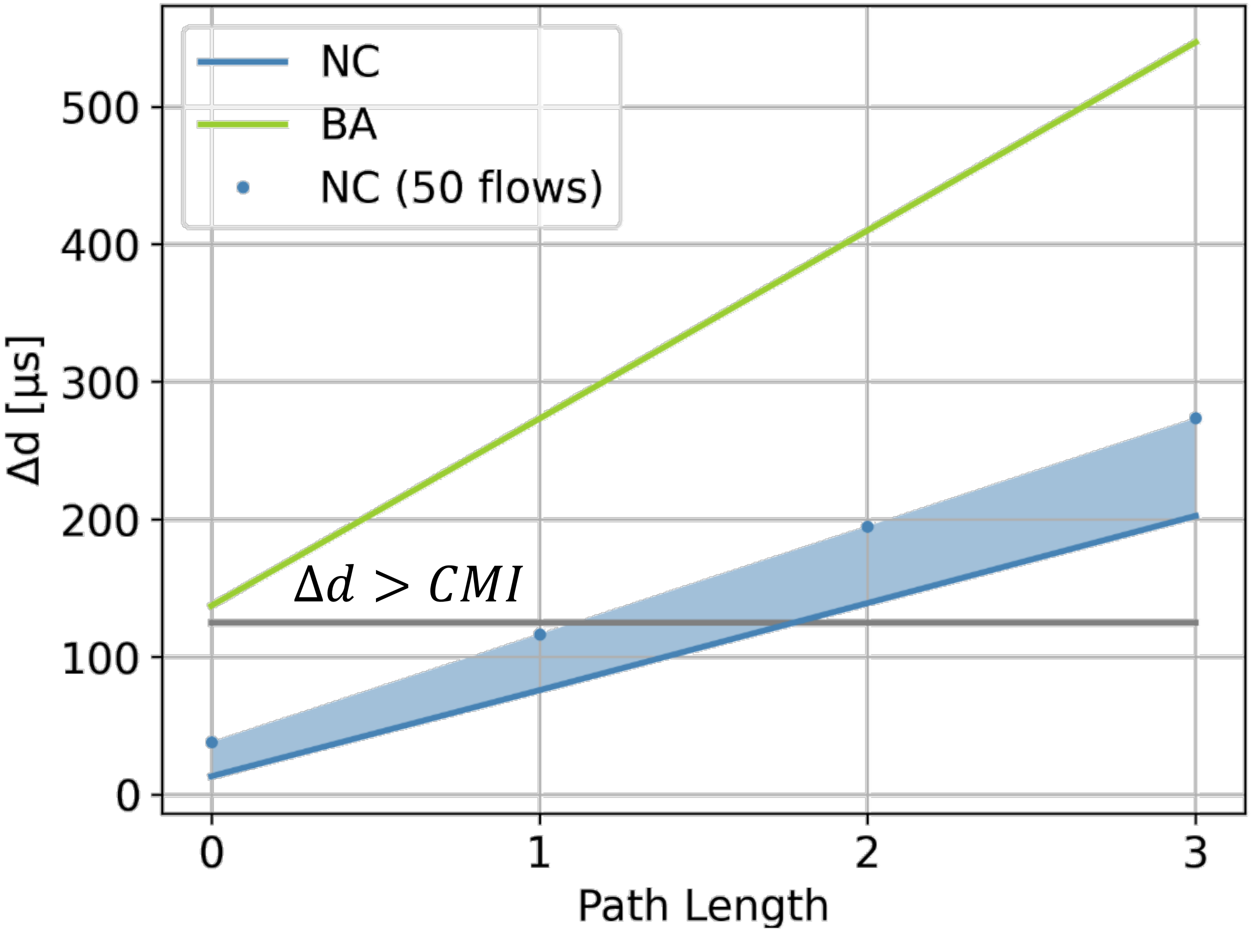
IEEE 802.1BA-2021 Standard

$$D^{u,v,0} = D^{u,v}_{proc} + D_t^{'u,v} + \frac{L^{max}}{C} + \Big(\underbrace{\frac{idSl^{u,v,0}}{C}}_{\text{perc. of link rate}} \cdot CMI - D_t^{u,v} \Big) \cdot \frac{C}{idSl^{u,v,0}}$$

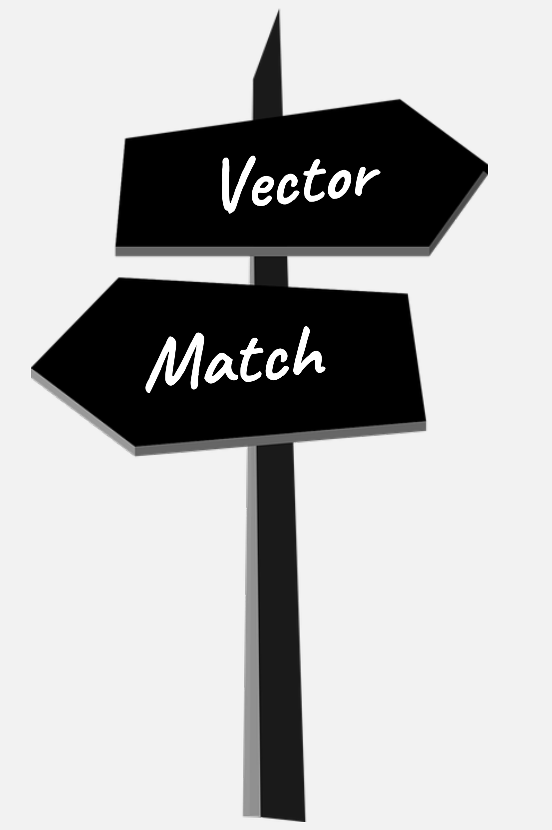
Match recovery algorithm

Central / NC versus Decentral / Standard

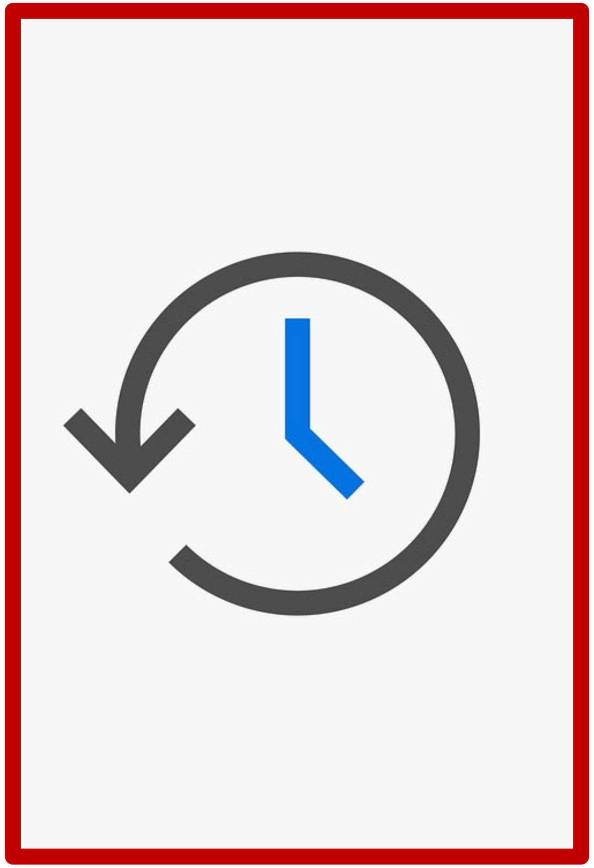




Limitations of the IEEE 802.1CB-2017 standard



Choosing match or vector recovery algorithm



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Vector recovery algorithm: History Length

Problem Description

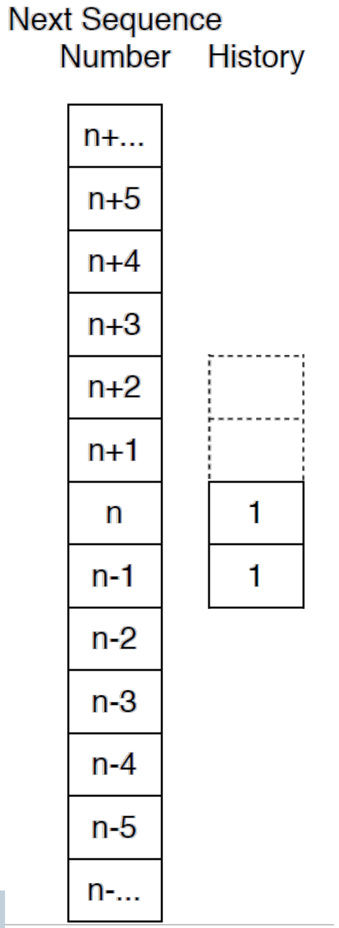
Vector Recovery Algorithm (VRA)

- 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



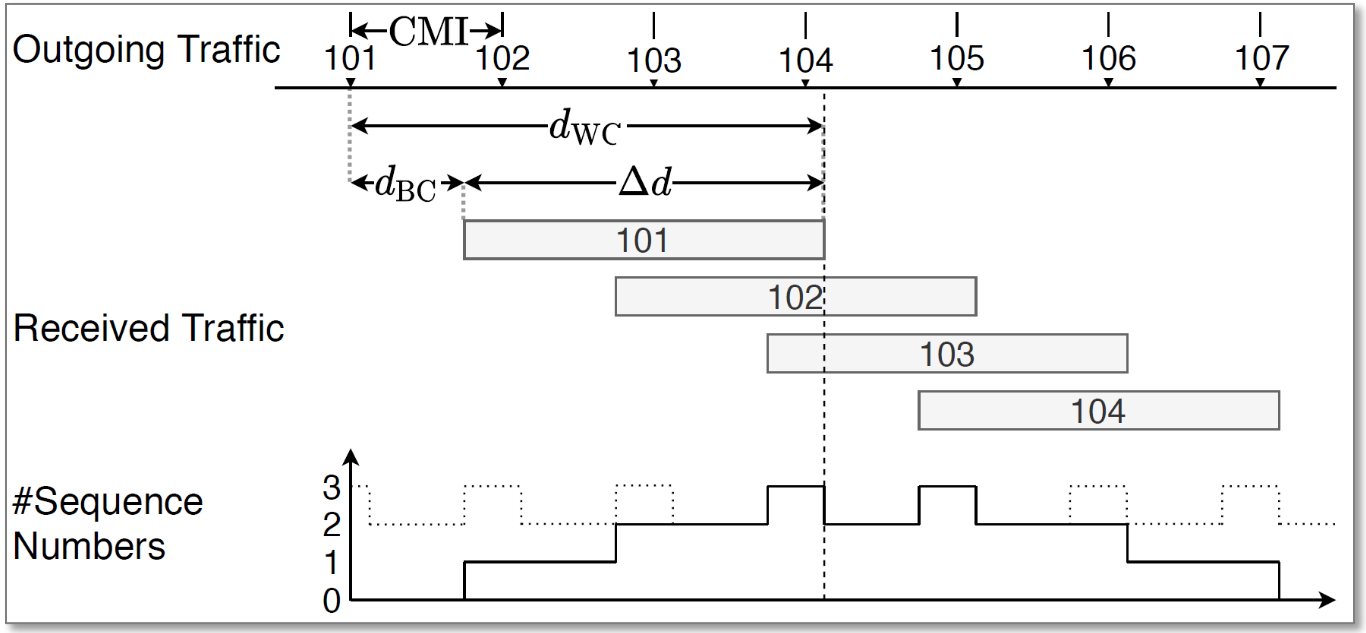
Vector recovery algorithm: History Length

Solution

Define *frerSeqRcvyHistoryLength* (short: L)

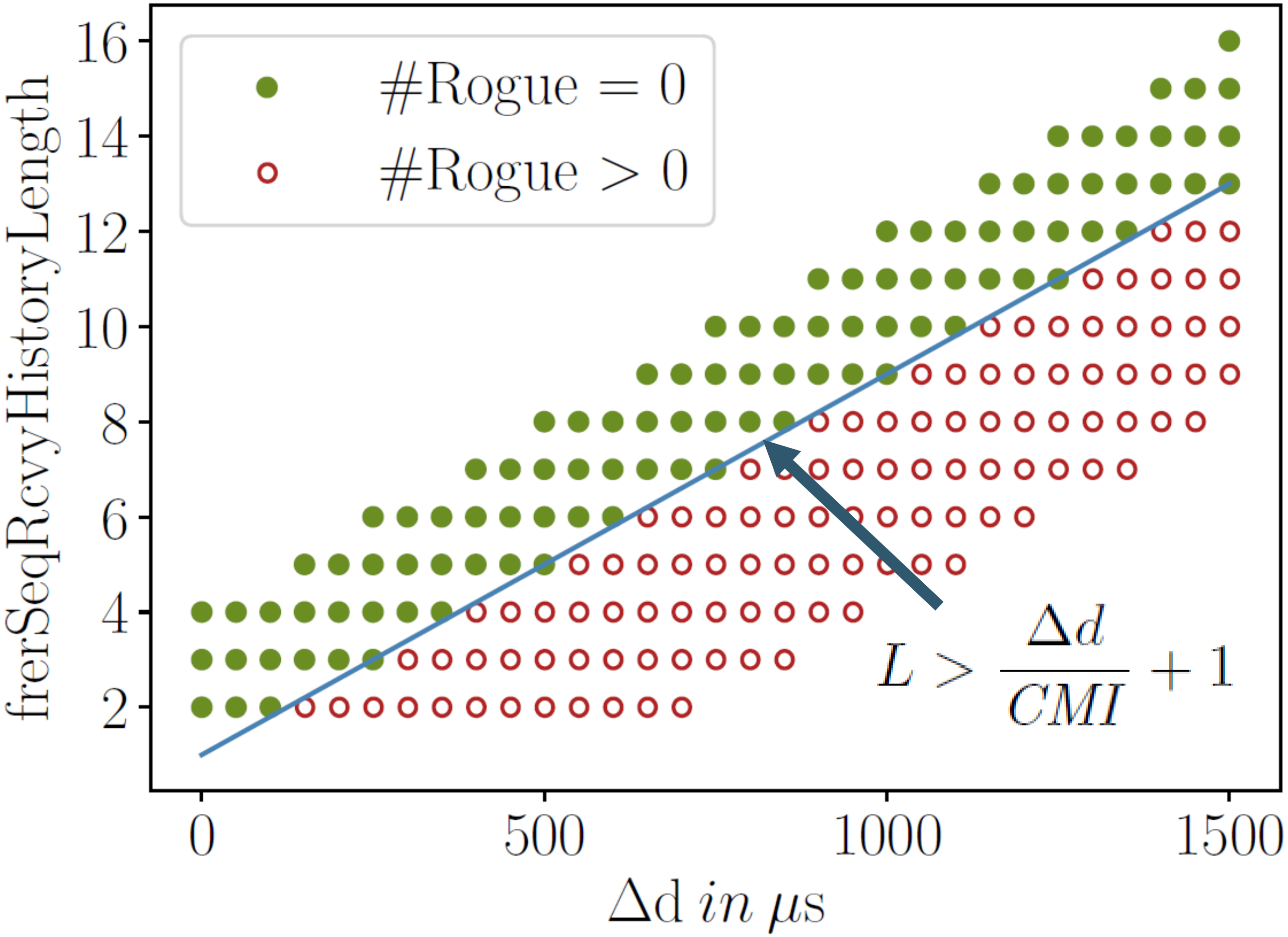
- the worst integer number of overlapping sequence numbers is $N = \left\lfloor \frac{\Delta d}{CMI} \right\rfloor + 1.$
- However, only the reception of new packets triggers a shift of the sequence history, which leads to

$$L > \frac{\Delta d}{CMI} + 1$$

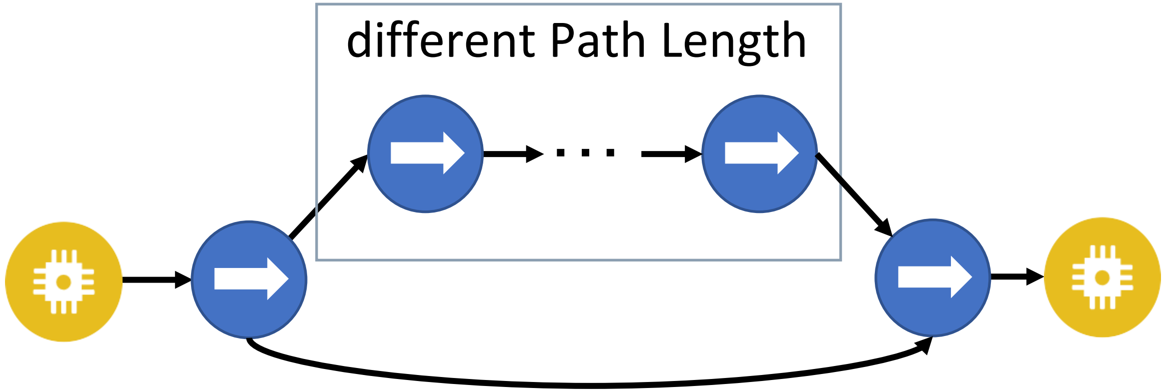


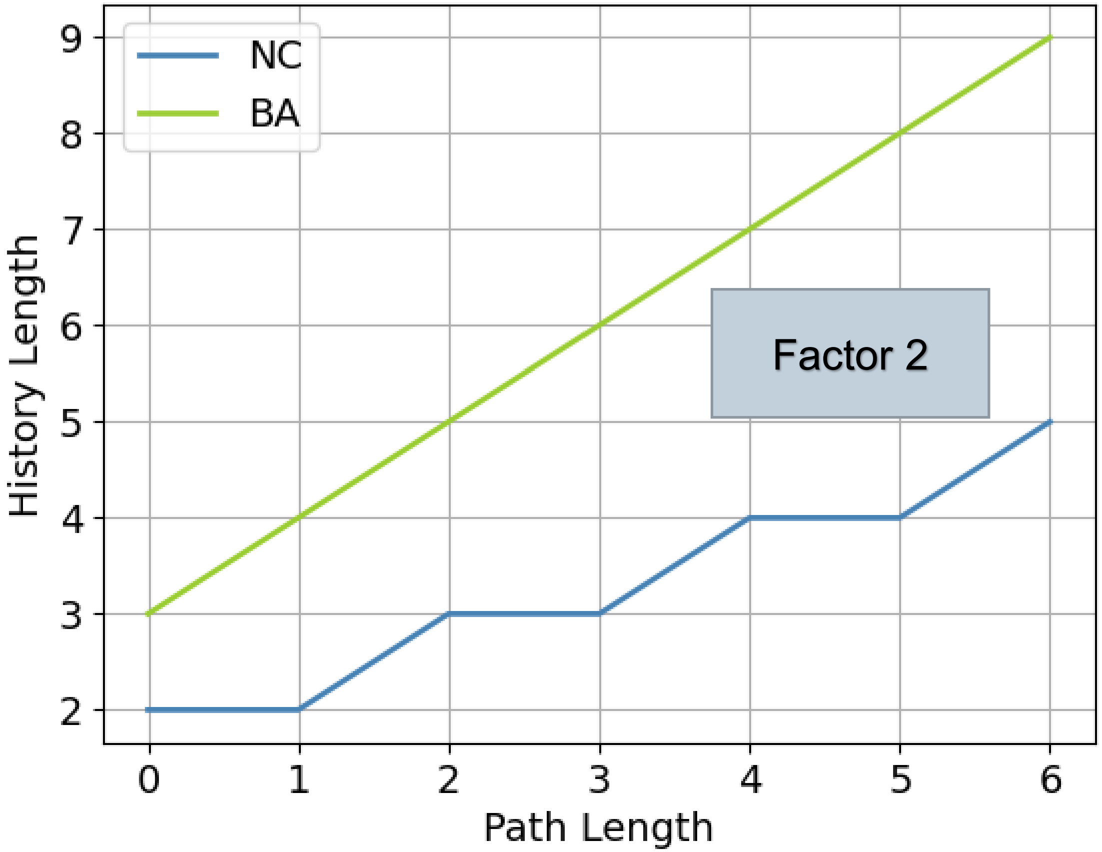
Vector recovery algorithm: History Length

Evaluation

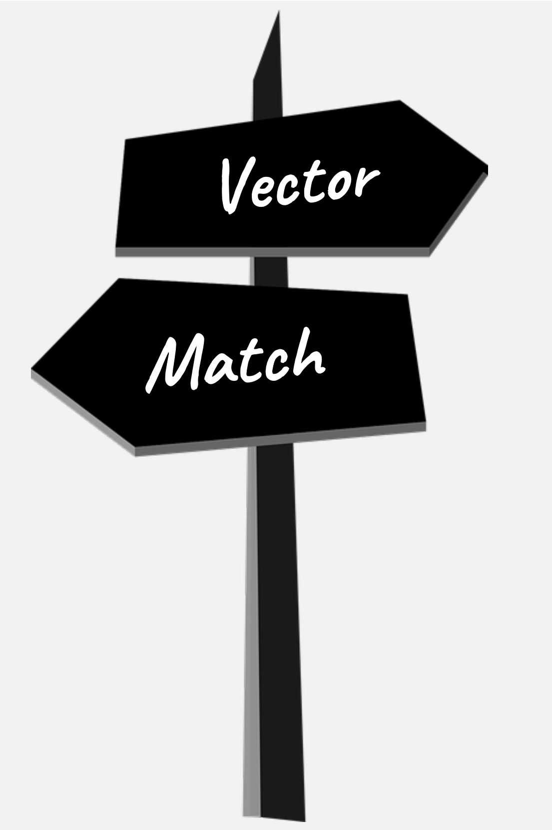


$$L > \frac{\Delta d}{CMI} + 1$$


different Path Length
. . .


NC
BA
Factor 2
History Length
Path Length
2
3
4
5
6
7
8
9
0
1
2
3
4
5
6

Limitations of the IEEE 802.1CB-2017 standard



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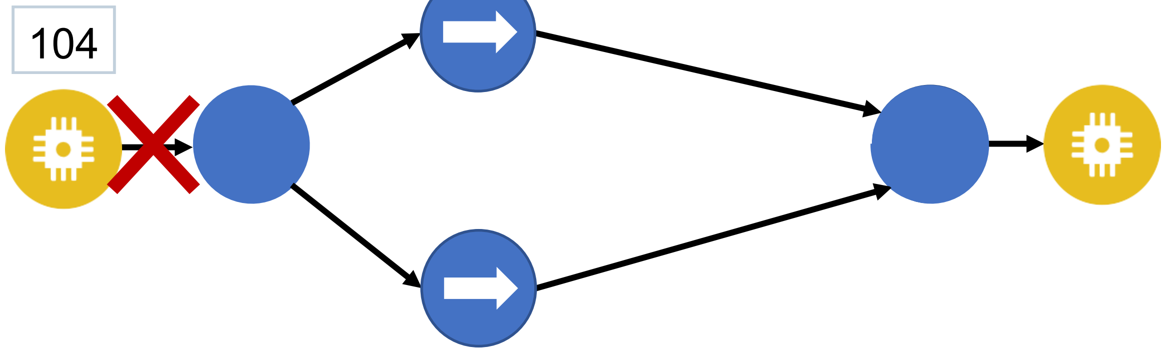
Reset Timer Configuration

Problem Description and Solution

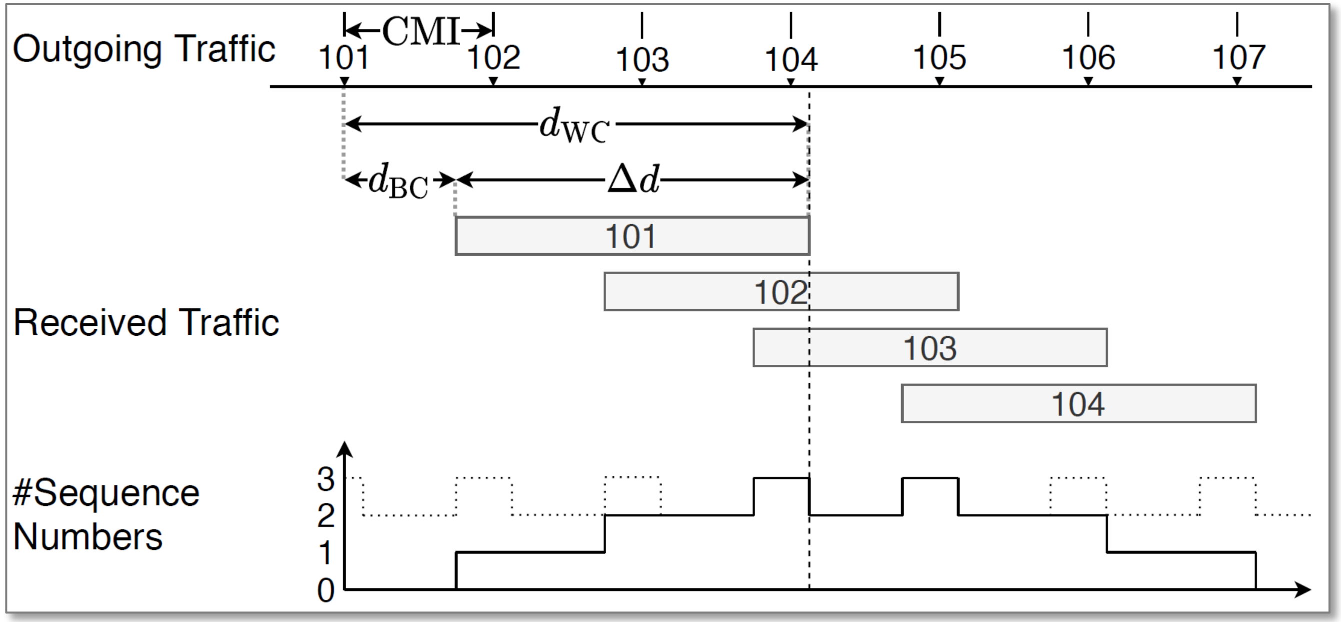
SequenceRecoveryReset function

- FRER triggers a reset after a period of time in which no packets have been accepted
- too short: duplicates passed
- too long: valid packets discarded (from interrupted connections)



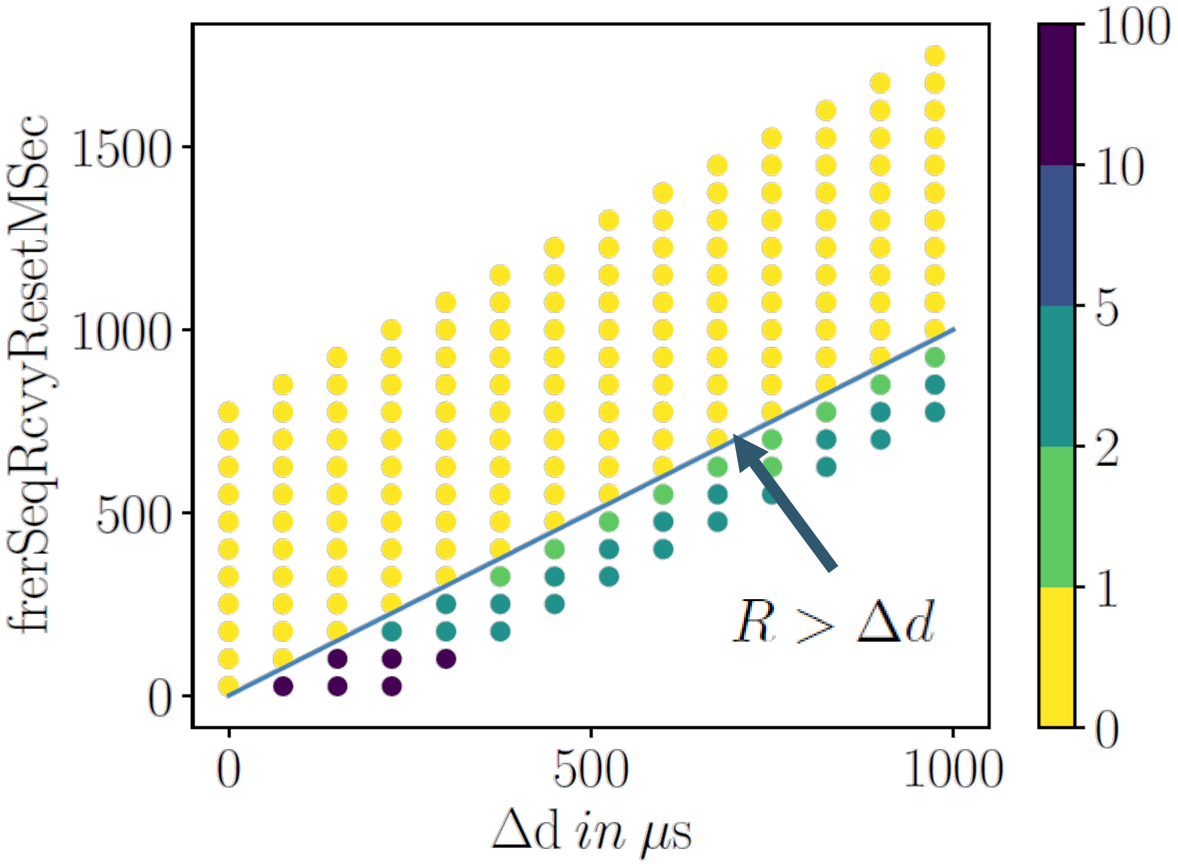
SequenceRecoveryResetMSec (short: R)

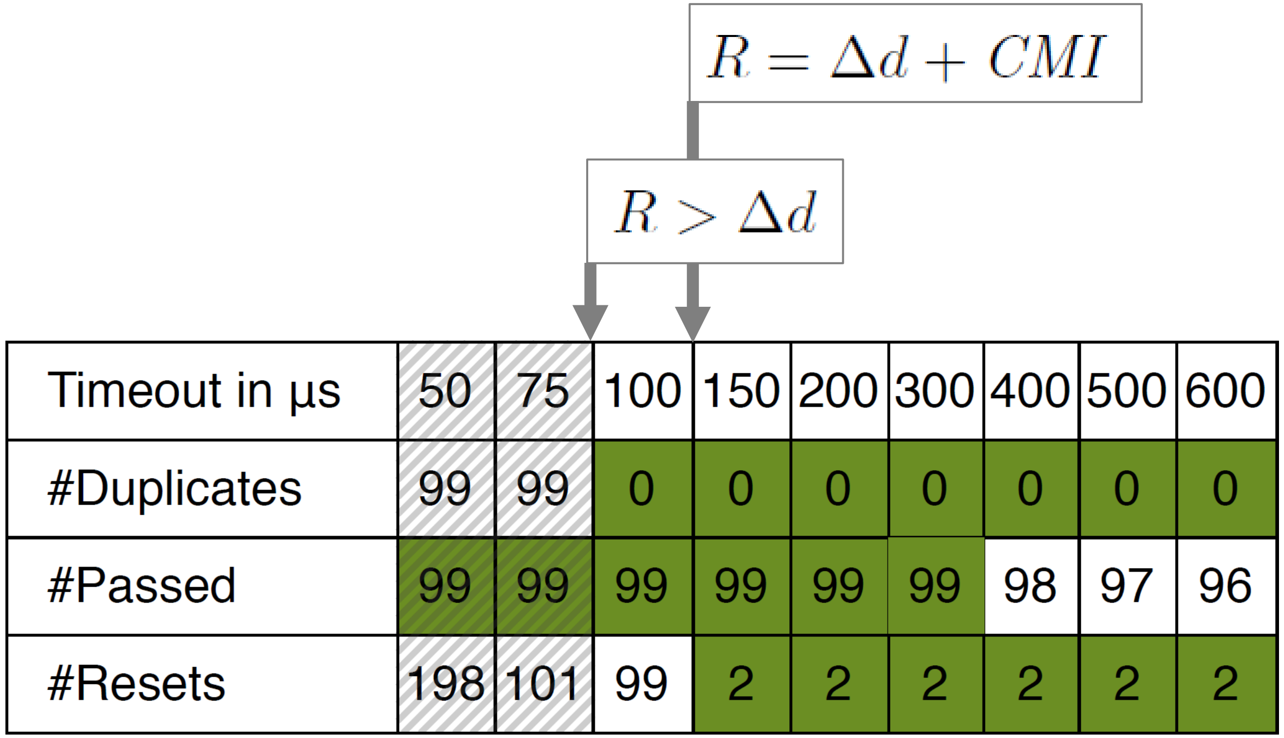
- save: $R > \Delta d$
- optimal: $R = \Delta d + CMI$



Reset Timer Configuration

Evaluation



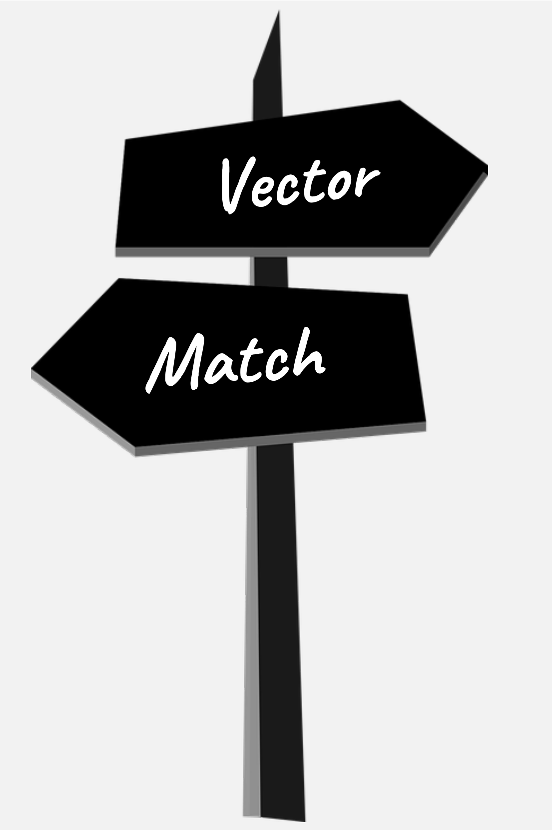


$R = \Delta d + CMI$

$R > \Delta d$

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

Limitations of the IEEE 802.1CB-2017 standard



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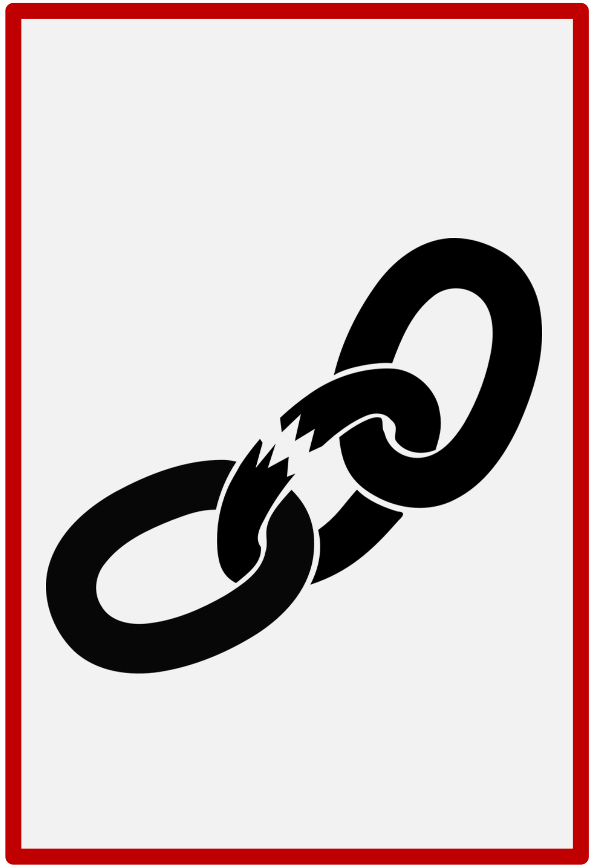


Studying the length of bursts in case of link failure

Burst Size Prediction

Problem Description

Burst dimensioning after link failure

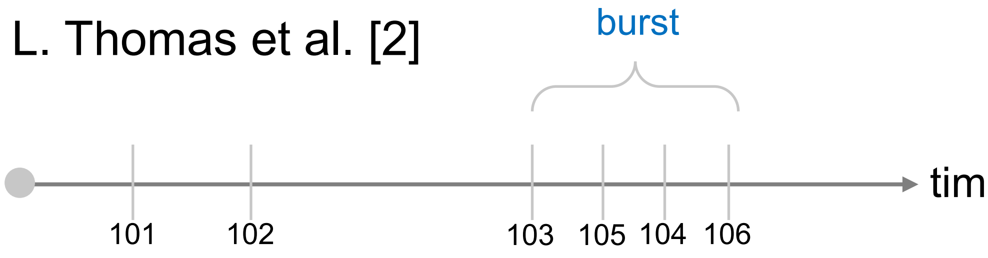
$$n_{max} = \max\left(2\cdot\left\lceil\frac{\Delta d}{CMI}\right\rceil - 1,\ 0\right)$$

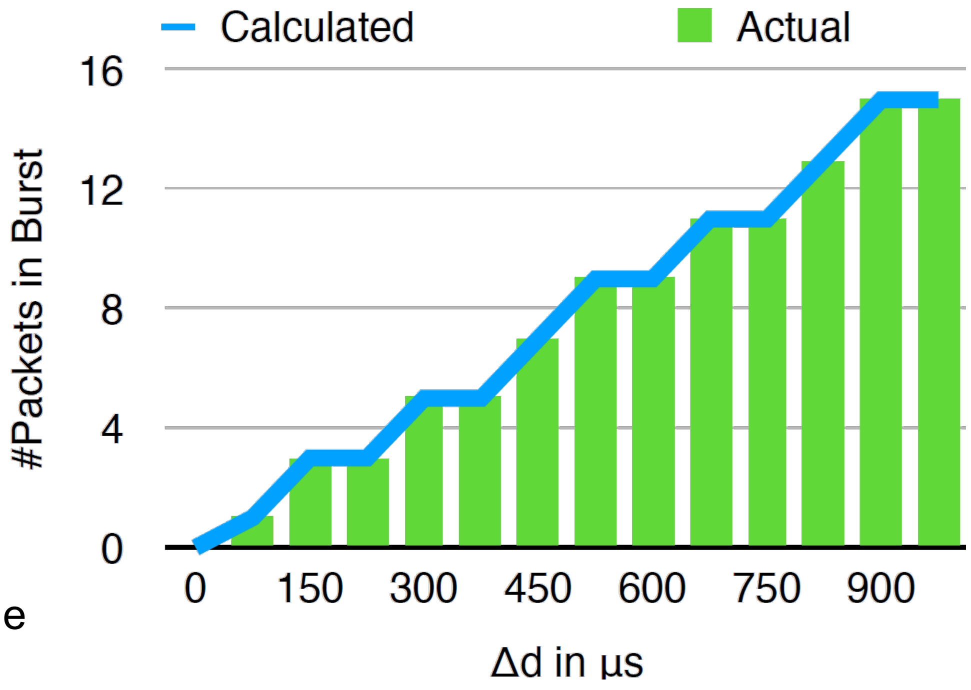
- transmission errors occur on the fastest path
- faster path resumes transmission: slower paths continue to transmit, new packets from fast path

Burst dimensioning after link failure

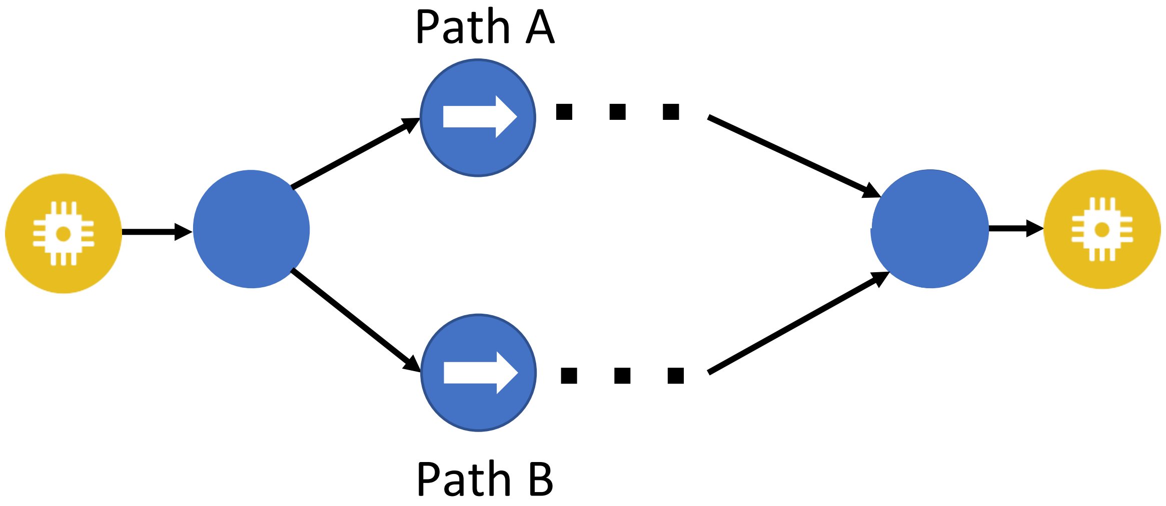
- for a duration of Δd
  - → arrival rate doubles
  - → burstiness doubles

also refer to L. Thomas et al. [2]





Comparison Evaluation



#Nodes Path A/B	2/2	4/2	8/2	12/2	16/2
Network Calculus Δd	37.5	164.4	419.4	675.7	933.5
Network Calculus Configuration					
History Length	2	3	5	7	9
#Passed	100	100	100	100	100
#Rogue	0	0	0	0	0
Default Values					
History Length	2	2	2	2	2
#Passed	100	100	72	72	72
#Rogue	0	0	90	90	90

Ongoing Work

Central Admission Control

Central Admission Control for TSN/CBS using NC

- online flow reservation, no re-configuration of reserved flows
- deadline guarantees and zero buffer overflow (with NC)
- routing and priotization
- definition of IdleSlopes
- future work: automatic configuration of FRER devices

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Accepted at: IEEE Open Journal of the Communications Society, *Sep. 2022.*

Conclusion

- IEEE 802.1CB-2017 seeks to add reliability to critical traffic in TSN
- four critical configurations of the IEEE 802.1CB-2017 TSN standard
- proofed solutions, theoretically and in simulation
- safe configuration possible with NC
- hope that these considerations will be helpful in future standardization processes

Thank you!

[1]
L. Maile, D. Voitlein, K.-S. Hielscher and R. German, "Ensuring Reliable and Predictable Behavior of IEEE 802.1CB Frame Replication and Elimination," IEEE International Conference on Communications, 2022.

[2]
L. Thomas, A. Mifdaoui and J. -Y. L. Boudec, "Worst-Case Delay Bounds in Time-Sensitive Networks With Packet Replication and Elimination," in IEEE/ACM Transactions on Networking, 2022.