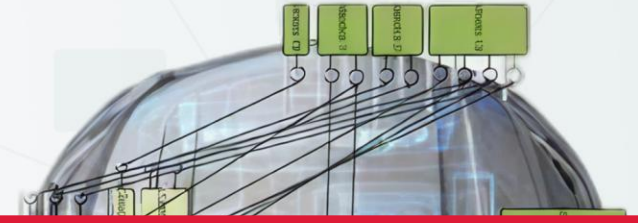
PEGaSE

RTaW
RealTime-at-Work



Automotive Real-Time Communication with PON: How Far Does Standard PON Get Us?



Dr Jörn Migge

November, 2026

Automotive Ethernet Summit Europe 2026

Agenda

- Overview of Passive Optical Networks (PON) in relation with timing
- Automotive timing requirements and potential advantages of PON
- Meeting of band-width and latency requirements with classical PON
- Optimal configuration of PON priority queues
- Conclusion & Outlook

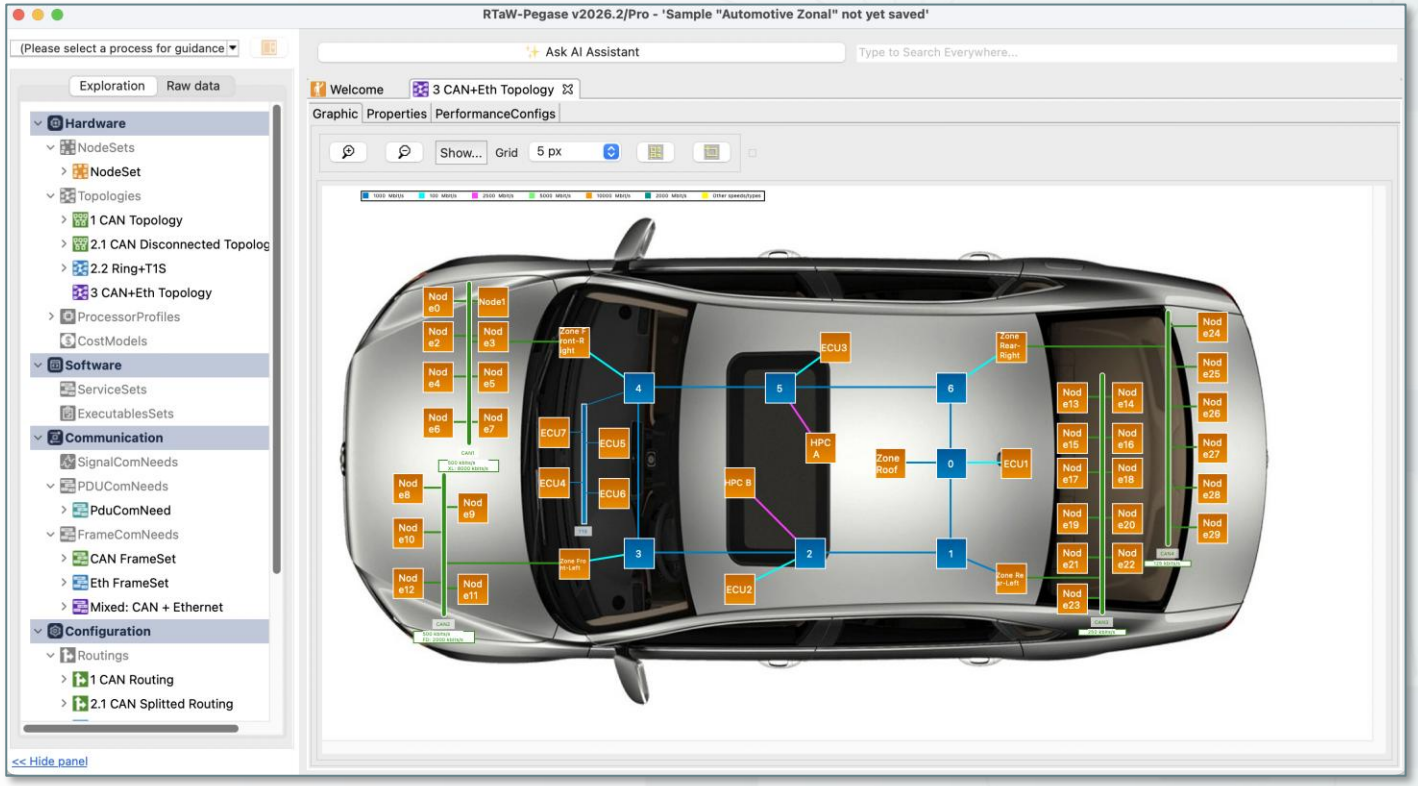
RealTime-at-Work

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Modelled based network design tool

RTaW-PEGaSE®

- Ethernet/TSN: CBS, ATS, TAS, CB, AS, Qci
- AFDX, TTEthernet
- CAN (CC, FD, XL), LIN, FlexRay
- SOME/IP, DDS
- Ongoing: PON, M1553, Profinet
- Timing Verification through Worst-Case Analysis, Simulation
- Worst-Case Analysis based scheduling configuration and optimization ⇨ hard guarantees
- Configuration file export: YANG
- Trace analysis: Ethernet, CAN



From the access network to the vehicle

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Passive optical networks began as a way to share one fiber among many telephone subscribers. The same all-passive, point-to-multipoint idea has since spread well beyond telecom — and is now arriving in the car.

THE TELECOM LINEAGE · ITU-T STANDARDS GENERATIONS

1998	2003	2010	2015	2016	2021
BPON	**GPON**	**XG-PON**	**NG-PON2**	**XGS-PON**	**50G-PON**
ITU-T G.983	ITU-T G.984	ITU-T G.987	ITU-T G.989	ITU-T G.9807.1	ITU-T G.9804
622 Mbit/s	2.5 Gbit/s	10 Gbit/s	40 Gbit/s TWDM	10 Gbit/s sym.	50 Gbit/s

AND BEYOND THE ACCESS NETWORK

Mobile backhaul · **Enterprise POL** · Industrial / Industry 4.0 · Avionics · Data centre → **In-vehicle networks**

Deployed · Investigated / research · Focus of this talk

Limitations PON allows to overcome

[1] "*Analysis on in-vehicle optical communication trends and suggestions for developing **V-PON***", CHEN Shanzhi, LUO Wenyong, 2026

According to [1], **PON** could **overcome** the following **limitations** of traditional copper-based in-vehicle communication:

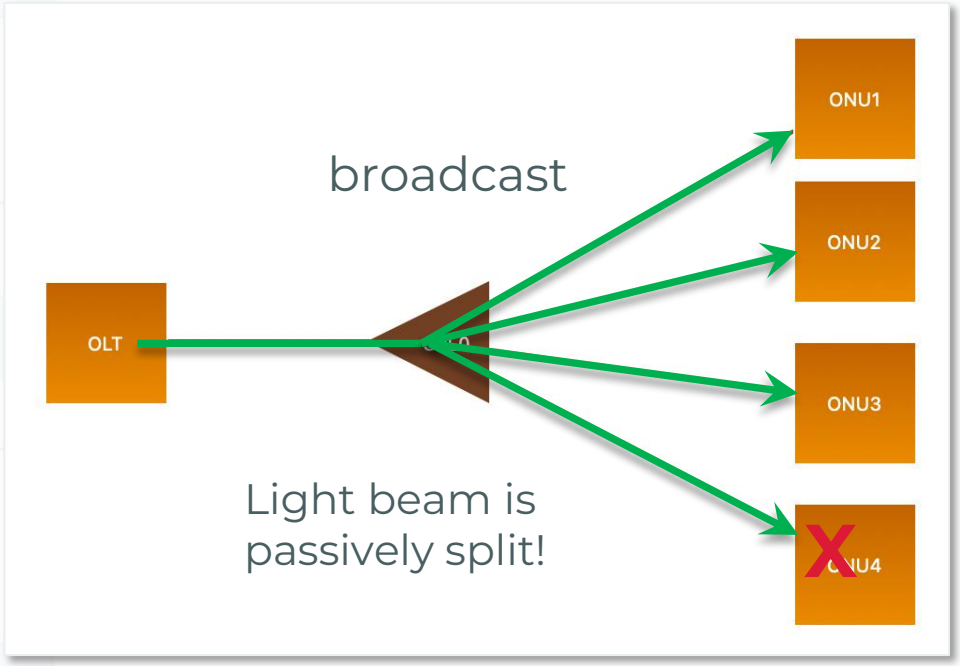
- Difficulties to meet the **high-bandwidth** requirements of growing numbers of cameras, radars, and other sensors.
- Transient error rates due to **electromagnetic interference** can no longer readily satisfy the requirements of Level ≥ 2 automated driving.
- Copper-based buses make major **harness simplification** difficult.
- **Copper** is **expensive** and **heavy**.

PON Down- and Up-Stream communication

OLT: Optical Line Terminal

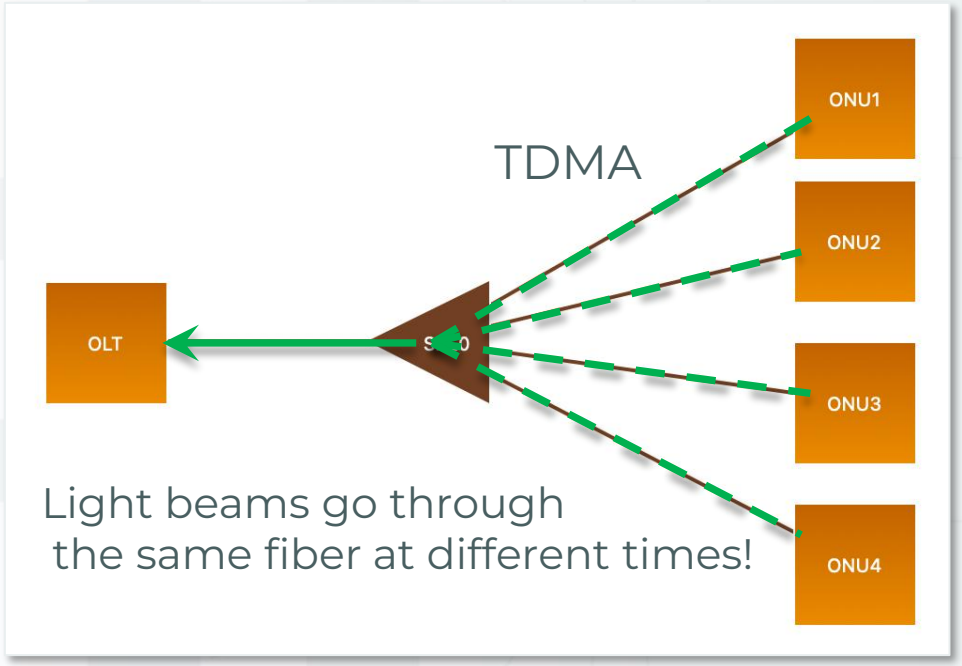
ONU: Optical Network Unit

Down-Stream



Only ONUs with the right decryption key can read the data!

Up-Stream



ONUs transmit in reserved "slots" toward the OLT.

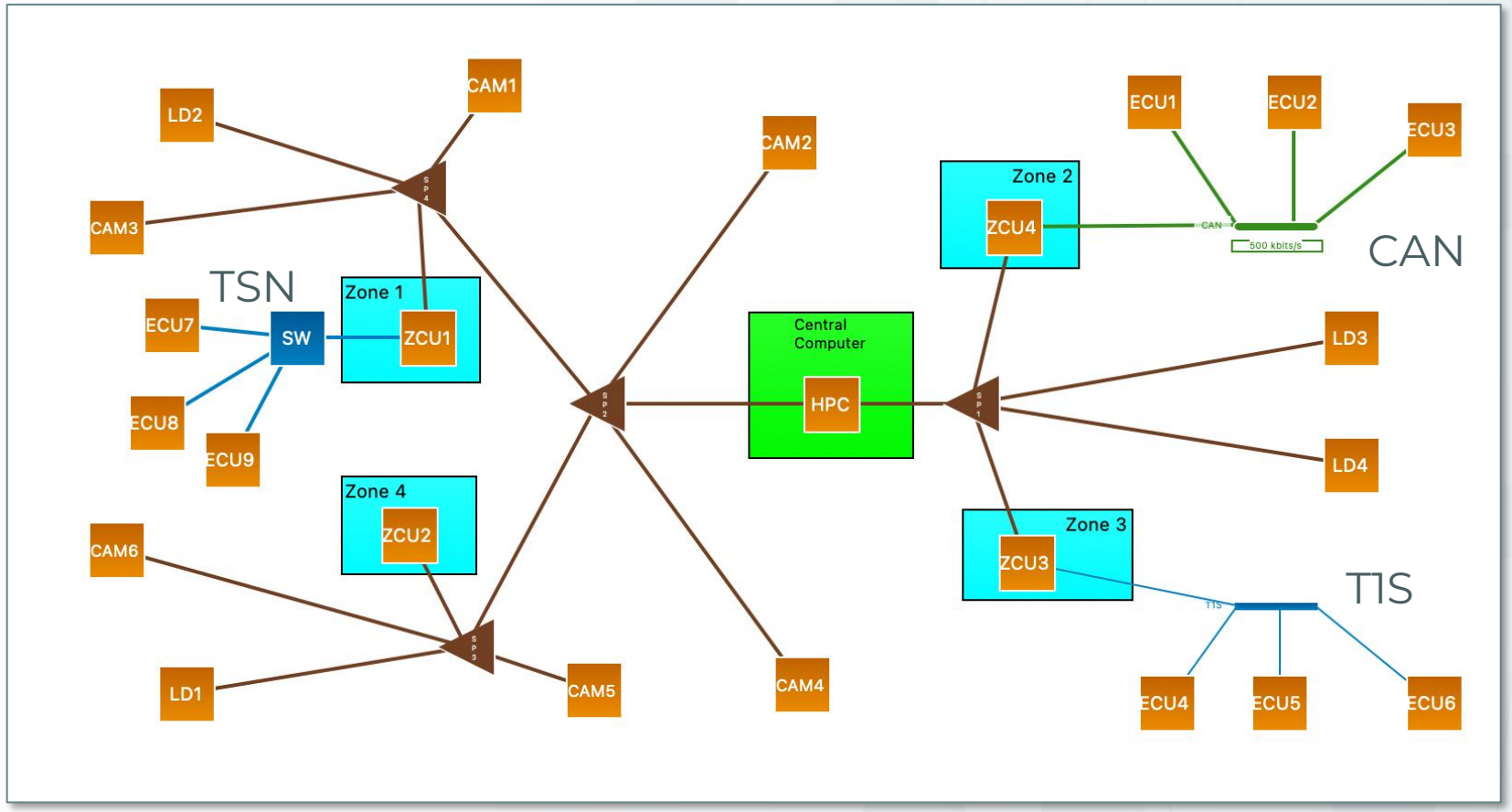
Typical architecture

PON connects

- Central computer

With

- Zonal controllers
- Cameras
- Lidar
- Radar



Focus on Real-Time communication

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Capabilities of PON

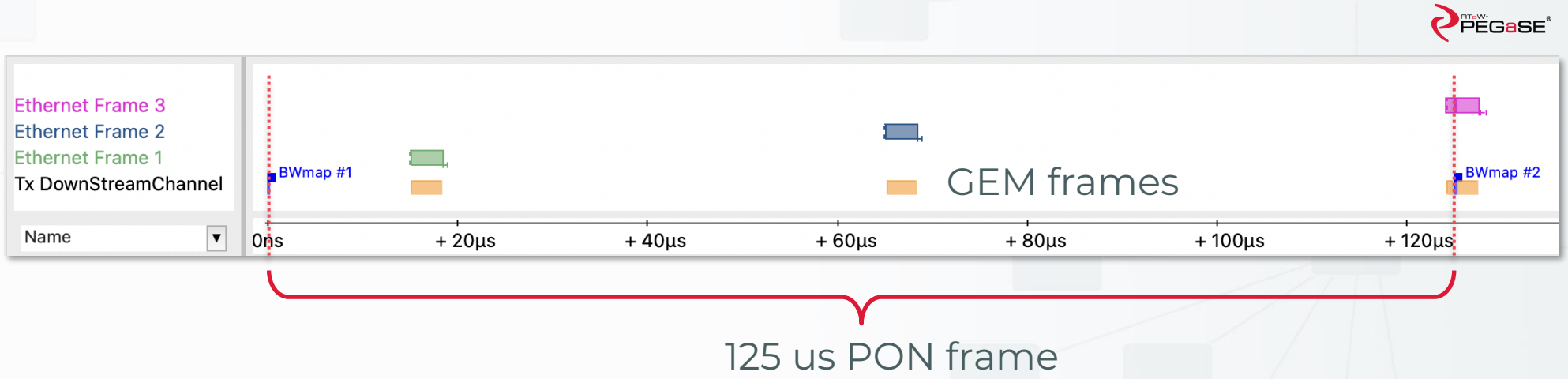
- OLT Ports and T-CONTs (ONU) allow to define hierarchical static priority schedulers or WRR schedulers for waiting data
- Band-width for T-CONTs may be allocated in different ways: fixed, assured, non-assured, best-effort, mixed

To achieve real-time guarantees, we consider:

- One level of **static priorities**
- **Fixed band-width** allocation for T-CONTs (up-stream)

125 us PON **down**-stream frames

- Transmissions are sub-divided into **PON frames** that have a fixed length of **125 us** and start with a Physical Control Block (PCBd).
- **Payload** is transported inside of **GEM frames**, that may be preempted by the PCBds

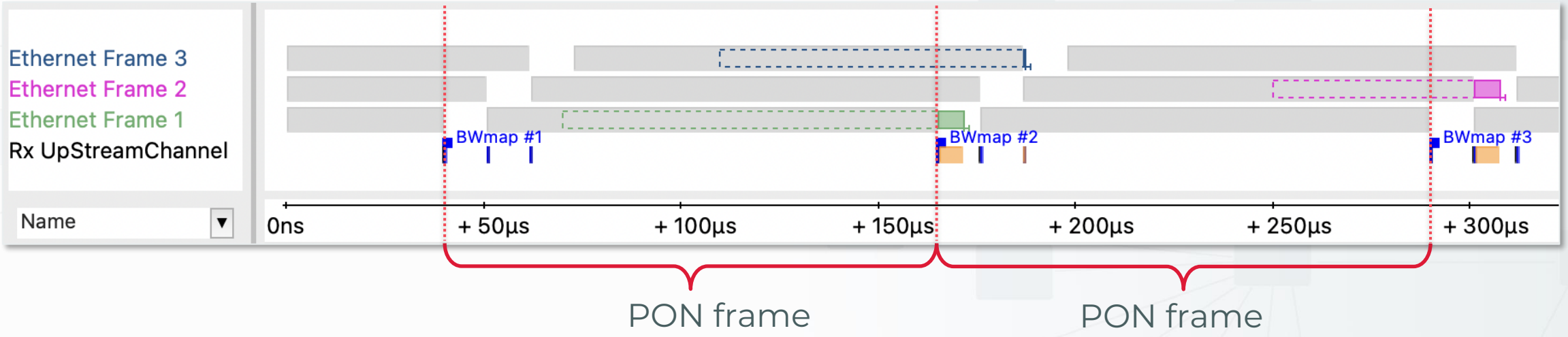


Assumption:

- If the link is idle, payload is transmitted ASAP (idle response delay).

125 us PON **up**-stream frames

- Payload is transported inside of slots allocated to T-CONTs
- Allocations are defined by the BWmap which is regularly sent by the OLT



Assumption:

- Payload must wait until the next slot allocated to its T-CONT, but can be sent ASAP if slot is on-going.

Timing requirements

- Most dimensioning automotive timing requirements listed in [1]:

Function	Sensor / Interface type	Bandwidth per device	Estimated quantity	Estimated total bandwidth	Typical applications
Multiple displays	Display interface	1–4 Gbit/s	4–6 screens	4–18 Gbit/s	Navigation, center console, entertainment
Perception	Forward/surround -view cameras	1–4 Gbit/s	7–15	12–30 Gbit/s	Object recognition, SLAM mapping

Vehicle domain	End-to-end latency requirement	Bandwidth requirement
Body and comfort	<10 ms	Low
Cockpit and human-machine interaction	<10 ms	High
Driver assistance and safety	<100 µs or <1 ms, depending on the system	High
Powertrain and chassis	<10 µs	Low

Forward Error Correction in PON (FEC)

- PON optics have high raw bit-error ratios.
- Forward Error Correction (FEC) delivers the needed error rates.

RAW LINK BER

GPON 10^{-4} XGS-PON 10^{-3} 50G-PON $\sim 10^{-2}$ → FEC $\leq 10^{-12}$

FEC CODEWORD — SYSTEMATIC BLOCK



	GPON	XGS-PON	50G-PON
Standard	ITU-T G.984.3	ITU-T G.9807.1	ITU-T G.9804.2
Line rate	2.5G / 1.25G	10G symmetric	50G
FEC code	**RS(255,239)**	**RS(248,216)**	**LDPC(17280,14592)**
Codeword / block	255 B	248 B	2160 B (17 280 b)
Parity	16 B	32 B	336 B (2 688 b)
FEC overhead	**~6.7%**	**~14.8%**	**~18.4%**

Parity overhead grows with the line rate!

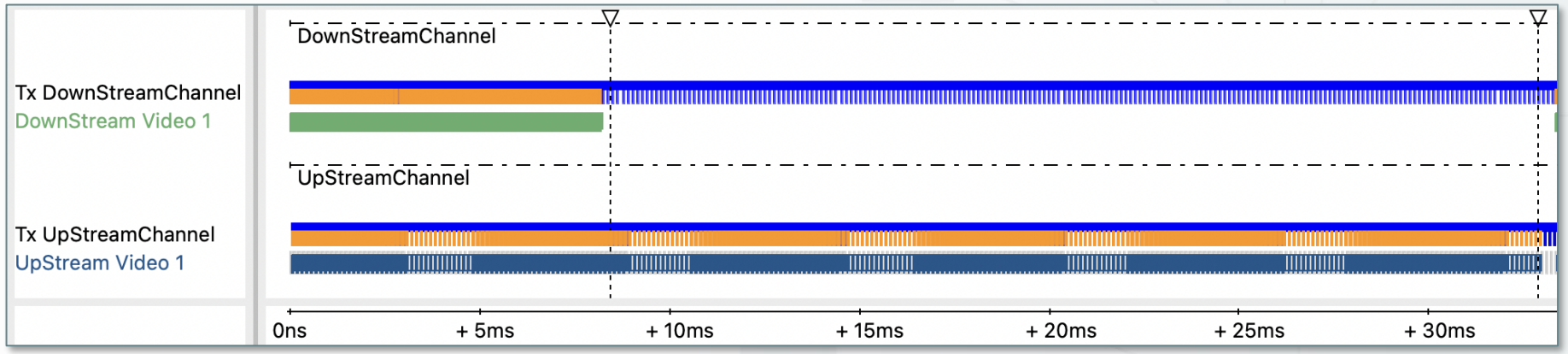
High Bandwidth Streams

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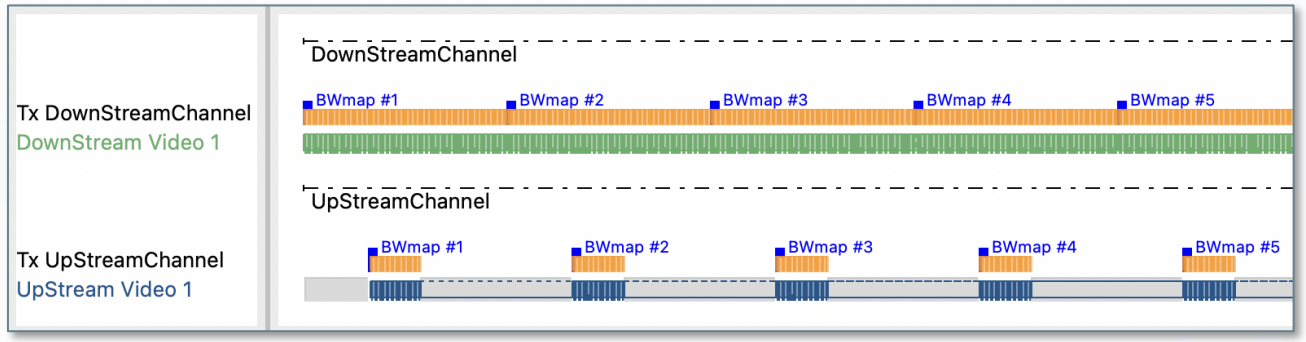
Single 2.14 Gbit/s, 30 fps video streams in both directions on XGS-PON:

Down-stream
Delay: 8,1 ms

Up-stream
Delay: 33 ms



zoom

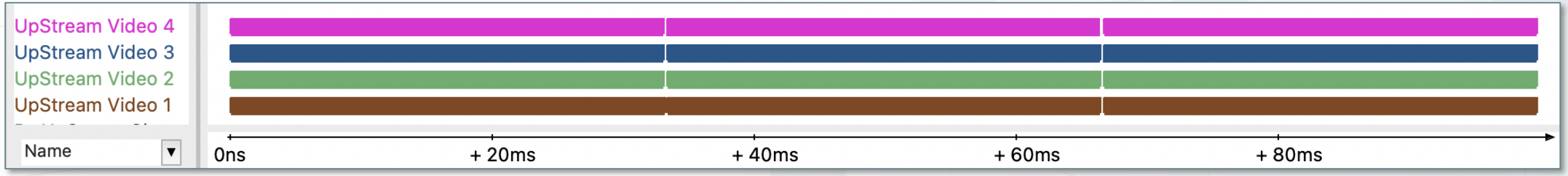


Down-stream:
Video stream alone
⇨ entire 9.95 Gbit/s available

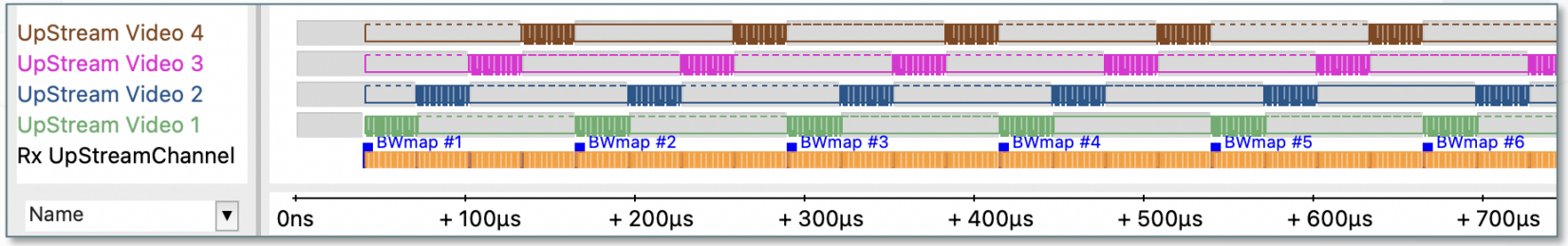
Up-stream:
fixedBW = 2,150 Gbit/s
⇨ delay ≈ period

High Bandwidth Streams

4 x 2.14 Gbit/s video streams, sent **up-stream** by 4 different ONUs



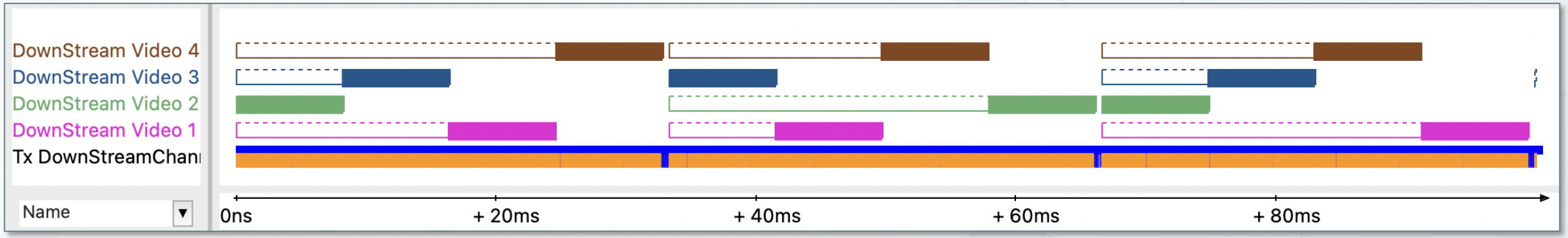
zoom



Video stream transmission
Looks like round-robin
because of separate T-CONTs

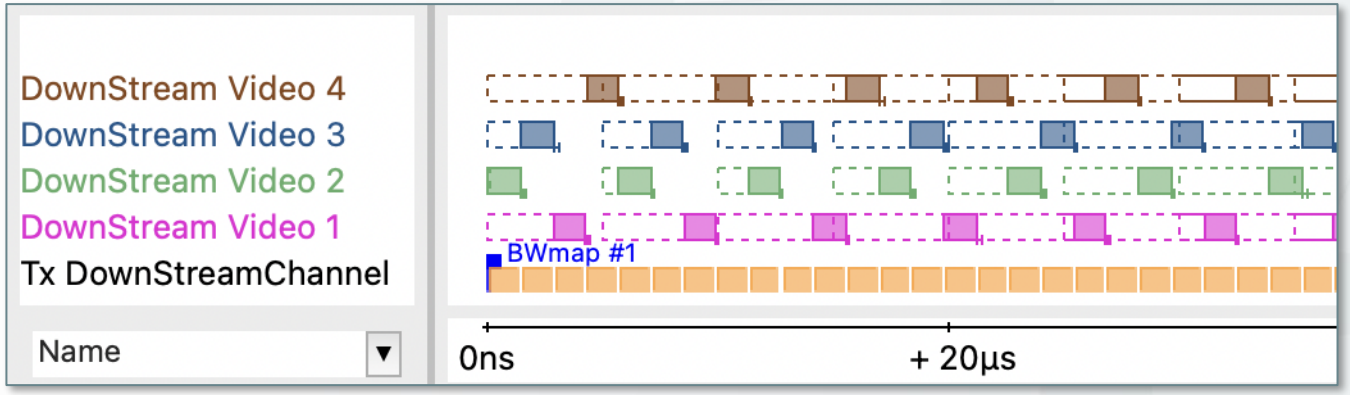
High Bandwidth Streams

- 4 x 2.14 Gbit/s video streams, sent **down-stream** by the OLT

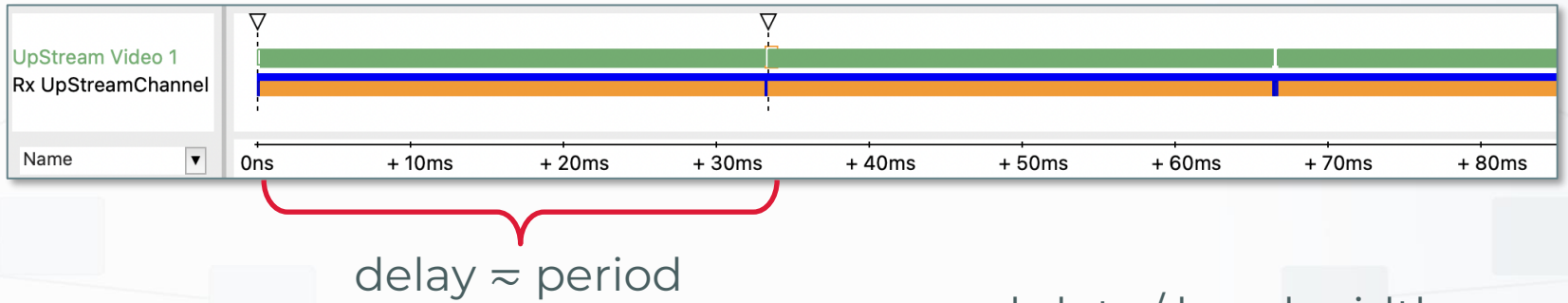


If all fragments of an image are queued "at the same time" we get per-stream bursts.

Otherwise, some kind of multiplexing occurs.



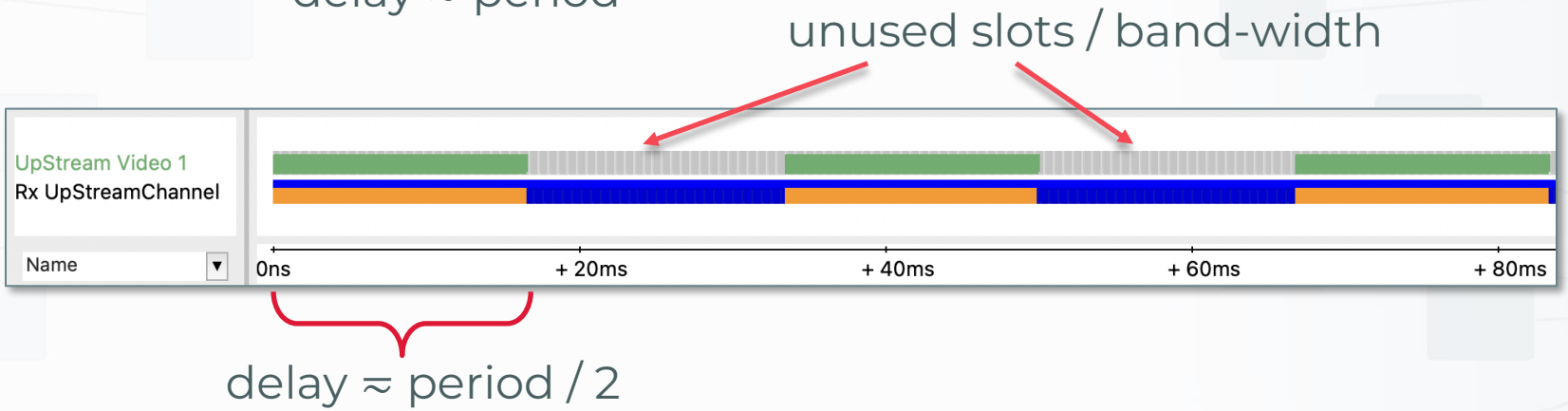
High Bandwidth + low latency



Allocated band-width

= required band-width

⇨ Delay ≈ period



Doubled bandwidth:

fixedBW = 4,300 Gbit/s

⇨ **Delay ≈ period / 2**

Note: the potentially unused band-width could be used by other streams or the same T-CONT with longer latencies.

Very tight latency constraint < 10 us ?

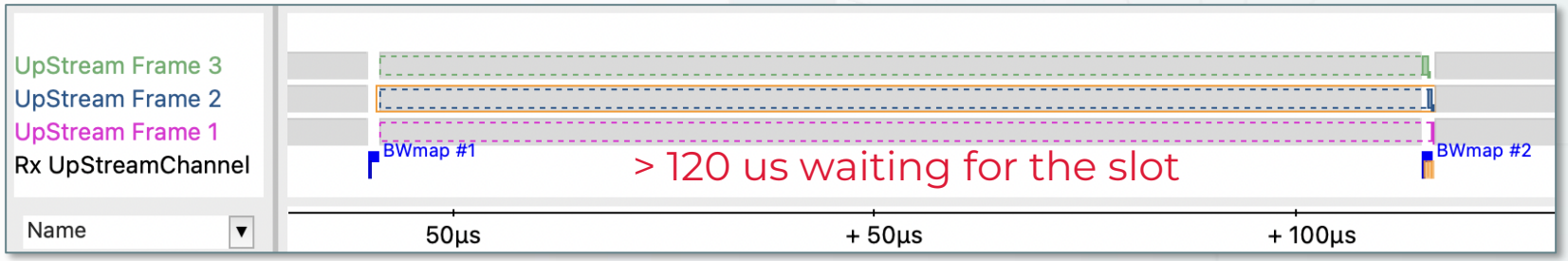
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3 frames with sizes: 150 bytes + 400 bytes + 700 bytes = **1250 bytes**

XGS-PON, fixedBW:

1300 bytes every 125 us

⇨ delay up to 126,3 us



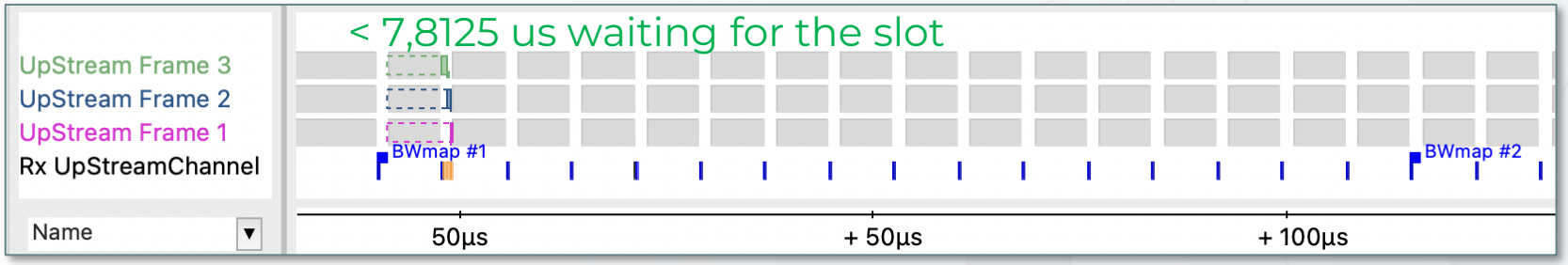
The standard does not say how bandwidth shall exactly be allocated …

… we could work with sub-periods: an allocation every 7,8125 us (=125 us / 16)

1300 bytes every 7,8125 us

⇨ delay up to 9,1 us

but jitter also up to 9,1 us



Notice: load: 1.011 % ⇨ 16.512 %

Very tight latency constraint < 10 us ?

RTaW
RealTime-at-Work

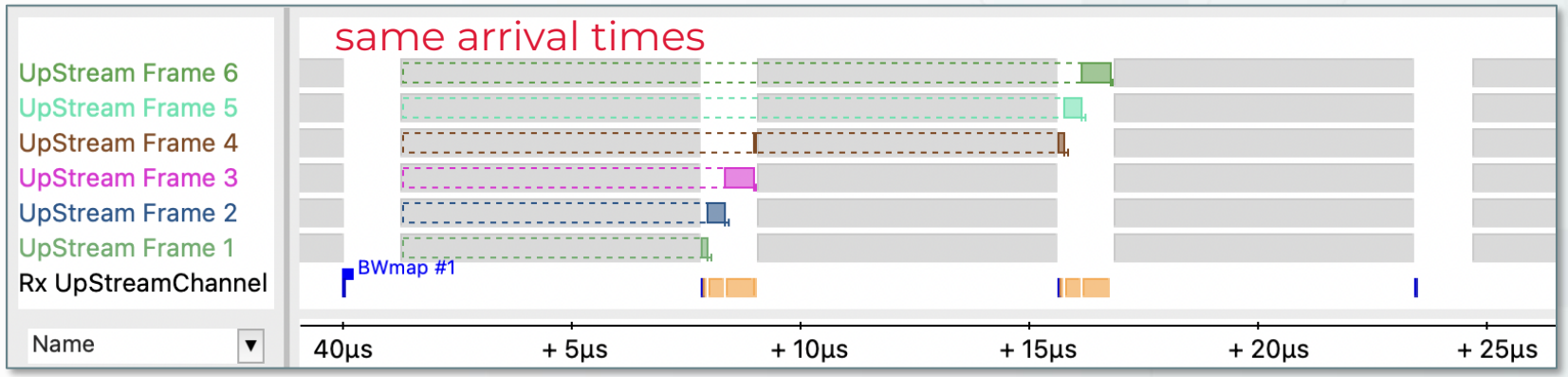
Let's consider 6 frames:

Total frame length 2500 bytes

Budget 1300 bytes

⇨ waiting for second slot

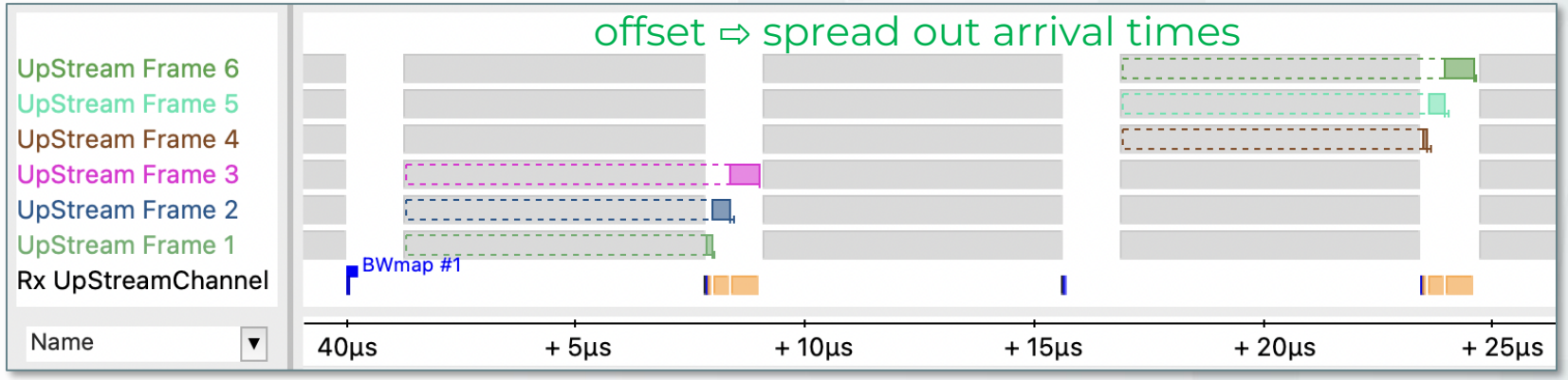
⇨ delay 15,9 us



But for frames with very tight constraints, **offsets** are usually known …

For instance, approaches like det-DBA (application-network co-scheduling) are based on them.

Known offsets:
⇨ less simultaneous arrivals
⇨ bandwidth reserved for frequent allocations can be exploited



Many streams: "Concise Priorities"

Let us consider an example on **GPON**, consisting of **100 Ethernet frames**

- Periodic streams
  - Period: 100 us, 500 us, 1 ms, 10 ms, 20 ms, 100 ms, 500 ms, 1000 ms
  - Sizes: 100 byte – 1500 byte
- Video streams
  - 500 x 1472 bytes every 16,666 ms
  - 1000 x 1472 bytes every 50 ms
- Latency constraints equal to periods
  notice: 100 us latency constraint < 125 us PON period
- All Ethernet frames transmitted up-stream (1.25 Gbps) by the same ONU.
- ⇨ PON load: 75%

Many streams: "Concise Priorities"

By default, all streams are assigned to the same priority queue.

⇨ all worst-case delays are equal (FIFO)

⇨ many latency constraints are not met

Priorities are an **efficient** scheduling mechanism, but hardware offers a limited number.

How to assign priorities optimally?

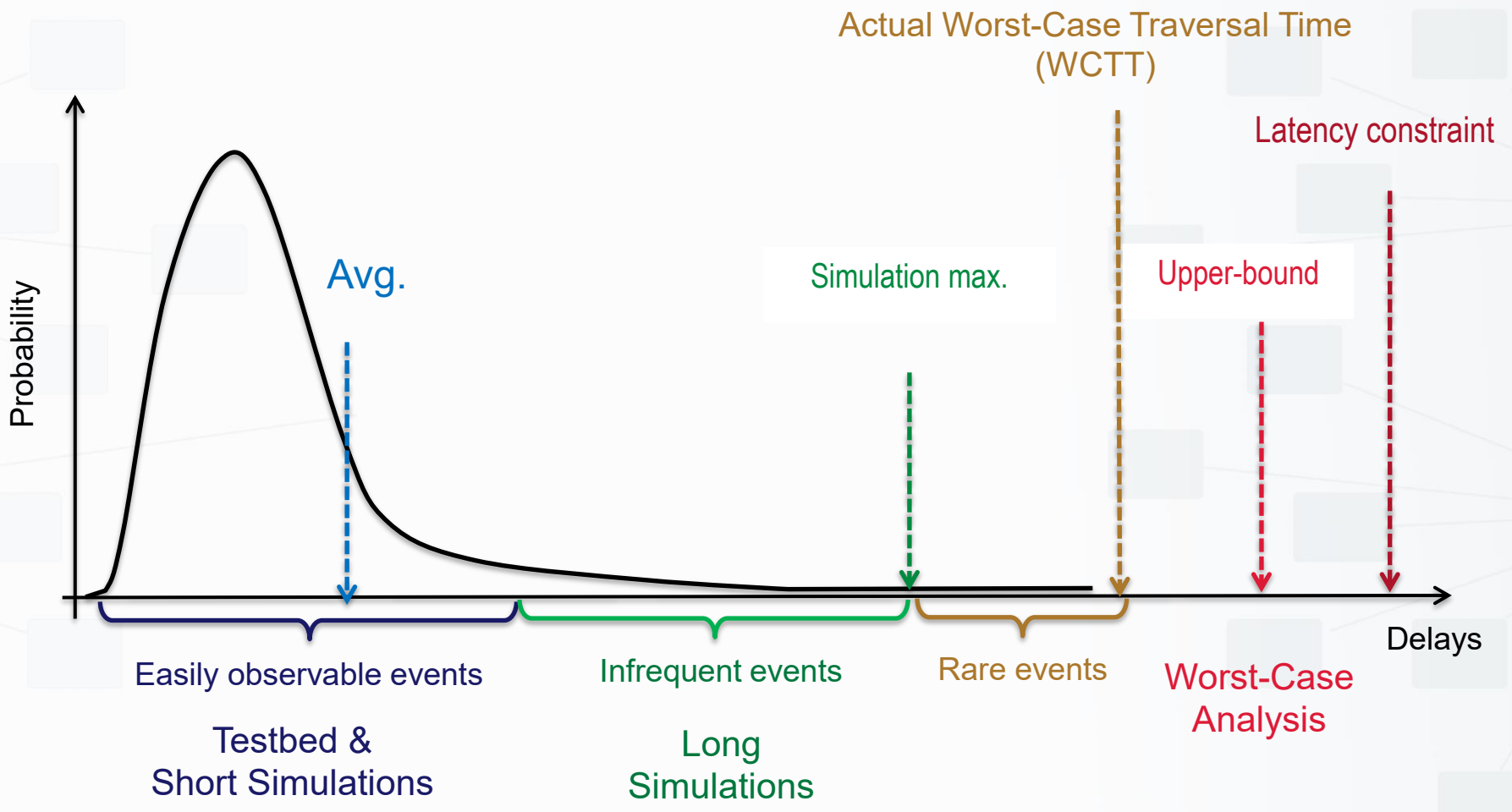
delay statistics worst-case bounds

Name	MinDistance	MaxSize	Sender	Receiver	Min	Average	Max	WCTT	Constraint	Slack
Video 50ms	50 ms	1000 x 1472 byte	ONU1	HPC-OLT	20,891 ms	20,892 ms	20,892 ms	21,359 ms	50 ms	28,642 ms
Video 16,666ms	16,666 ms	500 x 1472 byte	ONU1	HPC-OLT	6,954 ms	9,613 ms	16,058 ms	21,359 ms	16 ms	-5,358 ms
20ms_1	20 ms	600 byte	ONU1	HPC-OLT	2,240 ms	6,842 ms	13,929 ms	21,359 ms	20 ms	-1,358 ms
50ms_1	50 ms	500 byte	ONU1	HPC-OLT	21,044 ms	21,045 ms	21,045 ms	21,359 ms	50 ms	28,642 ms
50ms_2	50 ms	200 byte	ONU1	HPC-OLT	21,011 ms	21,012 ms	21,012 ms	21,359 ms	50 ms	28,642 ms
100ms_1	100 ms	300 byte	ONU1	HPC-OLT				21,359 ms	100 ms	78,642 ms
0,5ms_1	0,5 ms	100 byte	ONU1	HPC-OLT	0,000 ms	5,823 ms	21,045 ms	21,359 ms	0,5 ms	-20,858 ms
0,5ms_2	0,5 ms	300 byte	ONU1	HPC-OLT	0,003 ms	5,825 ms	21,060 ms	21,359 ms	0,5 ms	-20,858 ms
0,5ms_3	0,5 ms	100 byte	ONU1	HPC-OLT	0,000 ms	5,823 ms	21,037 ms	21,359 ms	0,5 ms	-20,858 ms
0,5ms_4	0,5 ms	300 byte	ONU1	HPC-OLT	0,002 ms	5,825 ms	21,055 ms	21,359 ms	0,5 ms	-20,858 ms
0,1ms_1	0,1 ms	100 byte	ONU1	HPC-OLT	0,000 ms	5,755 ms	20,976 ms	21,359 ms	0,1 ms	-21,258 ms
1000ms_1	1000 ms	1400 byte	ONU1	HPC-OLT				21,359 ms	1000 ms	978,642 ms
10ms_1	10 ms	300 byte	ONU1	HPC-OLT	0,023 ms	7,598 ms	21,057 ms	21,359 ms	10 ms	-11,358 ms
0,1ms_2	0,1 ms	100 byte	ONU1	HPC-OLT	0,000 ms	5,756 ms	20,986 ms	21,359 ms	0,1 ms	-21,258 ms
50ms_3	50 ms	400 byte	ONU1	HPC-OLT	20,921 ms	20,922 ms	20,922 ms	21,359 ms	50 ms	28,642 ms
0,5ms_5	0,5 ms	100 byte	ONU1	HPC-OLT	0,001 ms	5,822 ms	20,994 ms	21,359 ms	0,5 ms	-20,858 ms
10ms_2	10 ms	300 byte	ONU1	HPC-OLT	0,006 ms	7,566 ms	21,035 ms	21,359 ms	10 ms	-11,358 ms
20ms_2	20 ms	600 byte	ONU1	HPC-OLT	2,258 ms	6,816 ms	13,820 ms	21,359 ms	20 ms	-1,358 ms
500ms_1	500 ms	1300 byte	ONU1	HPC-OLT				21,359 ms	500 ms	478,642 ms
20ms_3	20 ms	300 byte	ONU1	HPC-OLT	2,128 ms	6,823 ms	13,922 ms	21,359 ms	20 ms	-1,358 ms
20ms_4	20 ms	200 byte	ONU1	HPC-OLT	2,199 ms	6,814 ms	13,878 ms	21,359 ms	20 ms	-1,358 ms

⇨ **"Concise Priorities" Algorithm**

Assignment to the smallest possible number of priority levels such as to meet all latency constraints.

Distribution of communication delays



Simulation
- statistics
- unfavorable scenarios (illustrating long delays)

Worst-Case Analysis
- upper bound
- guarantees
- basis for configuration and optimization with latency guarantees

Many streams: "Concise Priorities"

RTaW RealTime-at-Work

"**Concise Priorities**" algorithm has been applied:

⇨ 3 priority queues are enough to meet all latency constraints

"Concise Priorities" uses network-calculus based worst-case analysis.

It has originally been developed for Ethernet/TSN and can be used in combination with PON if priorities are aligned.

delay statistics worst-case bounds

Name	Prio	MinDistance	MaxSize	Min	Average	Max	WCTT	Constraint	Slack
10ms_7	1	10 ms	300 byte	0,046 ms	3,194 ms	9,855 ms	9,920 ms	10 ms	0,081 ms
10ms_8	1	10 ms	400 byte	0,046 ms	3,195 ms	9,829 ms	9,920 ms	10 ms	0,081 ms
10ms_9	1	10 ms	400 byte	0,047 ms	3,195 ms	9,865 ms	9,920 ms	10 ms	0,081 ms
20ms_1	1	20 ms	600 byte	0,047 ms	3,208 ms	9,860 ms	9,920 ms	20 ms	10,081 ms
20ms_10	1	20 ms	400 byte	0,047 ms	3,207 ms	9,853 ms	9,920 ms	20 ms	10,081 ms
20ms_2	1	20 ms	600 byte	0,047 ms	3,208 ms	9,857 ms	9,920 ms	20 ms	10,081 ms
20ms_3	1	20 ms	300 byte	0,046 ms	3,207 ms	9,867 ms	9,920 ms	20 ms	10,081 ms
20ms_4	1	20 ms	200 byte	0,045 ms	3,207 ms	9,852 ms	9,920 ms	20 ms	10,081 ms
20ms_5	1	20 ms	400 byte	0,046 ms	3,207 ms	9,849 ms	9,920 ms	20 ms	10,081 ms
20ms_6	1	20 ms	300 byte	0,046 ms	3,207 ms	9,847 ms	9,920 ms	20 ms	10,081 ms
20ms_7	1	20 ms	200 byte	0,046 ms	3,208 ms	9,837 ms	9,920 ms	20 ms	10,081 ms
20ms_8	1	20 ms	500 byte	0,047 ms	3,208 ms	9,853 ms	9,920 ms	20 ms	10,081 ms
20ms_9	1	20 ms	600 byte	0,047 ms	3,208 ms	9,858 ms	9,920 ms	20 ms	10,081 ms
Video 16,666ms	1	16,666 ms	500 x 1472 byte	9,665 ms	9,732 ms	9,784 ms	9,920 ms	16 ms	6,081 ms
50ms_1	0	50 ms	500 byte	7,446 ms	28,218 ms	49,390 ms	49,672 ms	50 ms	0,329 ms
50ms_10	0	50 ms	200 byte	7,438 ms	28,248 ms	49,393 ms	49,672 ms	50 ms	0,329 ms
50ms_11	0	50 ms	800 byte	7,423 ms	27,790 ms	49,393 ms	49,672 ms	50 ms	0,329 ms
50ms_12	0	50 ms	200 byte	7,402 ms	28,414 ms	49,585 ms	49,672 ms	50 ms	0,329 ms
50ms_13	0	50 ms	200 byte	7,423 ms	28,446 ms	49,348 ms	49,672 ms	50 ms	0,329 ms
50ms_14	0	50 ms	600 byte	7,433 ms	28,382 ms	49,439 ms	49,672 ms	50 ms	0,329 ms
50ms_15	0	50 ms	900 byte	7,436 ms	28,613 ms	49,469 ms	49,672 ms	50 ms	0,329 ms

Conclusions

- Protocol Capabilities
  - PON provides **sufficient throughput** for high band-width stream in SDVs, even if a part is lost for error correction.
  - In principle, standard PON could support **latencies < 10us**, but not near-zero jitter: jitter≈latency

- Tool support available (RTaW-Pegase)
  - Simulation and Worst-Case Analysis
  - PON scheduling configuration/optimization algorithms

⇒ Enables the exploration of potential architectural solutions without (or before) the creation a physical POC.

Outlook

- Collaboration with OEMs
  - Clarification of **actual automotive latency constraints.**
  - Support for det-DBA or similar, if needed.
  - Which **TSN** scheduling mechanism (CBS, ATS, TAS) on the **Ethernet** would be useful in combination **with PON?**
  - Which **other buses or networks** should be supported **with PON?**

- Collaboration with Hardware providers
  - **Refined hardware modeling**: delays, capabilities, …
  - Common capabilities and configuration **file formats** for PON hardware?

Thank you for your attention

Contact: jorn.migge@realtimeatwork.com

Web: www.rtaw.com