TCP AND AUTOMOTIVE ETHERNET –
HOW TO RESOLVE THE EVERLASTING STRUGGLE.

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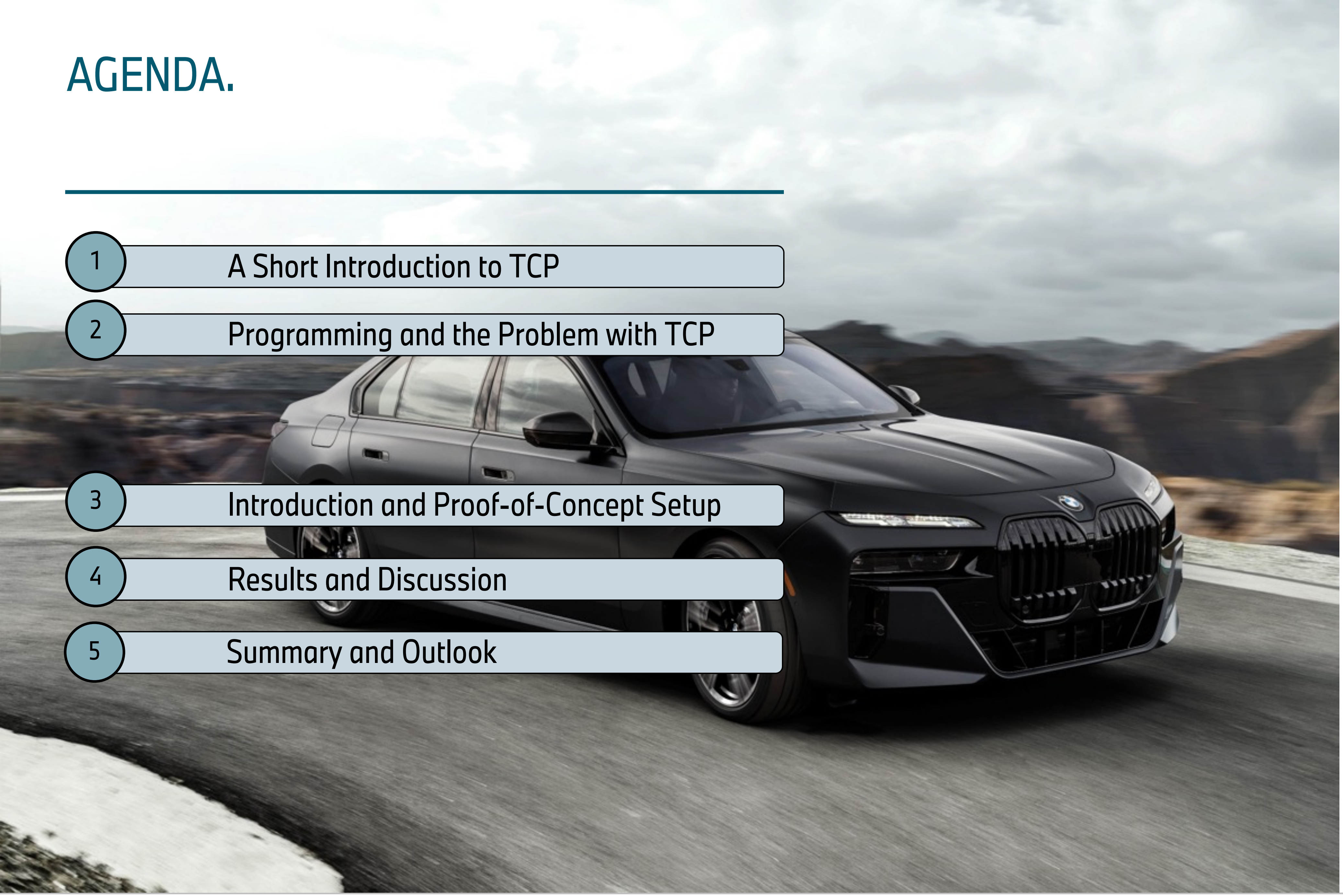
ETHERNET & IP @ AUTOMOTIVE TECHNOLOGY DAY

AGENDA.



1. A Short Introduction to TCP
2. Programming and the Problem with TCP
3. Introduction and Proof-of-Concept Setup
4. Results and Discussion
5. Summary and Outlook

TCP AND AUTOMOTIVE ETHERNET

A short Introduction to TCP

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A SHORT INTRODUCTION TO TCP. FUNDAMENTALS OF TCP.

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Connection oriented (end-to-end) protocol

- One sender, one receiver, bidirectional
- "Three way Handshake" to establish necessary states

Segmentation

- Packetization & reassembly of stream data in tx/rx buffer

Data Streaming

- Reliable, in-order delivery of packets, without duplications or loss
  - → Acknowledgements, sequence IDs, timeouts and clever retries

Pipelining

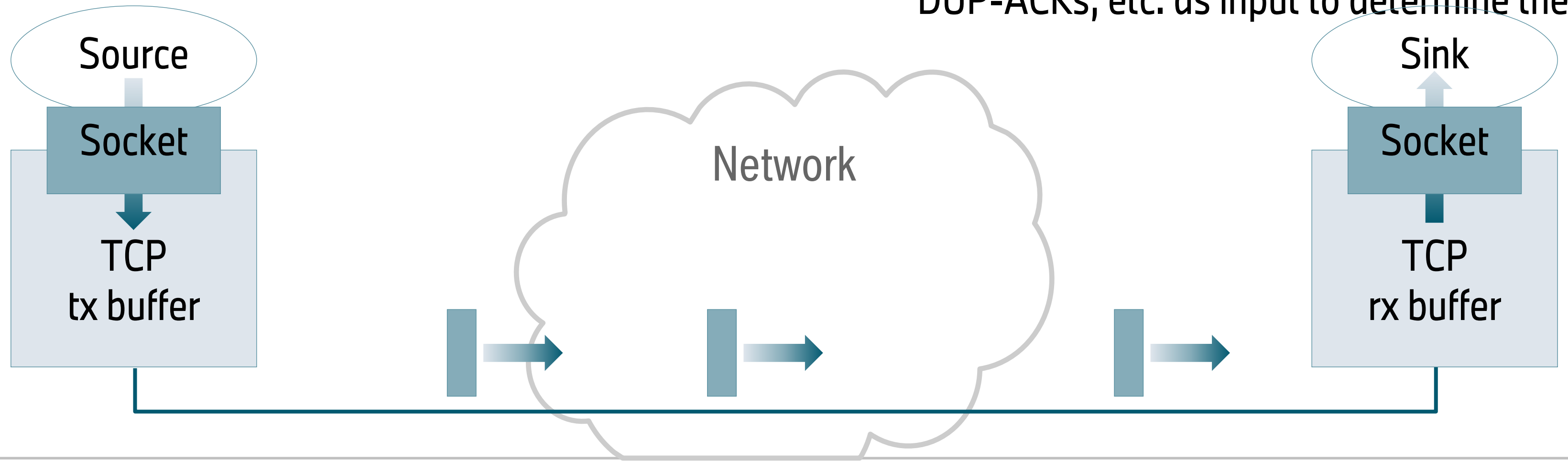
- Permission for parallel packet transmission

Flow Control

- Control sending rate to prevent sender from overwhelming receiver
  - → Sliding window protocol that synchronizes to "receive window"

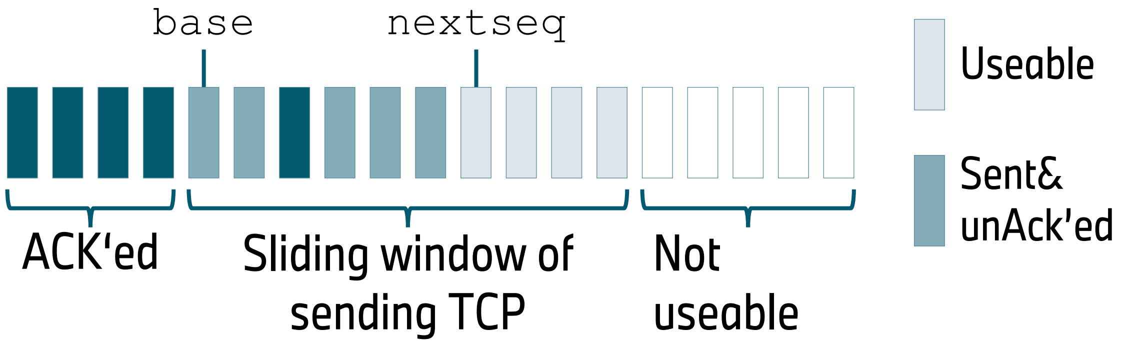
Congestion Control

- Avoid packet loss due to network congestion
  - → Adaptive algorithm that takes timeouts, timing variations, DUP-ACKs, etc. as input to determine the congestion window



A SHORT INTRODUCTION TO TCP.
FLOW CONTROL AND THE TCP SLIDING WINDOW PROTOCOL.

Basic principles of the TCP sliding window protocol:



- **Pipelining:** send window allows more than one "packet in-flight"
- **Flow Control:** continuous synchronization of send window to receive window using the `RcvWindow` field to slow down sender
- ACKs acknowledge all previous packets incl. the last received one according to the **acknowledgment policy**
  - DUP-ACKs hinting towards packet loss are possible
    → 3 DUP-ACKs: **Fast Retransmit** of oldest unACK'ed packet
- Sender has a timer for each unACK'ed packet
  → **RTO-Timeout:** unACK'ed packet is retransmitted

Acknowledgement policy:

Event	Action of receiving TCP
Reception of in-order segment with expected sequence number	Initiate **Delayed ACK** and wait 500ms for other in-order segment(s), otherwise send ACK
Reception of another in-order segment with `seq=nextseq`, while delayed ACK is active	Delayed ACK mechanism is still active
Reception of an out-of-order segment with `seq>nextseq`	Gap in data stream! Send DUP-ACK acknowledging again next expected segment (`nextseq`)
Reception of an in-order segment that fills a gap in the data stream	Send a cumulative ACK for all segments received w/o gap, provided that `seq=nextseq`

A SHORT INTRODUCTION TO TCP.
PRINCIPLES OF TCP CONGESTION CONTROL.

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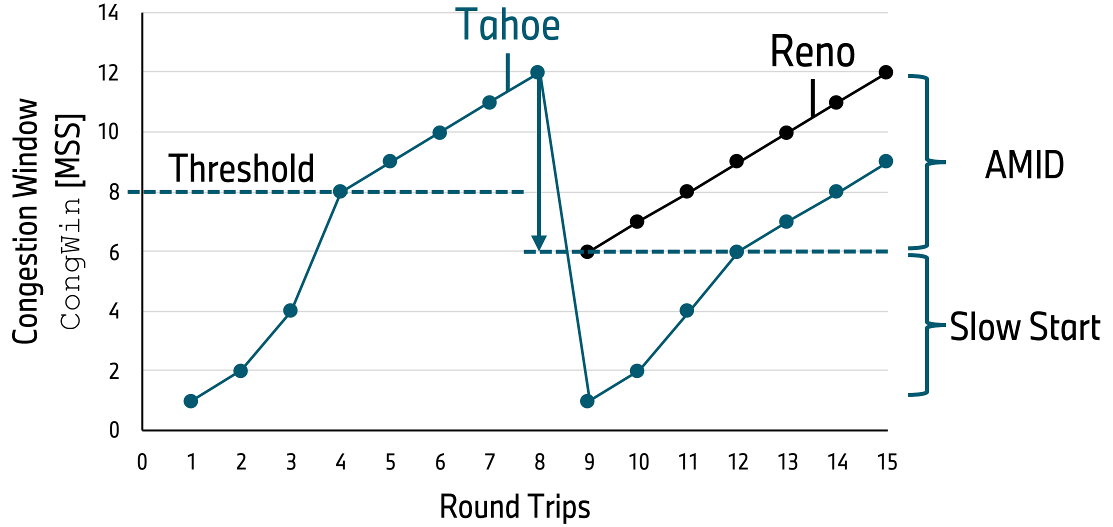
TCP Congestion Control: dynamic sending-side **fine-tuning of the send window** based on direct and indirect feedback from both network (timeouts) and receiver (DUP-ACKs) to avoid network overload scenarios.



- **Slow Start:** `CongWin++` for each ACK → exponential increase of congestion window until `Threshold` is reached
- **AIMD:** Additive Increase Multiplicative Decrease approach to be more careful&fair while searching for further bandwidth
  - Additive Increase: Increase `CongWin` by 1MSS per RTT (Round Trip Time) till an incident is detected
  - Multiplicative Decrease: Decrease `CongWin` and set `Threshold = CongWin/2`, when an incident is detected
- **Reaction to incidents:**
  - → 3 DUP-ACKs: **Fast Recovery** possible (see Reno) by setting `CongWin = CongWin/2`, as network is still able to deliver data
  - → Timeout: Set `CongWin = 1` and begin Slow Start

TCP AND AUTOMOTIVE ETHERNET

Programming and the Problem with TCP

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VEHICLE PROGRAMMING AND THE PROBLEM WITH TCP. COMMONALITIES IN OBD AND OTA PROGRAMMING.

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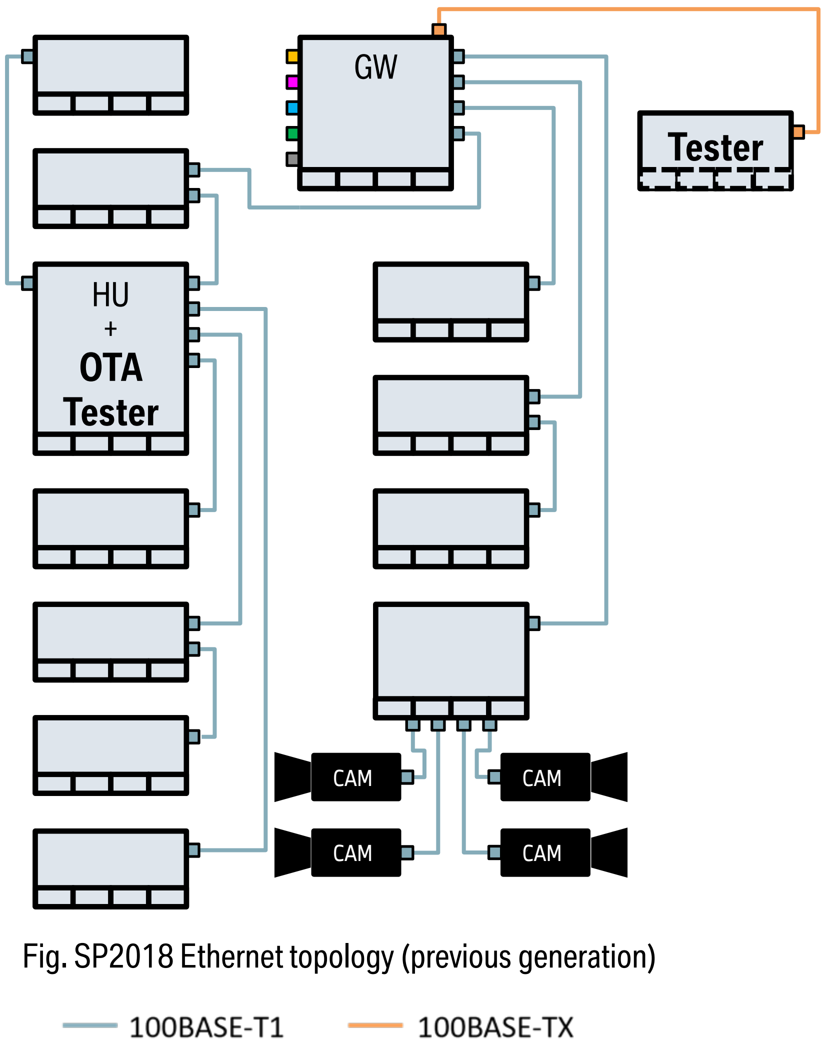

Fig. SP2018 Ethernet topology (previous generation)

Regular OBD programming procedure:

- Activation pins in OBD port of GW ECU are bridged physically:
  - → GW relays `StatusOBD` in SI OBD to signal Ethernet ECUs presence of an (external) tester
  - → Ethernet ECUs adapt to the external tester network by acquiring an (external) IP address
- GW announces IP addresses of Ethernet ECUs to the tester so that the acquired IP addresses can be linked with a VIN
- After changing the "Default Diagnostic Bus" from internal to external the tester can program Ethernet ECUs directly

Basic OTA programming procedure:

- OTA Tester requests form GW to mimic presence of an external tester by updating `StatusOBD`
  - → Regular OBD programming is started

VEHICLE PROGRAMMING AND THE PROBLEM WITH TCP.
TYPICAL LIMITATIONS OF EMBEDDED TCP STACKS.

No.	Time [s]	Delta [s]	Src	Dest	Protocol	Seq	Lenght	Seq.Next	ACK	Expert
9787	06.376114	--	HU	GW	TCP	60726	1460	**62186**	287	Bulk Transfer
9788	06.376659	0.000545	GW	HU	TCP	287	0	287	**62186**	ACK for Bulk Transfer
9789	06.377139	0.000480	HU	GW	TCP	63646	1460	65106	287	[Loss of segment 62186]
9790	06.377761	0.000622	GW	HU	TCP	287	0	287	62186	[Dup ACK 9788#1]
9791	06.419921	0.042160	GW	HU	DoIP	287	20	307	62186	Multiple payload, Delay!
9792	06.420241	0.000320	HU	GW	TCP	65106	0	65106	307	ACK & window probe
9793	06.420778	0.000537	GW	HU	TCP	307	65106	307	62186	[Dup ACK 9788#2]
(...)										
9810	06.581574	--	HU	GW	TCP	62186	1460	63646	387	[TCP Retransmission]
9811	0.6582413	0.000939	GW	HU	TCP	387	0	387	63646	[No Out-of-Order Support]

Findings in trace:

- tcp.analysis.zero_window and small `RcvWindow = 2MSS`
  → Indication of inefficient bulk transfer towards GW
- tcp.analysis.lost_segment shows packet loss
- >1 UDS messages packetized although `NODELAY = ON`

General Root Causes:

- Dependencies between UDS and TCP due to general protocol design issues: `UDS_Timeouts << RTO`
- No 3 DUP-ACK due to small `RcvWindow`, if GW isn't sending
- Retransmission chains due to missing OoO support

VEHICLE PROGRAMMING AND THE PROBLEM WITH TCP. ARCHITECTURAL LESSONS LEARNED.

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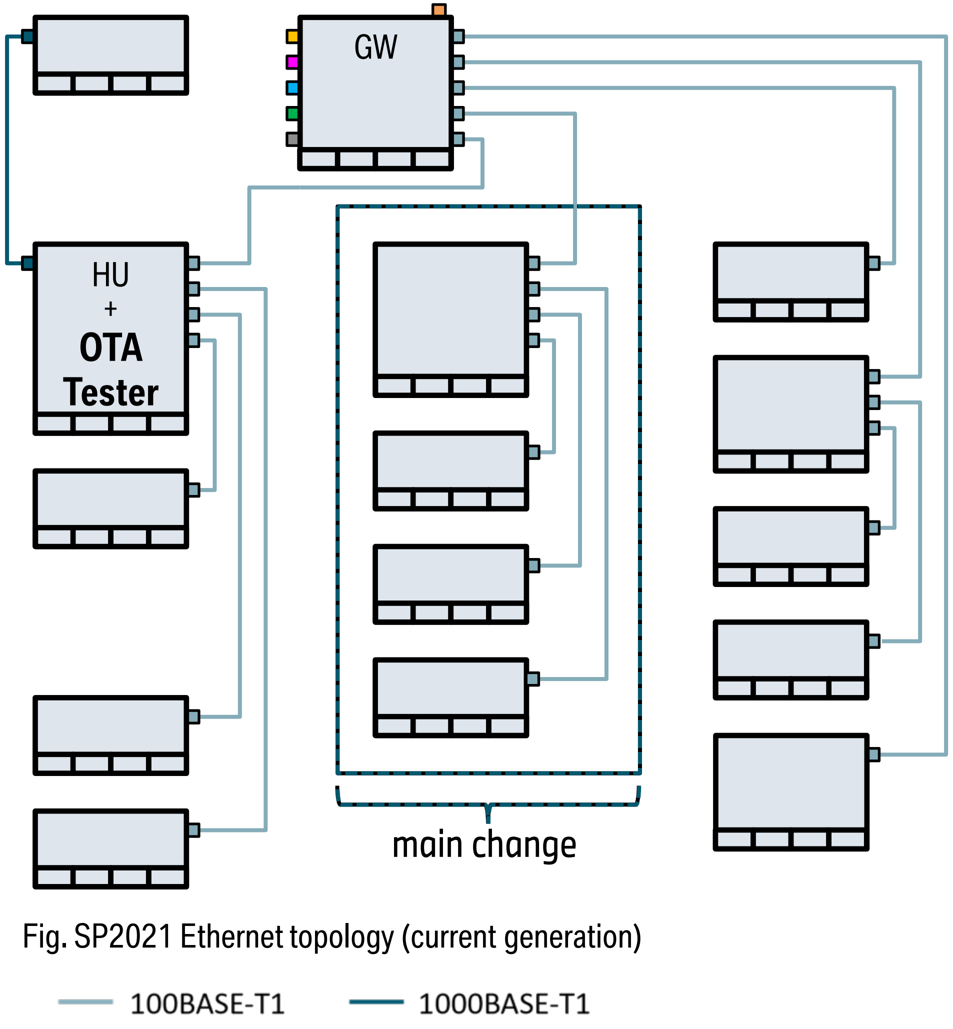

Fig. SP2021 Ethernet topology (current generation)

Architectural differences in OTA and their implications:

- Flash sequence optimized for diagnostic-access via GW
  - Packets are distributed less evenly across ports/links, when partitioning tester elsewhere
- Switches w/o dedicated packet buffer per port/TC may introduce unpredictable side effects on other streams that are a little bursty
- Issues from mixed speed-grades for OTA Tester that did not turn up in previously generation due to less performant HW
  - Less traffic offer from OTA Tester
  - Unknowing implicit "traffic shaping" by receivers due to smaller `RcvWindow` of SP2018 ECUs

Minor deficiencies may have severe consequences in presence of the slightest changes, when TCP is neither fine-tuned nor adapted to automotive constraints!

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TCP AND AUTOMOTIVE ETHERNET

Introduction and PoC Setup

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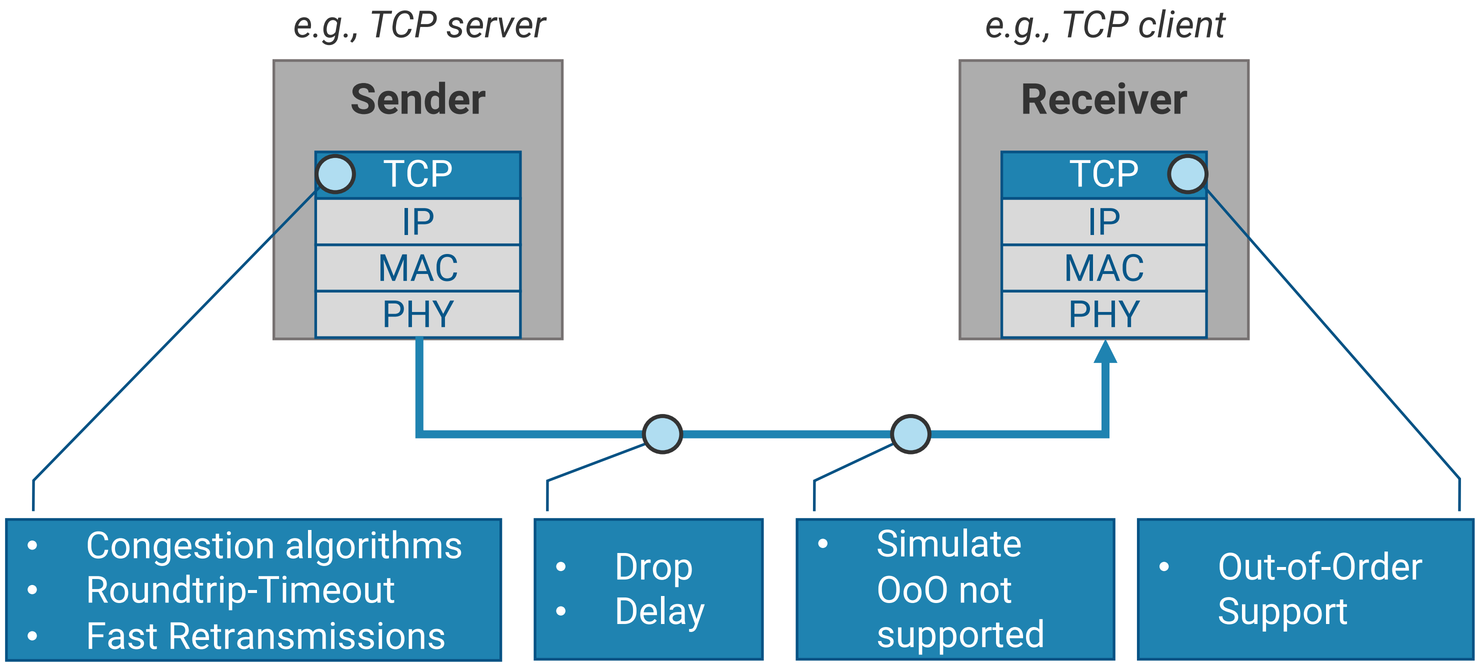
PROOF OF CONCEPT

INTRODUCTION AND POC SETUP

A PoC setup (under Linux) has been built to cover the following needs:

- **Tune the following TCP parameters:**
  - Roundtrip-Timeout
  - Out-of-Order support (OoO)
  - Congestion algorithms
  - Fast Retransmission support
- **Impairment simulation:**
  - Dropped segments
  - Delayed segments
  - OoO not supported
- **Evaluate effects on**
  - Round trip time / Latency
  - Goodput



TCP AND AUTOMOTIVE ETHERNET

Results and Discussion

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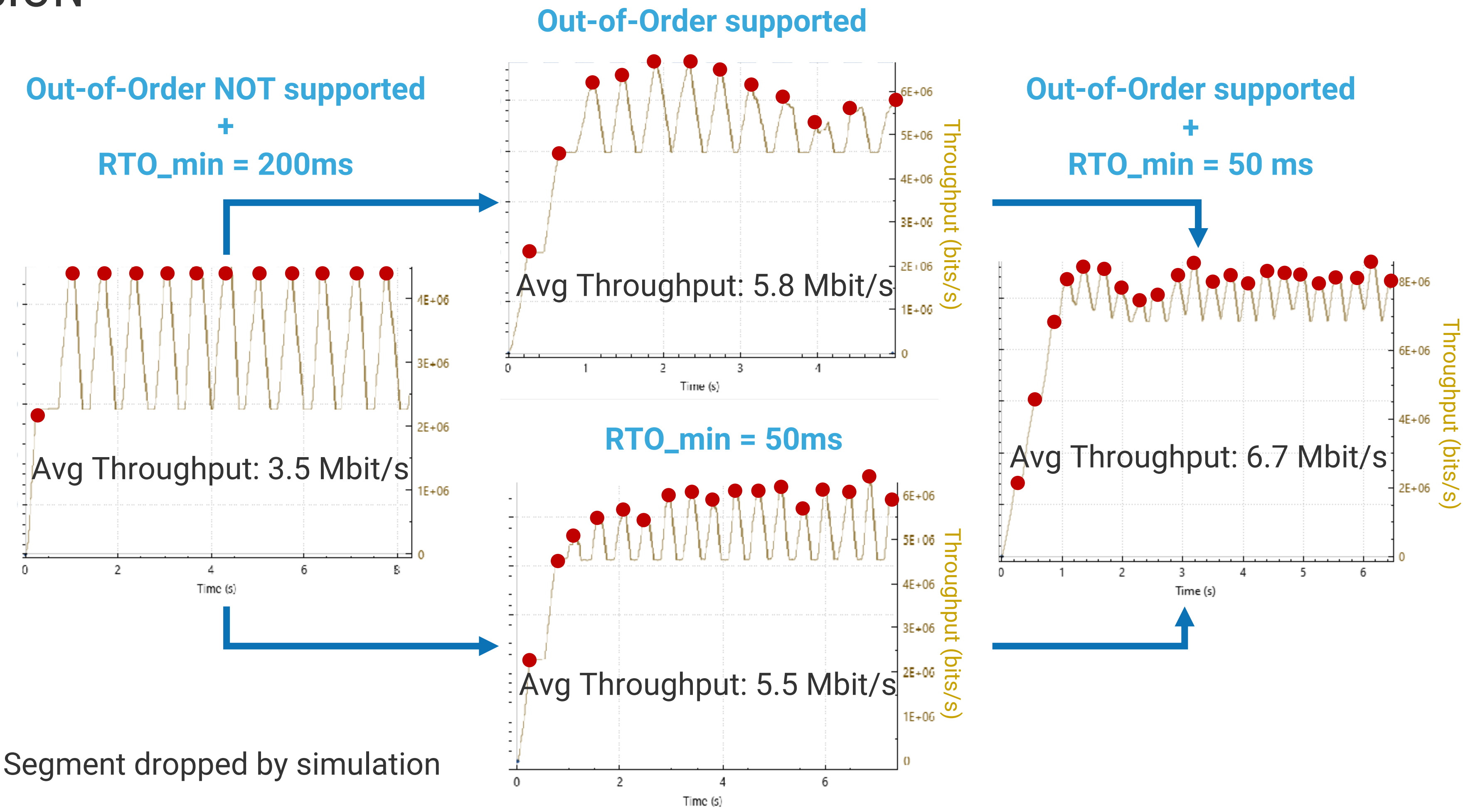
BIG IMPACT PROBLEMS IN EMBEDDED STACKS

RESULTS AND DISCUSSION

Issues

- Retransmission chains due to missing OoO support.
- Poor recovery speed / performance after loss.



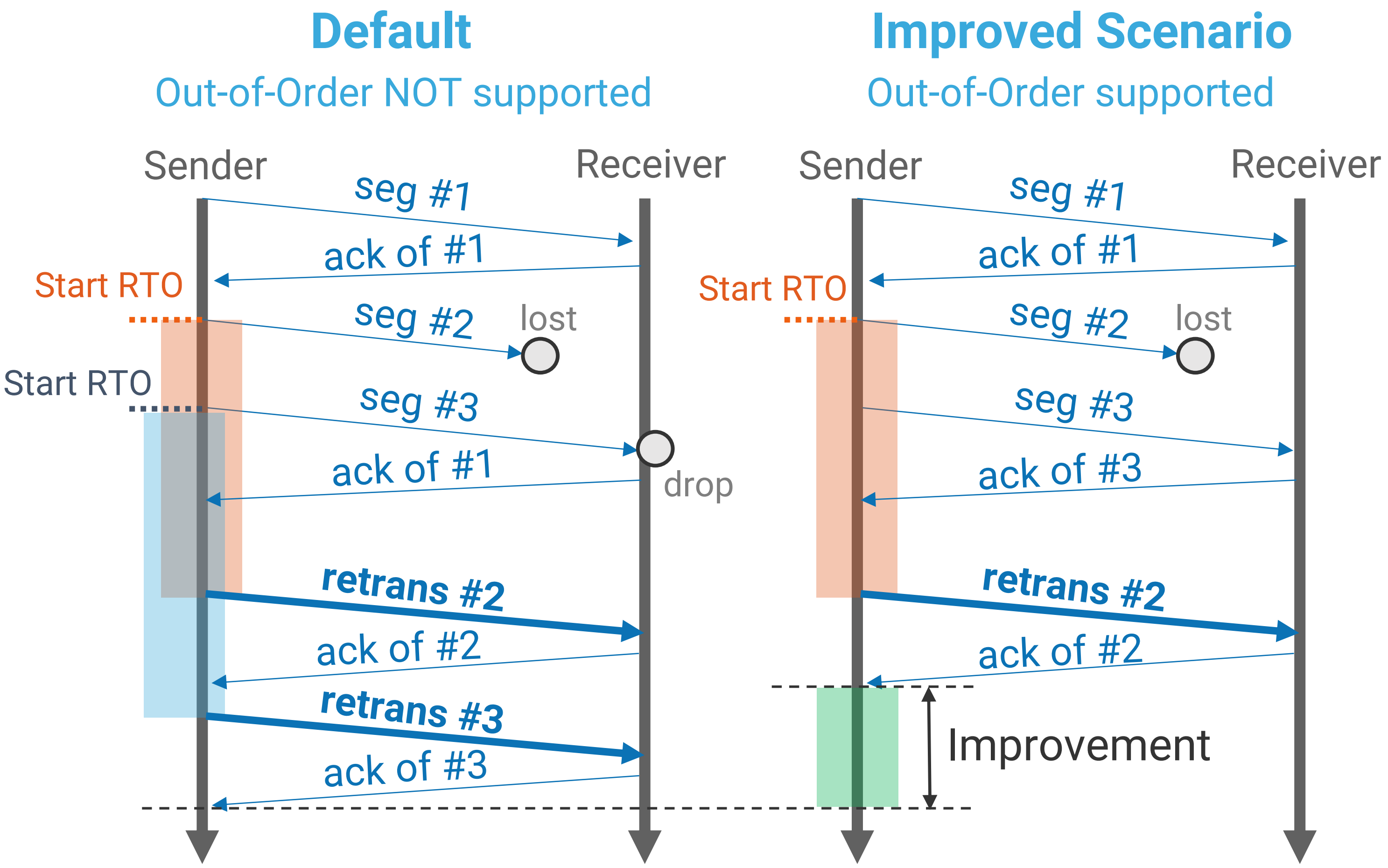
● Segment dropped by simulation

OUT-OF-ORDER SUPPORT

RESULTS AND DISCUSSION

Key Points

- The improved scenario enables the receiver to acknowledge the received OoO segments after a loss.
- Sender retransmits **only** what has been lost.
- OoO support prevents from loss chain effects, which are highly critical for transmission recovery.
- Selective Acknowledgment at the receiver provides additional advantages, if OoO is supported.
- Improvement depends on size of bytes in transit.



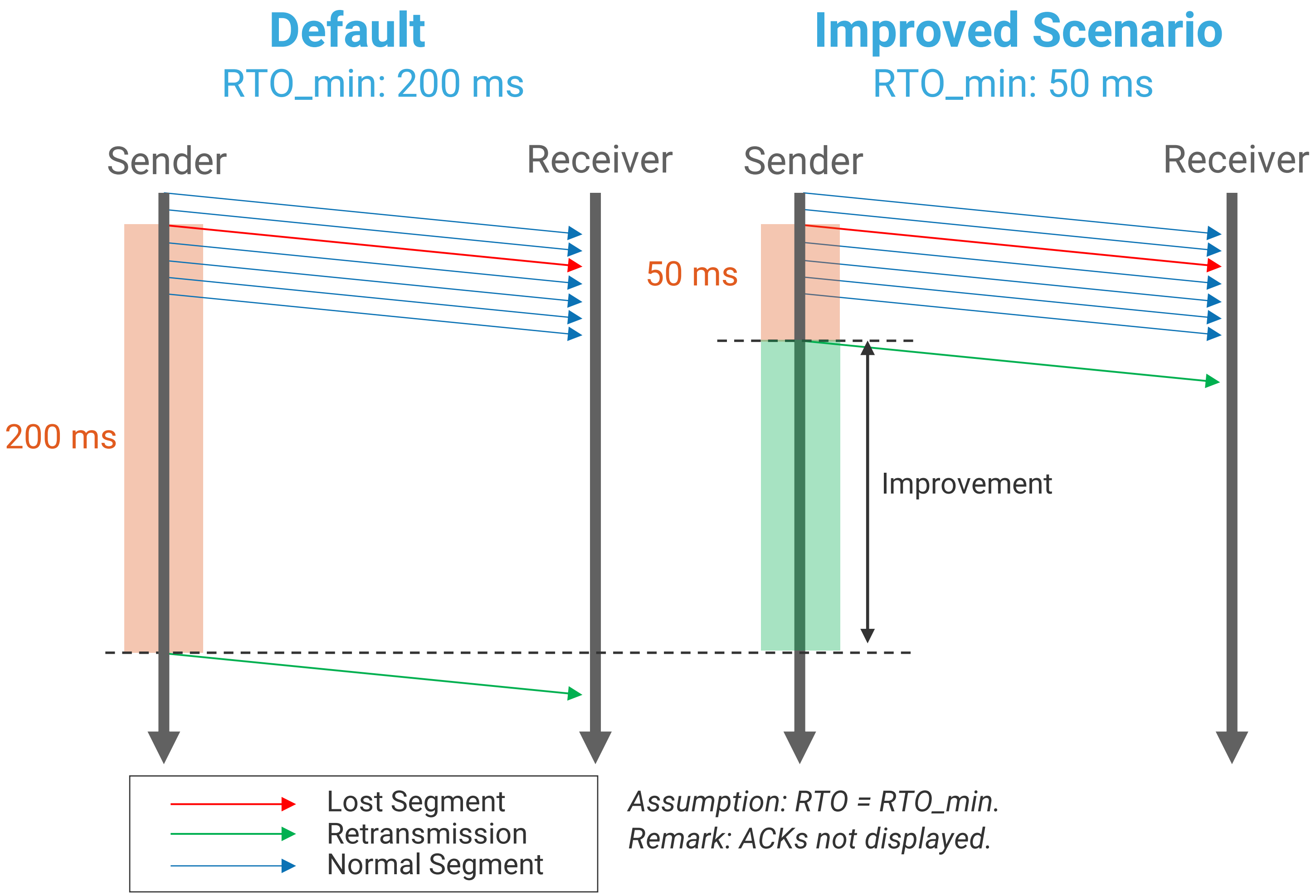
Remark: ack of #x refers to acknowledging segment x, not sequence number x.

RETRANSMISSION TIMEOUT (RTO)

RESULTS AND DISCUSSION

Key Points

- RTO defines how long the sender waits for a segment to be ACKed before triggering a retransmission. RTO_min is the minimum RTO used by the stack.
- RTO_min > RTT (but similar range).
- In Linux, the standard RTO_min is 200 ms. This is too large for small networks with low latencies like in the automotive use-case.
- Lowering the RTO_min to a value of ~50 ms has been shown to be reasonable.



Assumption: RTO = RTO_min.
Remark: ACKs not displayed.

SELECTIVE ACKNOWLEDGMENT (SACK)

RESULTS AND DISCUSSION

Experimental Results

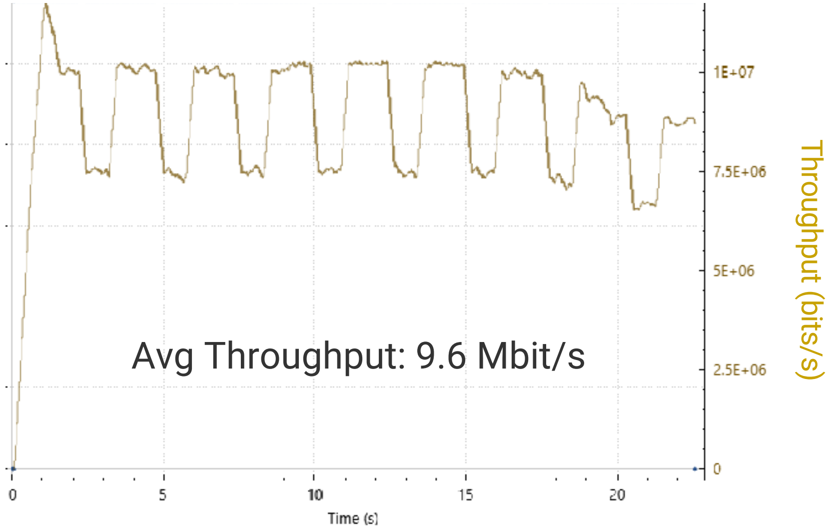
Latency

More than one “hole / gap” can be retransmitted within one RTT, thus improving latency.

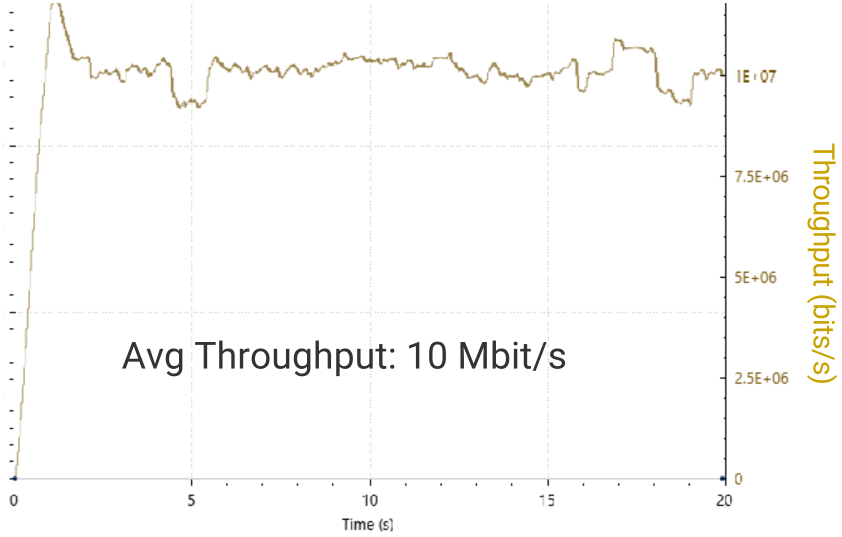
Throughput

SACK features have proven to speed up recovery and smooth out data throughput after losses.

Out-of-Order supported + SACK OFF



Out-of-Order supported + SACK ON

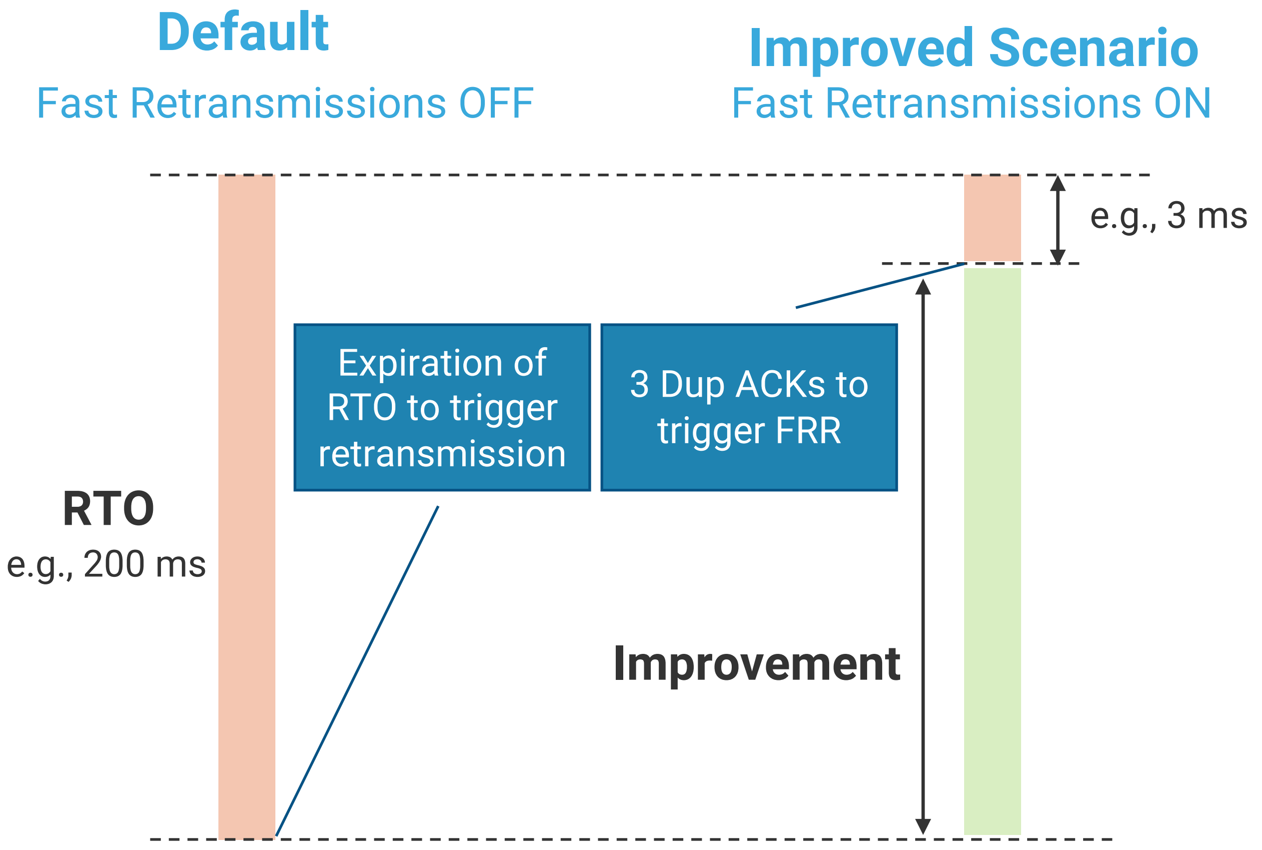


FAST RETRANSMISSIONS AND RECOVERY (FRR) (1)

RESULTS AND DISCUSSION

Key Points

- Upon receipt of a third Dup ACK, the sender assumes a segment loss and immediately retransmits it.
- Also, unsent segments within the window may be sent immediately after fast retransmissions.
- To trigger FRR, window size must be large enough: applications need to keep sending data. Typical issue with diagnostics and flash update.
- Selective Acknowledgment (SACK) can lead to FRR since every ACK is basically a Dup ACK.



FAST RETRANSMISSIONS AND RECOVERY (FRR) (2)

RESULTS AND DISCUSSION

- Due to a local network, no reordering is expected.
- Therefore, three Dup ACKs are not necessary to determine reordering.
- FRR have experimentally been triggered upon a second and even a first Dup ACK (faster recovery).

FRR after 3rd Dup ACK

Time [s]	Src	Dest	Seq	Lenght	Expert
-	sender	receiver	5178049	1448	Bulk Transfer
-	receiver	sender	1	0	ACK 5180945
REF	sender	receiver	5182393	1448	[Loss seg. 5180945]
0.0014266	receiver	sender	1	0	[Dup ACK 5180945 #1]
0.0012798	sender	receiver	5183841	1448	Bulk Transfer
0.0014155	receiver	sender	1	0	[Dup ACK 5180945 #2]
0.0024309	sender	receiver	5185289	1448	Bulk Transfer
0.0025945	receiver	sender	1	0	[Dup ACK 5180945 #3]
0.0036629	sender	receiver	518095	1448	[TCP Fast Retrans.]

FRR after 1st Dup ACK

Time [s]	Src	Dest	Seq	Lenght	Expert
-	sender	receiver	285257	1448	Bulk Transfer
REF	sender	receiver	288153	1448	[Loss seg. 286705]
0.0001592	receiver	sender	1	0	ACK 286705
0.0012001	sender	receiver	289601	1448	Bulk Transfer
0.0013388	receiver	sender	1	0	[Dup ACK 286705 #1]
0.0023545	sender	receiver	286705	1448	[TCP Fast Retrans.]

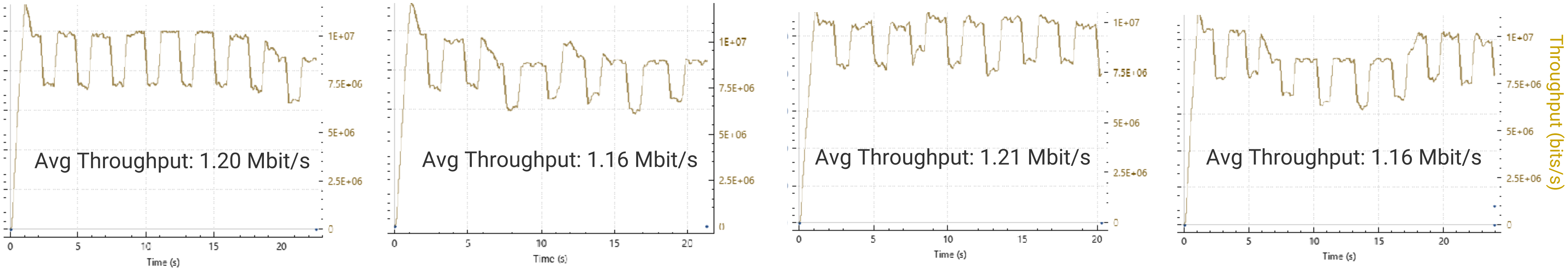
Significantly improved recovery time

LOW IMPACT PARAMETERS IN EMBEDDED STACKS

RESULTS AND DISCUSSION

Impact of Congestion Control?

Reno | Cubic | BIC | BBR



- Impact of different congestion control algorithms was minor (selected examples see above).
- None of these algorithms can cope with retransmission chains.

OVERALL RECOMMENDATION

RESULTS AND DISCUSSION

- RTO shall be tuned to 3-5x main function cycle of the TCP/IP stack: 50-70 ms.
- Out-of-Order shall be supported by TCP receiver to avoid unnecessary retransmissions.
- SACK can provide additional improvement.
- Fast Retransmissions shall be supported to enhance recovery time after segment loss.
  → Larger application messages and TCP window size. Otherwise, 3 Dup ACKs might never be seen.

Limitation

If drop occurs at the end of the message (seg #6) only RTO_min tuning helps to detect loss.

- Congestion control shall be optimized for automotive network properties
  → No reordering expected, therefore no three Dup ACKs necessary to trigger fast retransmissions.

TCP AND AUTOMOTIVE ETHERNET

Summary and Outlook

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SUMMARY & OUTLOOK
CONCLUSION

- Embedded stacks without OoO support result in loss chains.

- Optimization with most performance impact:
  - **RTO_min tuning** improves TCP reaction time for retransmissions.
  - **Out-of-Order support** stops loss chains.

- Outlook:
  - Advanced traffic shaping can prevent loss due to switch congestion.
  - Custom congestion control algorithm for automotive could improve reaction time.
  - Investigation of application keepalives (e.g., SOME/IP magic cookie) after application data.

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