Insights on the performance and configuration of AVB and TSN in automotive applications

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Use-cases for Ethernet in vehicles

Infotainment

- Synchronous traffic
- MOST like

Cameras

- High data rates

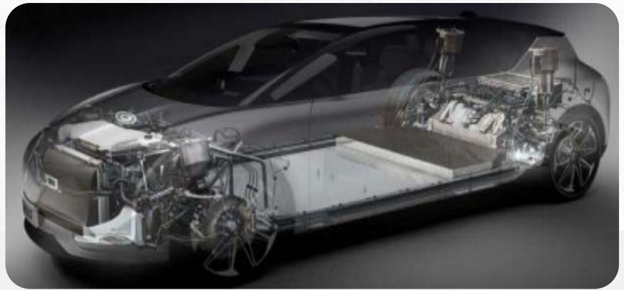
e.g. 10-30ms latency constraints per image (e.g. 42 frames)

Diag. & flashing

- Interfacing to external tools
- High throughput needed

Bandwidth guarantees: e.g. 10Mbit/s

Control functions ADAS



- Time-sensitive communication
- Small and large data payload
- Cover CAN / Flexray use cases

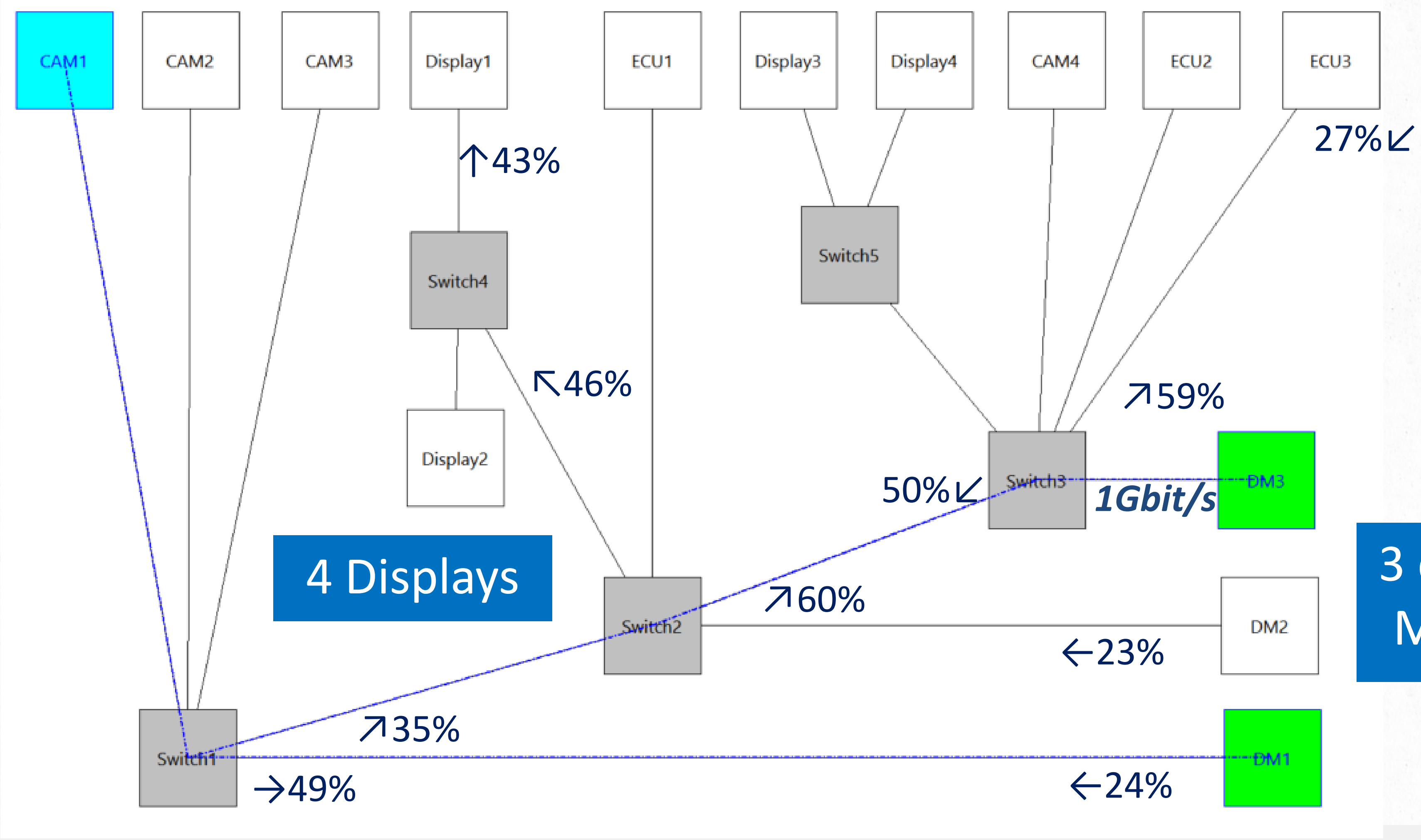
e.g., sub-10ms latency constraints

1 TWISTED-PAIR

Renault Ethernet prototype network

4 Cameras
30 and 60fps

3 Control Units



4 Displays

3 domain Masters

#Nodes	**14**
#Switches	**5**
#streams	**41**
Workload per link	Min: <1%, med:11% max:60%
Link data rates	100Mbit/s and 1Gbit/s (1 link)

Types of traffic

Audio streams	✓ 8 streams ✓ 128 and 256 byte frames ✓up to sub-10ms period and deadline ✓ deadline constraints (soft)
Video Streams	✓ 2 ADAS + 6 Vision streams, up to 30*1446byte frame each 16ms ✓10ms or 30ms deadline ✓ hard and soft deadline constraints
Command & Control (CC)	✓ 11 streams, 256 to 1024 byte frames ✓ up to sub-10ms period and deadline ✓deadline constraints (hard)
File & data transfer, diag.	✓14 streams, TFTP traffic pattern ✓ Up to 0.2ms period ✓Bandwidth guarantee: up to 20Mbits

QoS protocols on top of Ethernet

Temporal QoS = managing interfering traffic

Priority-based

IEEE802.1Q

Streams can be assigned to 8 priority levels

Benefits:

✓Standard and simple

✓efficient at the highest priority levels

Limitations:

✓ Not fine-grained enough to accommodate all kinds of requirements

Traffic Shaping

Audio Video Bridging (AVB)

Credit-Based Shaper (CBS) and 6 priority levels below

Benefits:

✓Based on an existing standard

✓Performance guarantee for AVB

✓No starvation for best-effort traffic

Limitations:

✓Not suited for control traffic

Time-triggered (TT)

Time-Sensitive Networking (TSN)

Time-Aware Shaper (TAS) enables TT transmissions

Benefits:

✓ Strong time constraints can be met (if task scheduling is tailored to communication)

✓Can be combined with AVB

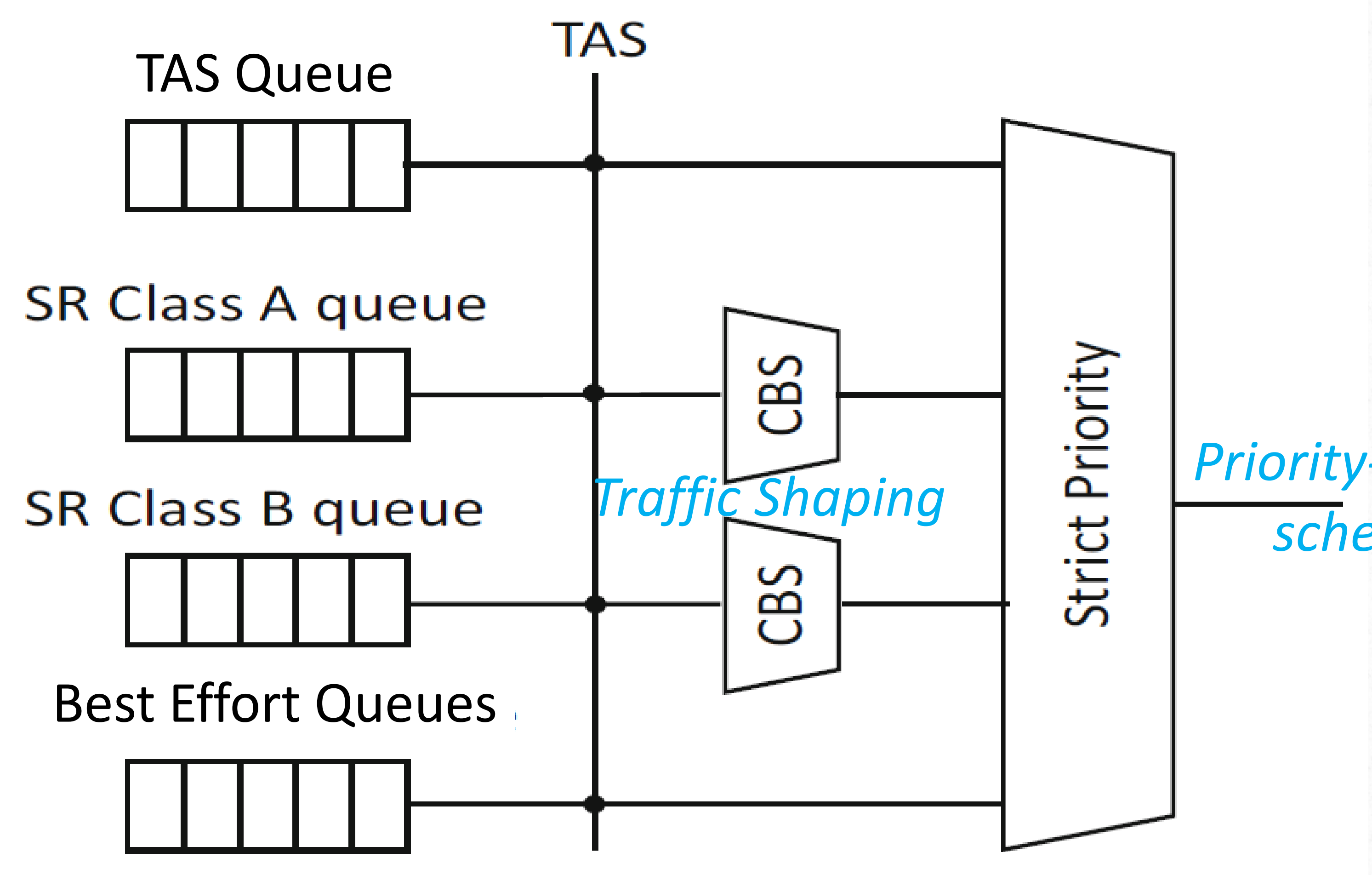
Limitations:

✓Quite complex and hard to configure

✓Rely on a clock synchronization protocol

QoS support in the switches – on each output port

Time-Triggered transmission



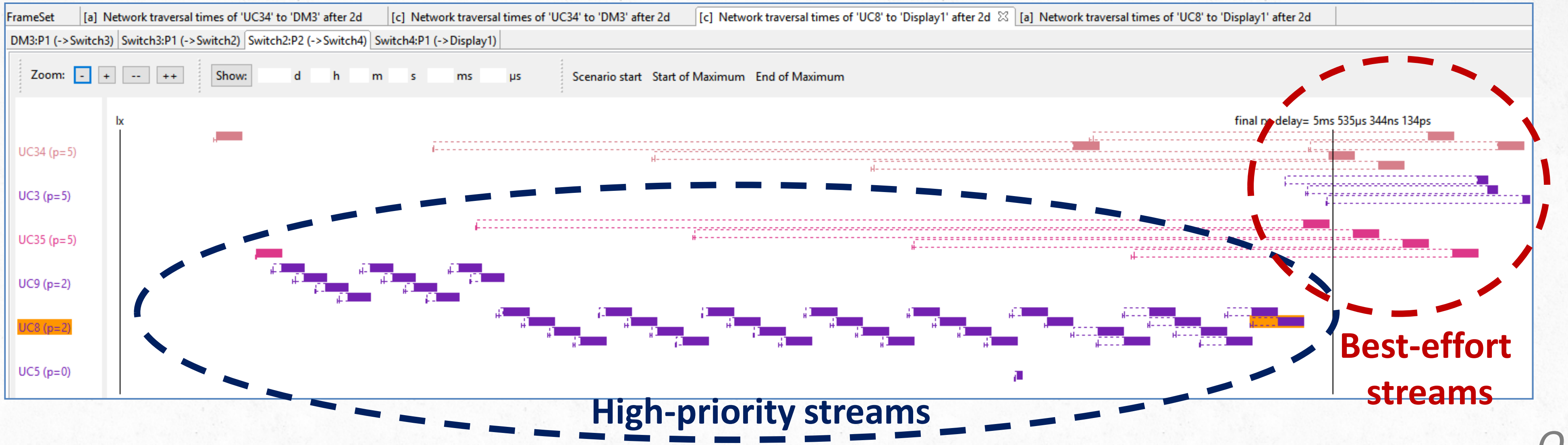
Traffic Shaping

Priority-based scheduling

Up to 8 priority level overall

[Figure from Ashjaei2017]

Under IEEE802.1Q – 3rd hop



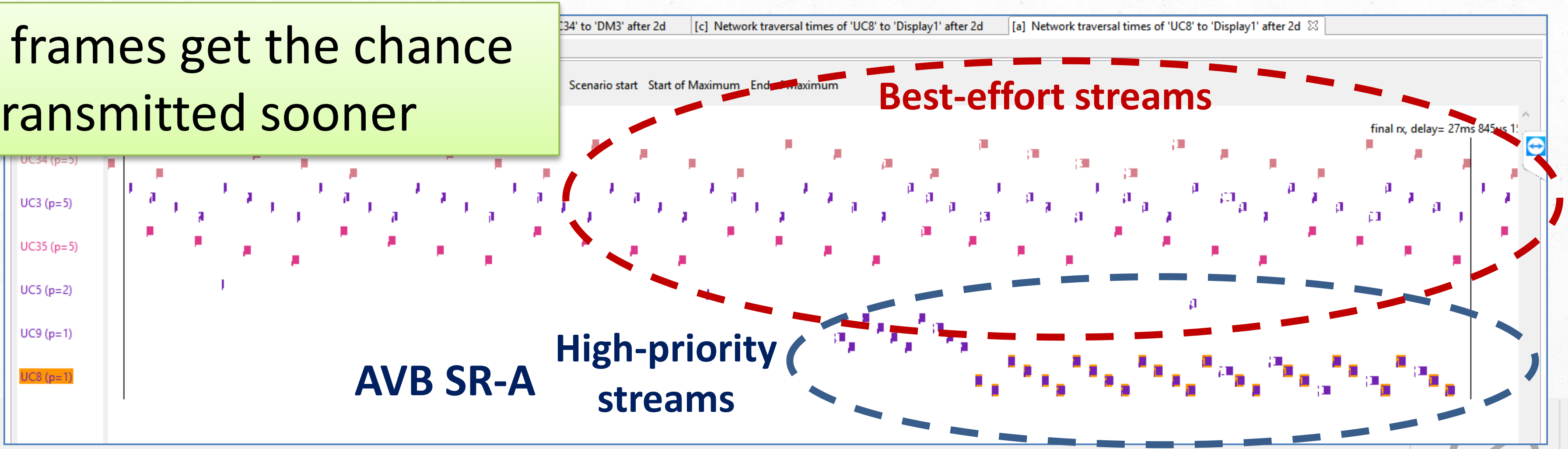
Best-effort streams

High-priority streams

Obtained by simulation in RTaW-Pegase

Under AVB/CBS – 3rd hop

Best-effort frames get the chance to be transmitted sooner



Best-effort streams

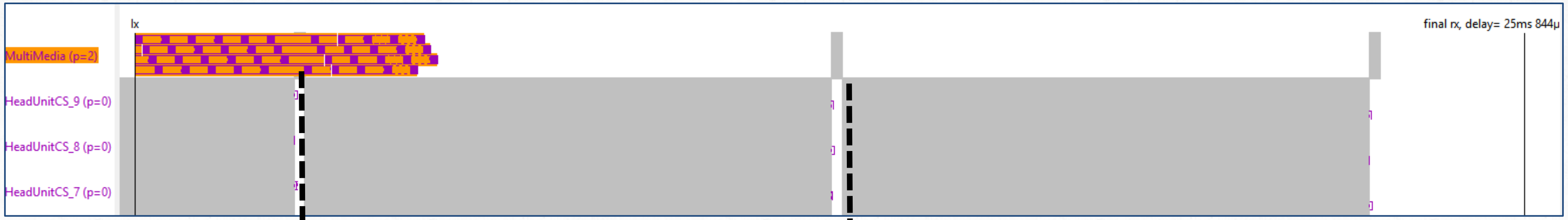
AVB SR-A

High-priority streams

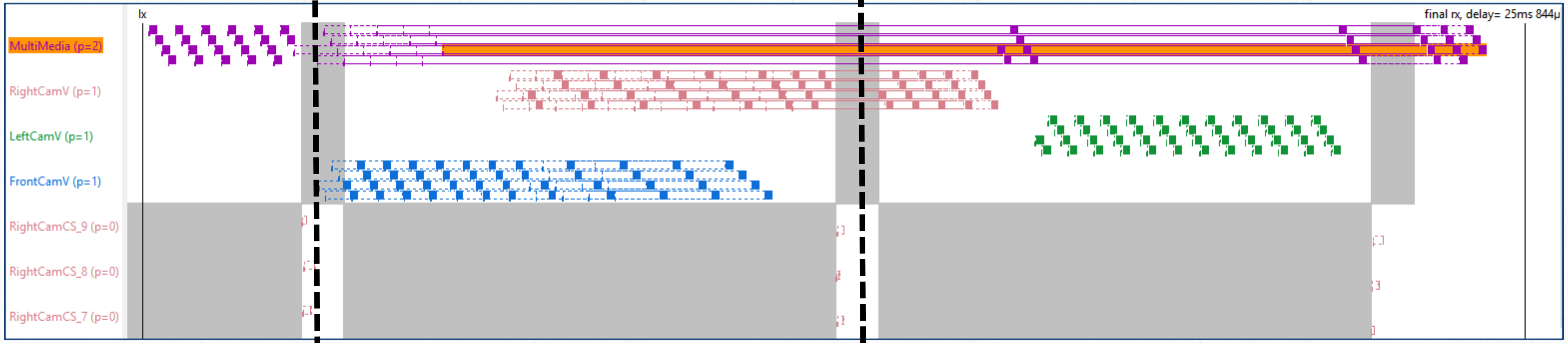
TSN/TAS: coordinating gate scheduling tables

White bands = transmission allowed | grey bands = not allowed

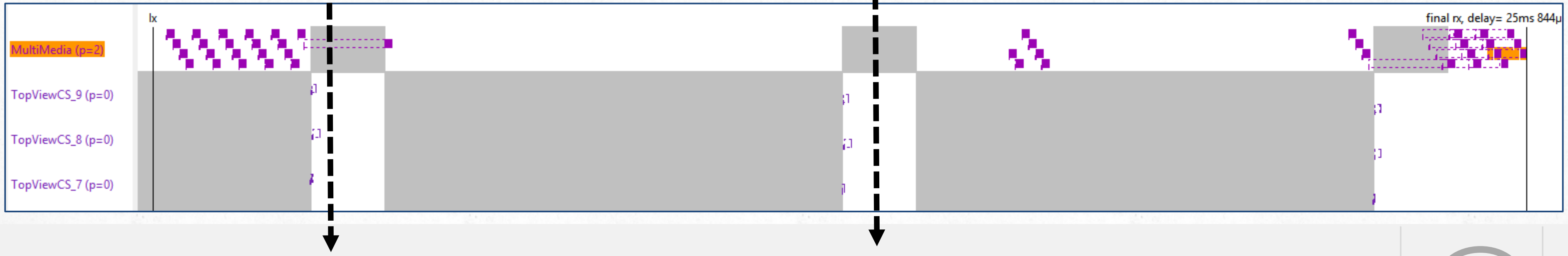
Sending node



Switch #1

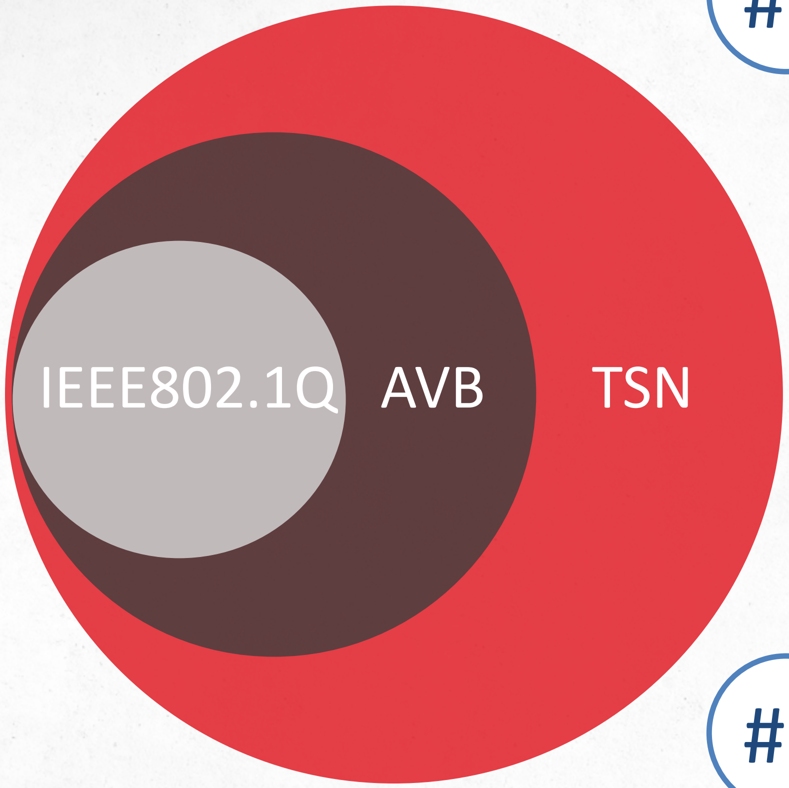


Switch #2



Solutions experimented

C&C = Command & Control

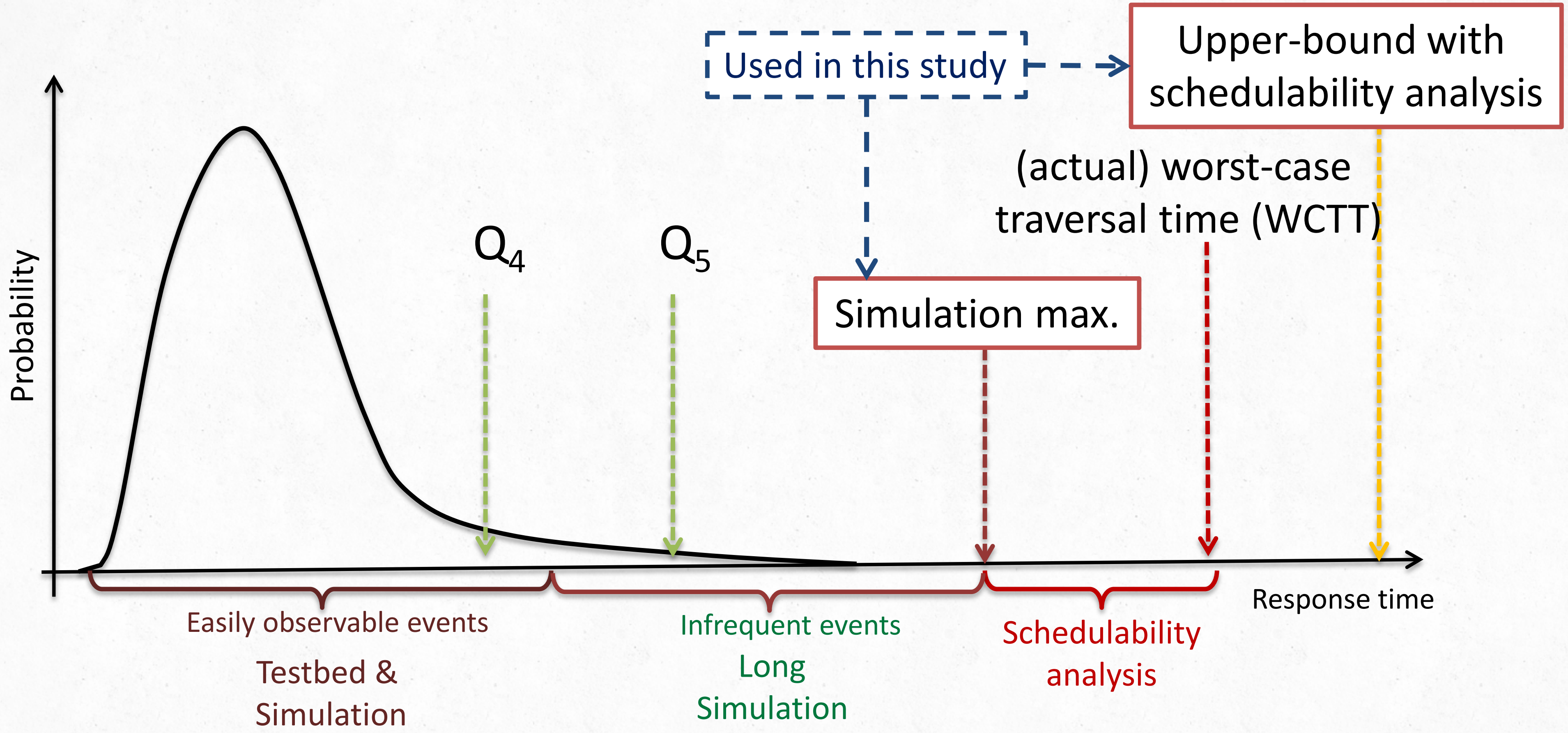


- #1 Standard AVB classes with C&C as best-effort
- #2 AVB “Custom-Classes” with C&C as best-effort
- #3 IEEE802.1Q with and without “pre-shaping”
- #4 AVB “Custom-Classes” with C&C under TSN/TAS
- #5 TSN/TAS to emulate AVB to shape audio/video streams

Not discussed here - see TSN/A 2017

Several mechanisms to ensure QoS w.r.t. timing ,
but which are the most efficient for automotive systems?

Verification techniques



- ✓ Long simulation here = 48 hours of driving → 350 000 transmissions for 500ms frames
- ✓ Metrics: communication latencies, bandwidth usage and buffer occupancies

Toolset

✓***RTaW-Pegase*** – modeling / analysis / configuration of switched Ethernet (automotive, avionics) + CAN (FD) + task scheduling

✓Higher-level protocols (e.g. Some IP) and functional behavior can be programmed in CPAL® language [4]

✓Developed since 2009 in partnership with Onera

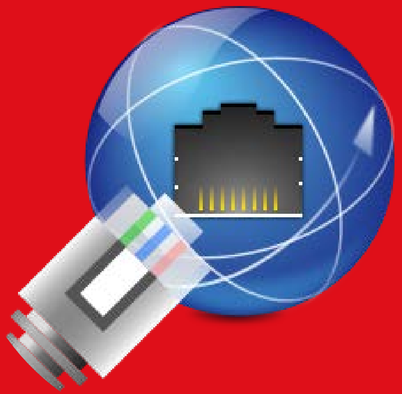
✓Ethernet users include Daimler Cars, Airbus Helicopters, CNES and ABB

Evaluation techniques

✓**Worst-case Traversal Time (WCTT) analysis** - based on Network-Calculus, core algorithms are published and proven correct

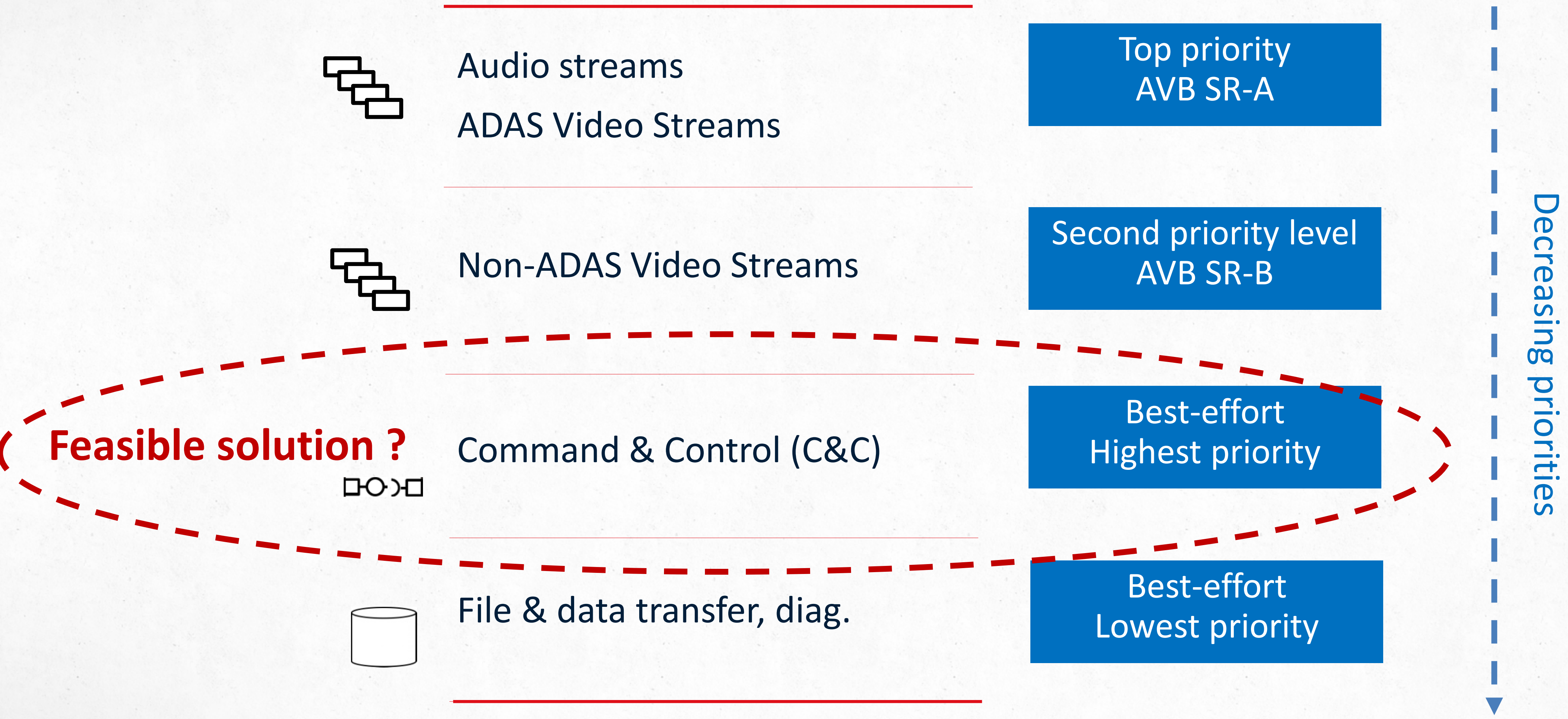
✓**Timing-accurate Simulation** – *ps* resolution, ≈ $4{\cdot}10^6$ events/sec on a single core (I7 - 3.4Ghz), suited up to ($1\text{-}10^6$) quantiles

✓**Lower-bounds on the WCTT:** “unfavorable scenario” **+ Benchmarking:** “NetAirbench”



Case-study – sol. #1 and #2
standard AVB and AVB custom classes

Default traffic priorities for AVB solution



Audio streams

ADAS Video Streams

Top priority
AVB SR-A

Non-ADAS Video Streams

Second priority level
AVB SR-B

Feasible solution ?

Command & Control (C&C)

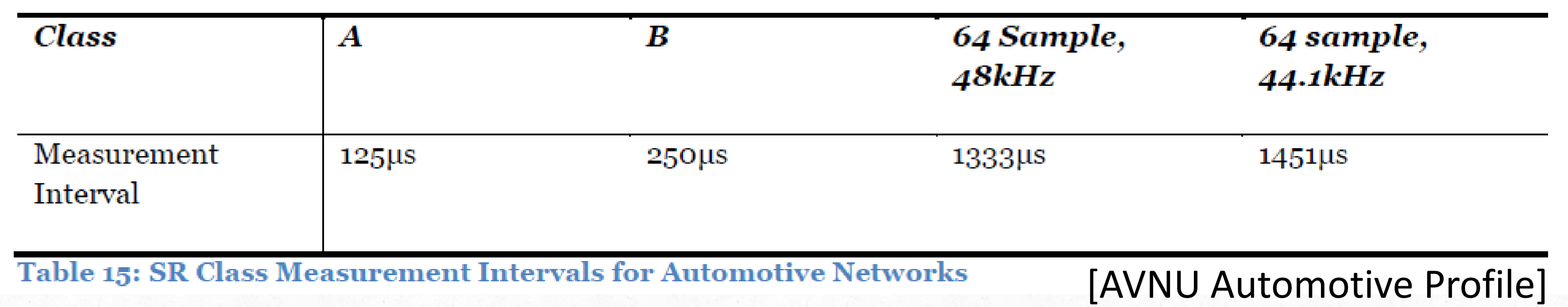
Best-effort
Highest priority

File & data transfer, diag.

Best-effort
Lowest priority

Decreasing priorities

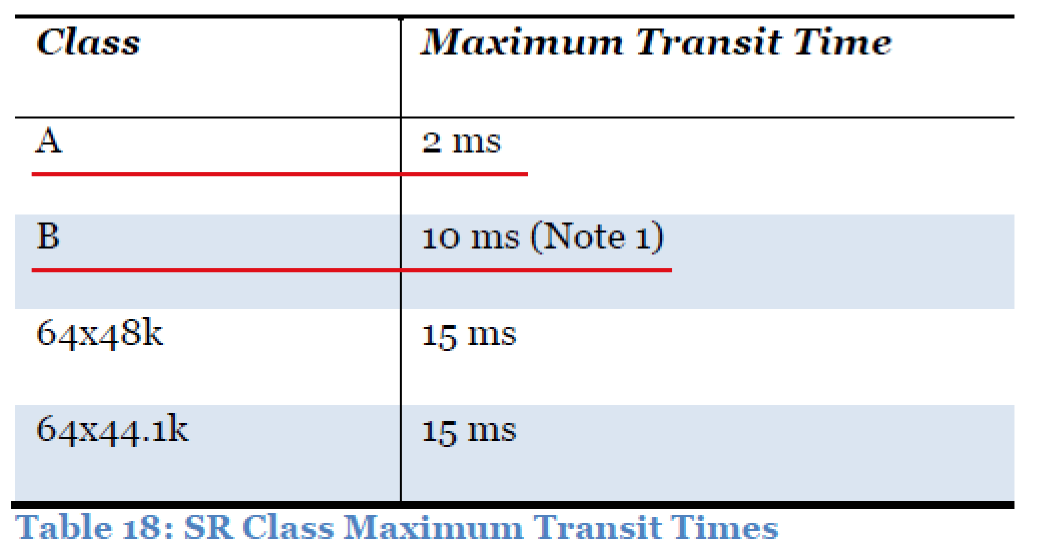
Automotive AVB SR Class and performance guarantees



Class	***A***	***B***	***64 Sample, 48kHz***	***64 sample, 44.1kHz***
Measurement Interval	125µs	250µs	1333µs	1451µs

Table 15: SR Class Measurement Intervals for Automotive Networks

[AVNU Automotive Profile]



Class	***Maximum Transit Time***
A	2 ms
B	10 ms (Note 1)
64x48k	15 ms
64x44.1k	15 ms

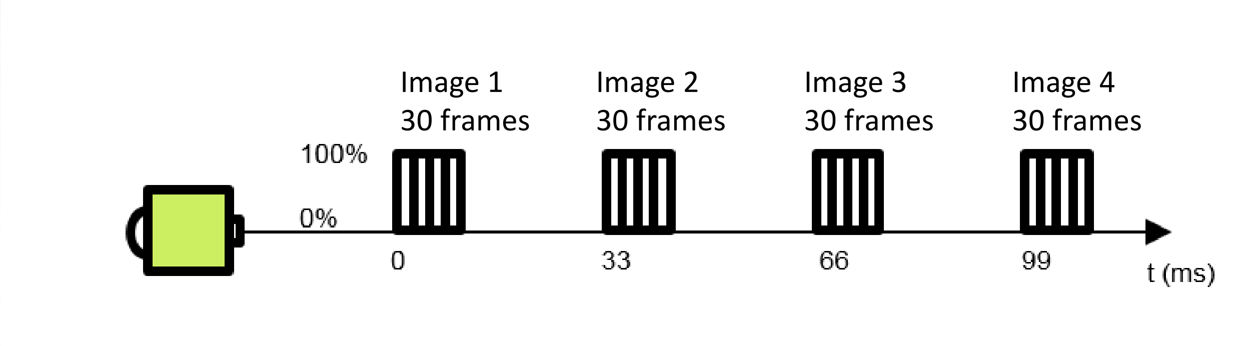
Table 18: SR Class Maximum Transit Times

Over 7 hops

[AVNU Automotive Profile]

Sol #1 - standard AVB

✓ Let's consider ADAS video stream UC36 10Mbit/s @30FPS - deadline to receive an image is 10ms



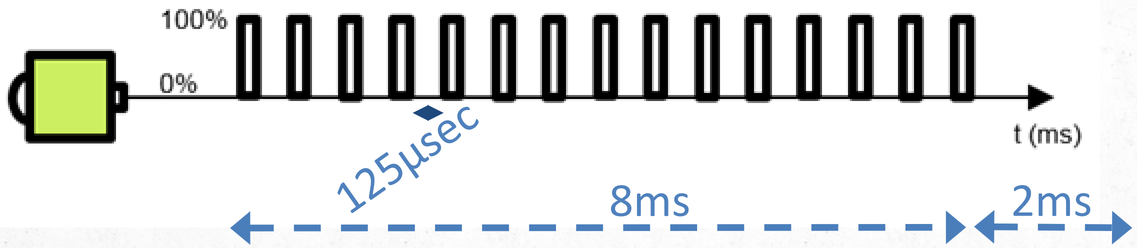
Native format :

30x1400bytes frames every 33ms

VS

SR-A: emission spread over 8ms = 10ms - 2ms

⇒ 64 frames of 703 bytes, one every 125us



Also worst-case analysis could not provide bounds because of overall peak-load > 100%.

Standard AVB does not provide a solution!

✓Overhead of using smaller frames – peak load over 8ms is 46% for UC36

✓2 such ADAS Video streams on a link

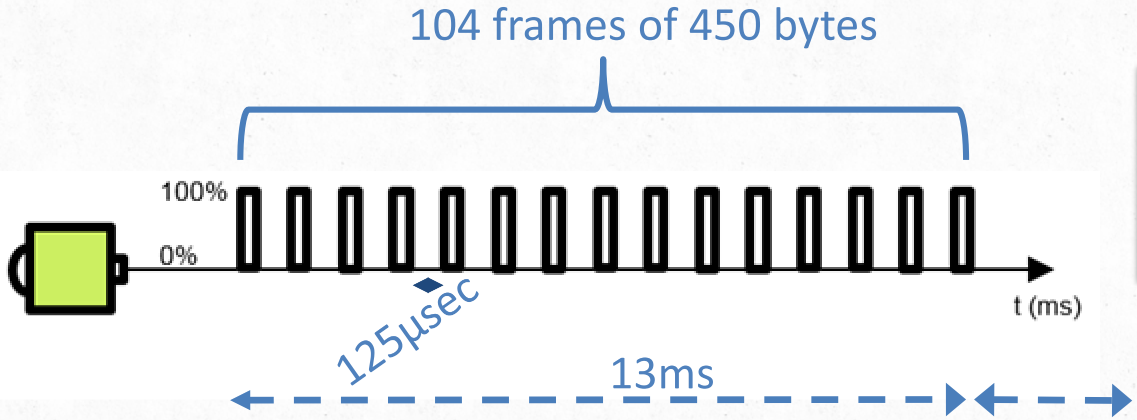
⇒ AVB load requirements of 75% not met

⇒ 2ms guarantee does not hold

Sol #1 - standard AVB

Relaxing image deadline to **15ms** instead of 10ms for the 2 ADAS video streams

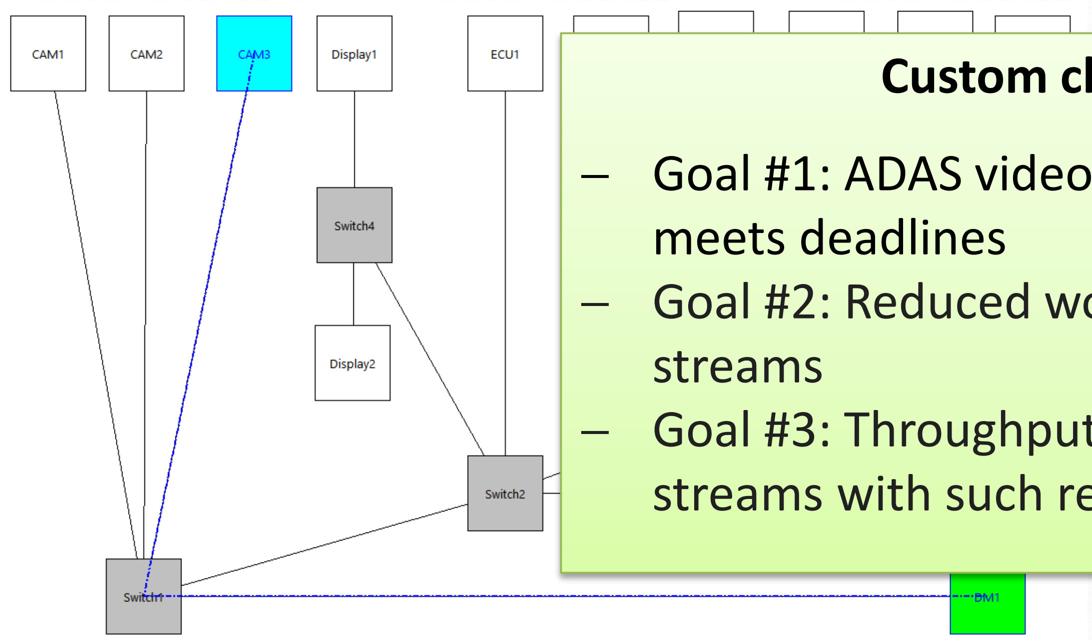
AVB solution : SR-A with 104 frames of 450 bytes, one every 125us ⇒ 13ms + communication latency < 2ms



Worst-case response time analysis needed since AVB load condition does not hold

Sol #2 – a feasible solution with AVB “custom classes”

- ✓ **Custom Class = non-125/250us CMI** ⇒ no AVB guarantees thus worst-case analysis needed
- ✓ Send video in “native format” = 30 frames of 1400bytes payload every 33.3 ms
  ⇒ no additional “repackaging” overhead
- ✓ Custom Idle slopes: minimal Idle Slopes along the path allowing to just meet AVB traffic timing constraints:
  ⇒ *Tight Idle-Slope* algorithm in RTaW-Pegase

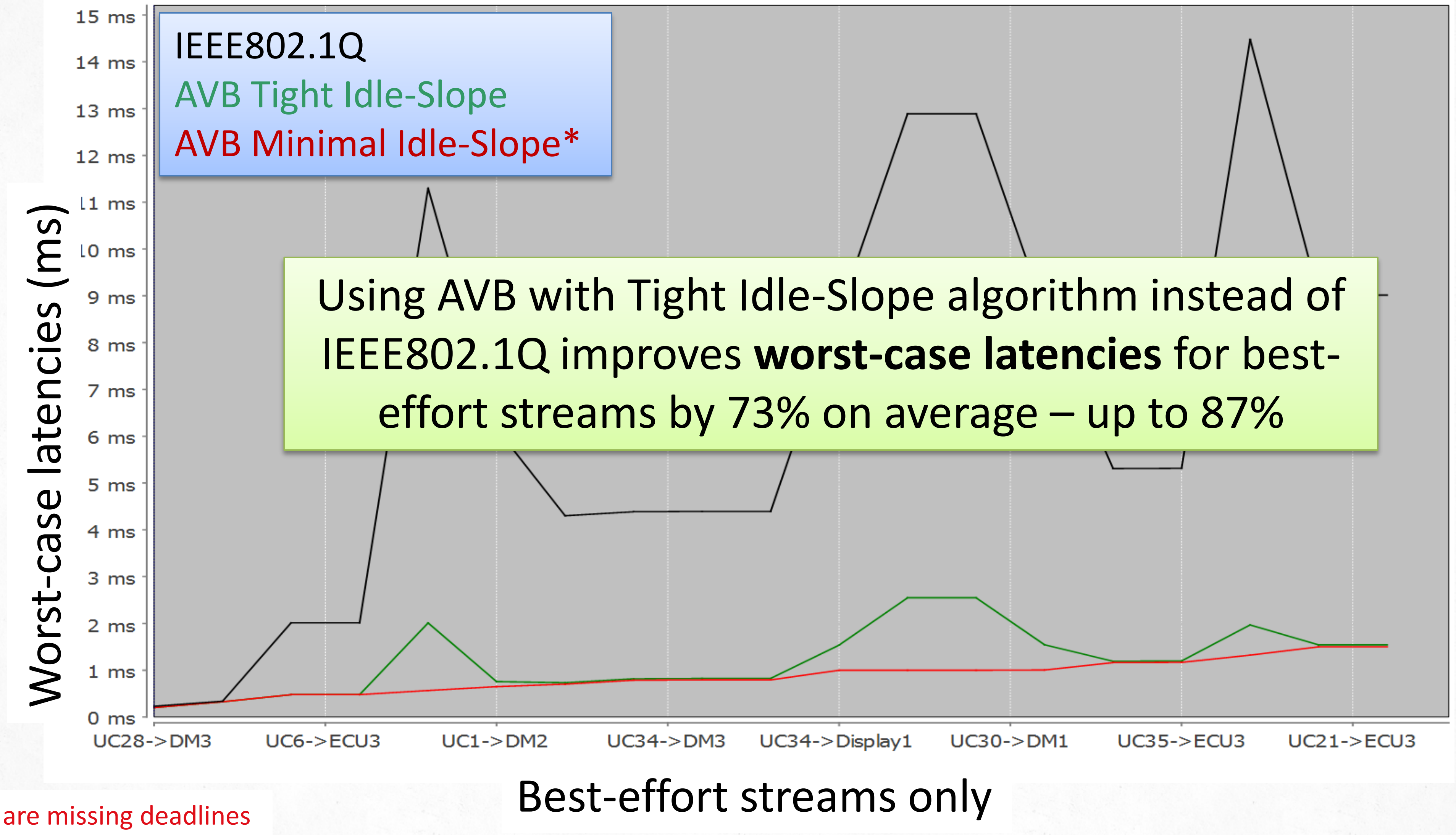


Custom classes offers a solution ✓

- Goal #1: ADAS video streams under AVB and C&C traffic meets deadlines
- Goal #2: Reduced worst-case latencies for best-effort streams
- Goal #3: Throughput requirements for best-effort streams with such requirements met

→ We can push the limits of AVB with “smart” configuration tools

Goal #2: Worst-case latencies for best-effort streams

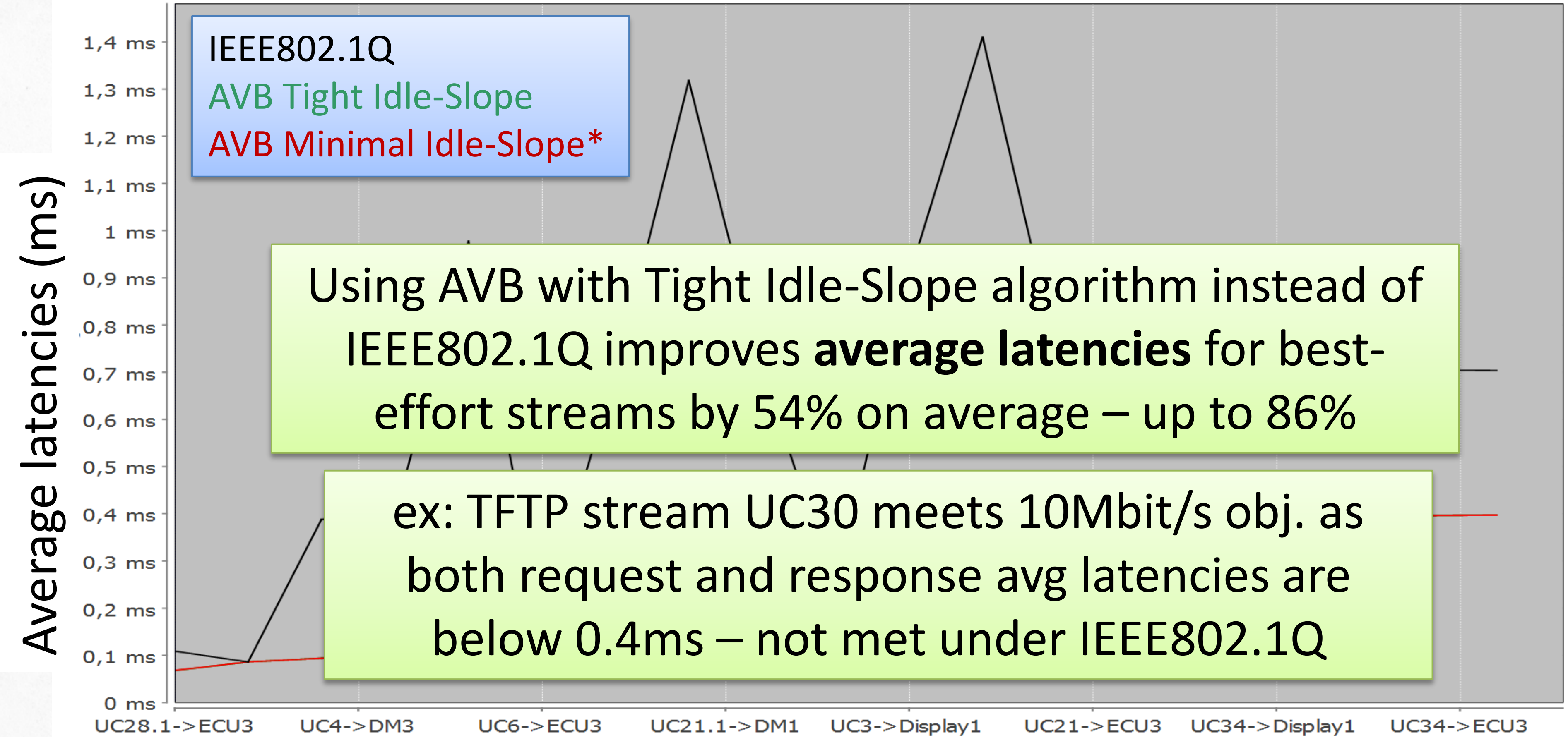


Using AVB with Tight Idle-Slope algorithm instead of IEEE802.1Q improves **worst-case latencies** for best-effort streams by 73% on average – up to 87%

* Video streams are missing deadlines

Goal #3: Bandwidth availability for specific streams

- ✓ Perf. requirements may not be latencies but bandwidth usage, e.g. 10Mbit/s for File Transfer stream → average latencies tell if objectives are met



Using AVB with Tight Idle-Slope algorithm instead of IEEE802.1Q improves **average latencies** for best-effort streams by 54% on average – up to 86%

ex: TFTP stream UC30 meets 10Mbit/s obj. as both request and response avg latencies are below 0.4ms – not met under IEEE802.1Q

* Video streams are missing deadlines

Best-effort streams only

Case-study – sol. #3
using IEEE802.1Q with pre-shaping

Case-study: priorities for IEEE802.1Q solution

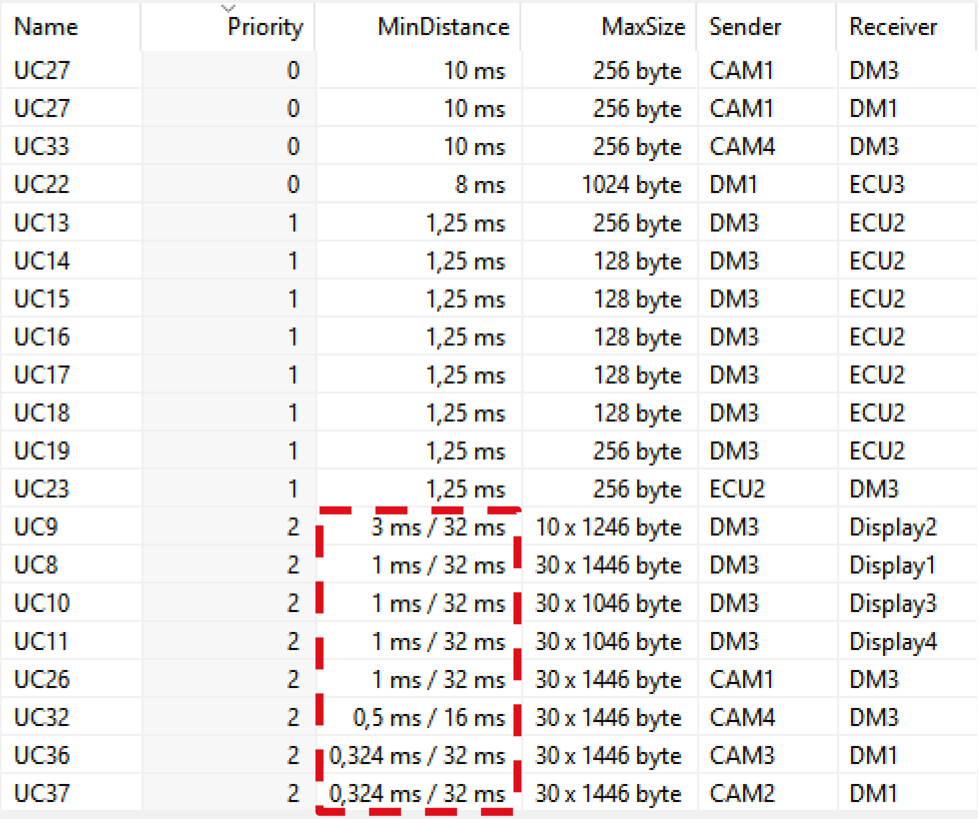
Command & Control (C&C)	Top priority
Audio Streams	Second priority level
Video Streams	Third priority level
File & data transfer, diag.	Best-effort

Decreasing priorities

IEEE802.1Q with pre-shaping

- ✓ Pre-shaping = inserting “well-chosen” minimum distance between frames of a segmented message ***on the sender side only*** - other characteristics of traffic unchanged
- ✓ Pre-shaping applied to Video streams

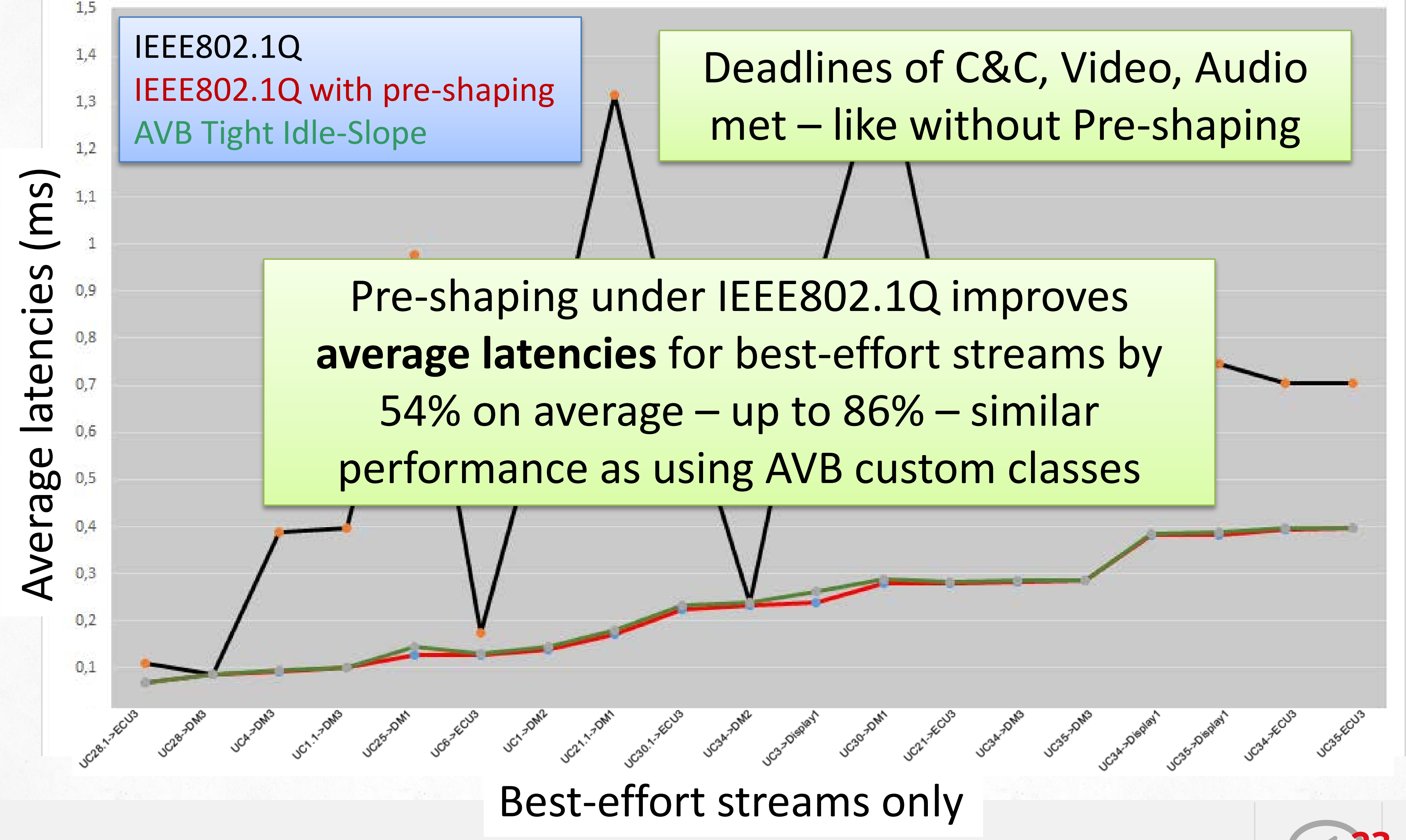
Finding appropriate values is not straightforward ..



Name	Priority	MinDistance	MaxSize	Sender	Receiver
UC27	0	10 ms	256 byte	CAM1	DM3
UC27	0	10 ms	256 byte	CAM1	DM1
UC33	0	10 ms	256 byte	CAM4	DM3
UC22	0	8 ms	1024 byte	DM1	ECU3
UC13	1	1,25 ms	256 byte	DM3	ECU2
UC14	1	1,25 ms	128 byte	DM3	ECU2
UC15	1	1,25 ms	128 byte	DM3	ECU2
UC16	1	1,25 ms	128 byte	DM3	ECU2
UC17	1	1,25 ms	128 byte	DM3	ECU2
UC18	1	1,25 ms	128 byte	DM3	ECU2
UC19	1	1,25 ms	256 byte	DM3	ECU2
UC23	1	1,25 ms	256 byte	ECU2	DM3
UC9	2	3 ms / 32 ms	10 x 1246 byte	DM3	Display2
UC8	2	1 ms / 32 ms	30 x 1446 byte	DM3	Display1
UC10	2	1 ms / 32 ms	30 x 1046 byte	DM3	Display3
UC11	2	1 ms / 32 ms	30 x 1046 byte	DM3	Display4
UC26	2	1 ms / 32 ms	30 x 1446 byte	CAM1	DM3
UC32	2	0,5 ms / 16 ms	30 x 1446 byte	CAM4	DM3
UC36	2	0,324 ms / 32 ms	30 x 1446 byte	CAM3	DM1
UC37	2	0,324 ms / 32 ms	30 x 1446 byte	CAM2	DM1

IEEE802.1Q with pre-shaping for Video

Average latencies for best-effort streams

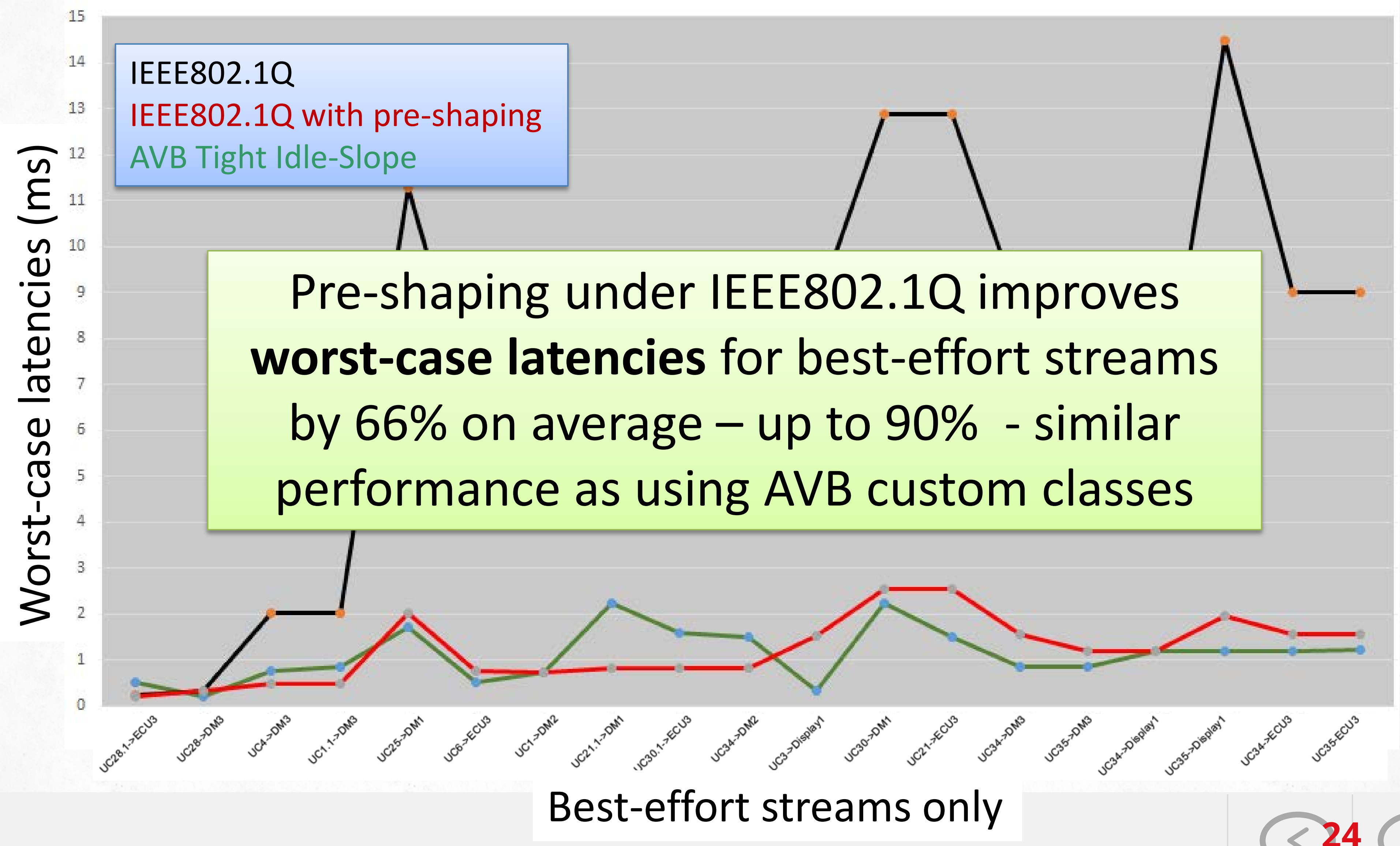


Deadlines of C&C, Video, Audio met – like without Pre-shaping

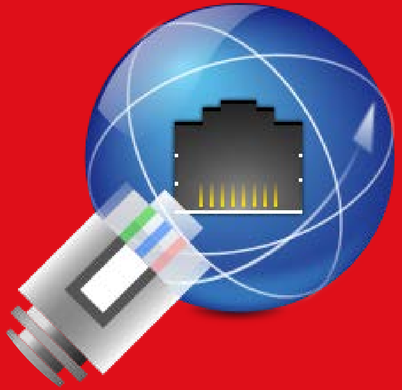
Pre-shaping under IEEE802.1Q improves **average latencies** for best-effort streams by 54% on average – up to 86% – similar performance as using AVB custom classes

IEEE802.1Q with pre-shaping for Video

Worst-case latencies for best-effort streams

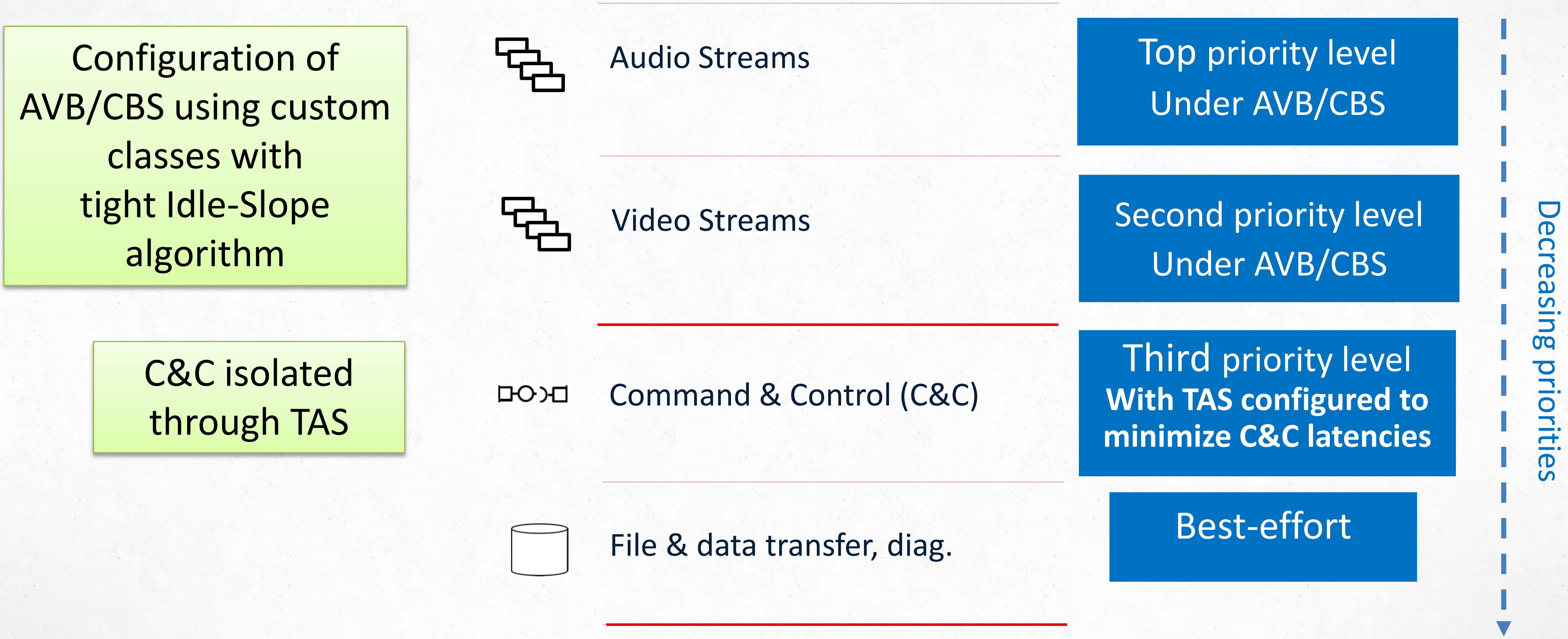


Pre-shaping under IEEE802.1Q improves **worst-case latencies** for best-effort streams by 66% on average – up to 90% - similar performance as using AVB custom classes



Case-study – sol. #4
using TSN/TAS to reduce C&C latencies

Case-study: priorities for TAS/CBS solution



Configuration of AVB/CBS using custom classes with tight Idle-Slope algorithm

C&C isolated through TAS

Audio Streams

Video Streams

Command & Control (C&C)

File & data transfer, diag.

Top priority level
Under AVB/CBS

Second priority level
Under AVB/CBS

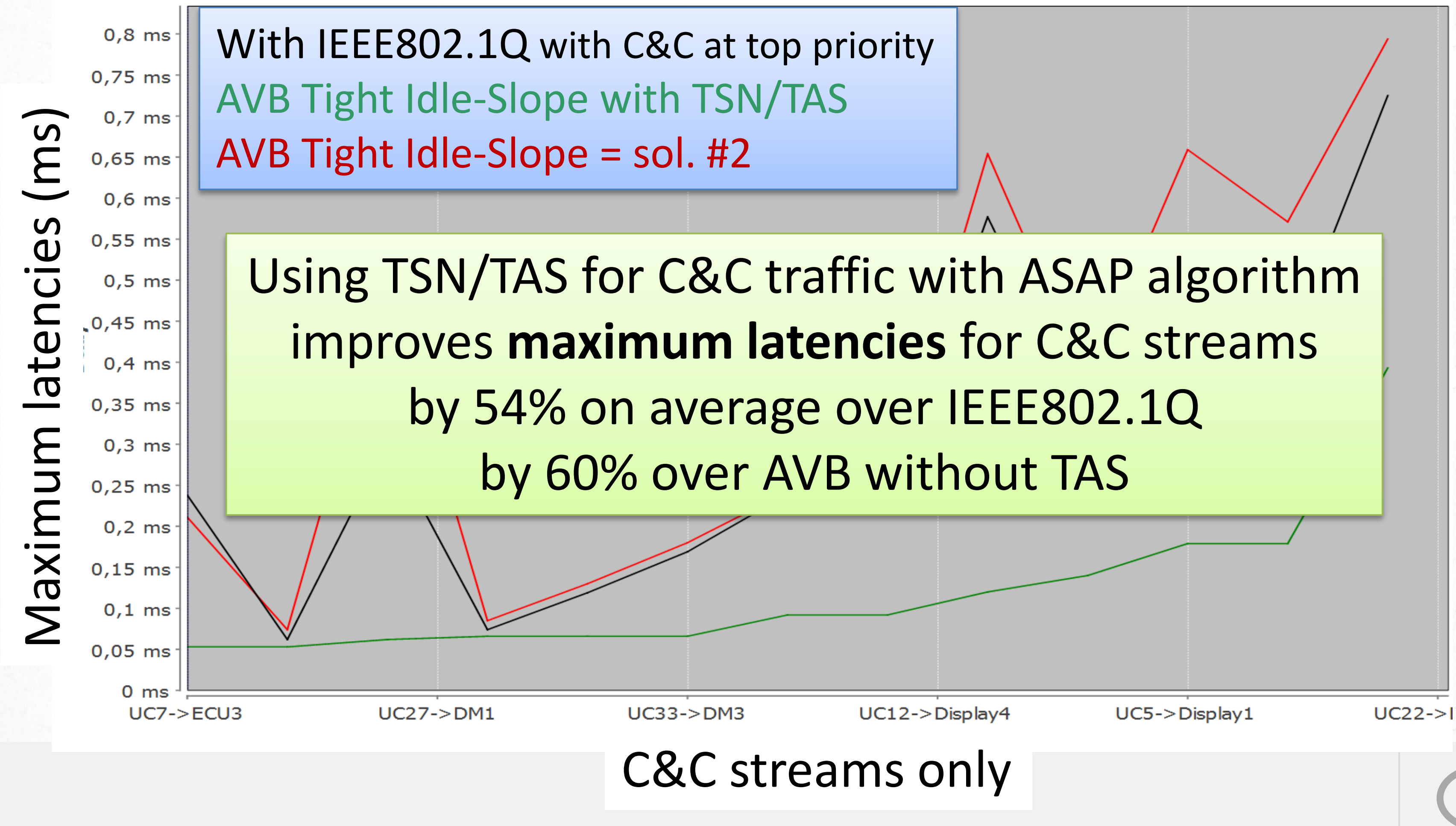
Third priority level
With TAS configured to minimize C&C latencies

Best-effort

Decreasing priorities

Improvements brought by TSN/TAS for Command & Control traffic

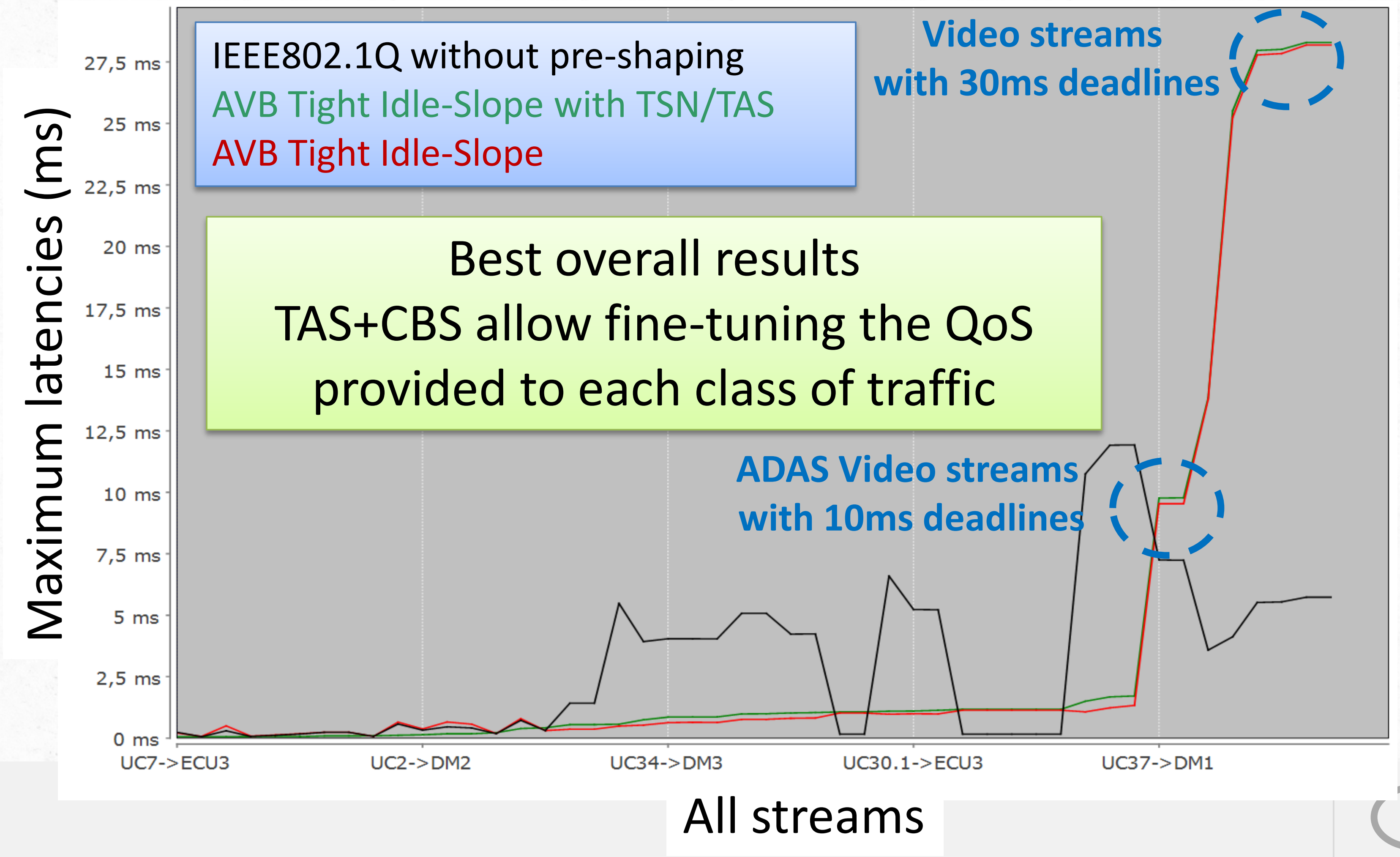
- ✓ All C&C streams under TAS – task and frames are synchronized
- ✓ Gate scheduling configuration done with *ASAP* algorithm in RTaW-Pegase that aims to minimize latencies for TAS traffic (*i.e.*, no trade-off)



Using TSN/TAS for C&C traffic with ASAP algorithm improves **maximum latencies** for C&C streams by 54% on average over IEEE802.1Q by 60% over AVB without TAS

TSN/TAS for C&C traffic + AVB/CBS for audio/video

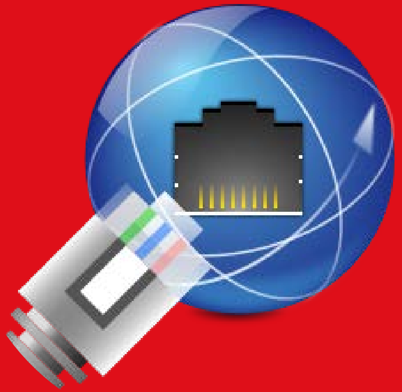
- ✓ Max latencies of Audio/Video/Best-effort almost unaffected by TAS (< 3% on avg)
- ✓ All deadlines and bandwidth availability constraints met.



Video streams with 30ms deadlines

ADAS Video streams with 10ms deadlines

Best overall results
TAS+CBS allow fine-tuning the QoS provided to each class of traffic



Conclusion and a look forward

Solutions experimented & results achieved

- ✗ IEEE802.1Q without pre-shaping

Throughput requirements for best-effort not met

- ✓ IEEE802.1Q with pre-shaping
- ✗ AVB standard classes

10ms for ADAS video not met

- ✓ AVB custom classes
- ✗ TSN/TAS for video without AVB/CBS

Bandwidth for best-effort not met

- ✓ TSN/TAS with AVB/CBS

Fine-grained configuration of protocols parameters required to obtain all 3 feasible solutions – no “one-fits-all” solution wrt parameters

Insight from the case-study

1 Mixed-criticality traffic implies a **diversity of communication requirements** in upcoming Ethernet networks : deadlines (soft/hard), bandwidth, segmented messages, client-server, buffer usage, etc

2 IEEE802.1Q not suited for bursty traffic (e.g., video) with best-effort traffic : pre-shaping the bursty traffic by inserting idle times provides improvements

3 AVB can be an answer to many needs but **standard classes are not enough**

- ✓ Scope of applicability too narrow even for video-streams
- ✓ pessimistic wrt timing guarantees

Custom classes enables to get the most out of standard AVB component *but tools must be used for configuration & timing verification*

Insight from the case-study

4 **TSN/TAS is effective at improving the latencies** for Command & Control traffic and can also be used to mimic AVB/CBS for streams *but tools must be used for configuration & timing verification*

5 **Gigabit/s and frame preemption** may help to simplify protocol stacks for some use-cases

6 **Configuration has become a challenge!** priorities, AVB classes, idle Slopes, TAS gate schedule table, co-scheduling task-messages, gatewaying strategies, etc → *impact on safety and cost-effectiveness*

Configuration and system synthesis (e.g., architecture) can and need to be much further automated in the years to come!

Thank you for your attention!

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