Part of this presentation is based on a paper to appear at ERTSS'2014: "Timing verification of automotive communication architectures using quantile estimation" co-authored with Shehnaz LOUVART (Renault), Jose VILLANUEVA (Renault), Sergio CAMPOY-MARTINEZ (Renault) and Jörn MIGGE (RealTime-at-Work).

Quantile-based performance evaluation on CAN

Nicolas NAVET

14th International CAN Conference
Paris, November 12-13, 2013.

1 Outline

- Early stage verification : simulation vs analysis
- Limitations of schedulability analyses
- How simulation can provide guarantees using quantiles

Schedulability analysis
"mathematic model of the worst-case possible situation"

VS

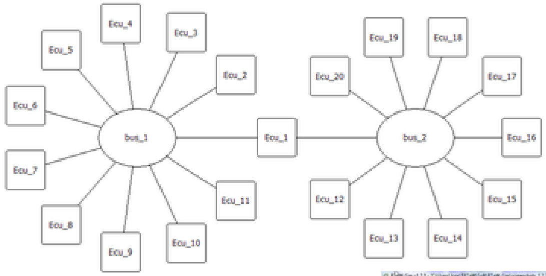
Simulation
"program that reproduces the behavior of a system"

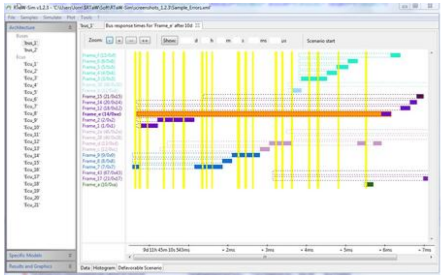
$$K_i^k(t) \stackrel{\text{def}}{=} \underbrace{\left\lfloor \frac{J_i^k + \varphi_i^k(\phi^i)}{T_i^k} \right\rfloor}_{\text{max number of instances that can accumulate at critical instants}} + \underbrace{\left\lfloor \frac{t - \varphi_i^k(\phi^i)}{T_i^k} \right\rfloor + 1}_{\text{max number of instances arriving after critical instants}}$$

max number of instances that can accumulate at critical instants

max number of instances arriving after critical instants

- ☺ Upper bounds on the perf. metrics → Safe (TBD)
- ☺ Analysis is known to be correct → Safe (TBD)
- ☹ Pessimistic → over-dimensioning
- ☹ Gap between models and real systems!
- ☹ Do not provide much information since a single trajectory is studied





- ☺ Models close to real systems
- ☺ Fine grained information
- ☹ Upper bounds are out of reach! → Unsafe (TBD)
- ☹ Model correctness is unsure

Beware of verification models !

"Schedulability analysis ensures safety!"
Our view: it might not be so…

1. Analytic models are pessimistic (except in the "ideal" case)
2. Analytic models are unrealistic (except in the "ideal" case)
3. Analytic models and their implementation can be flawed

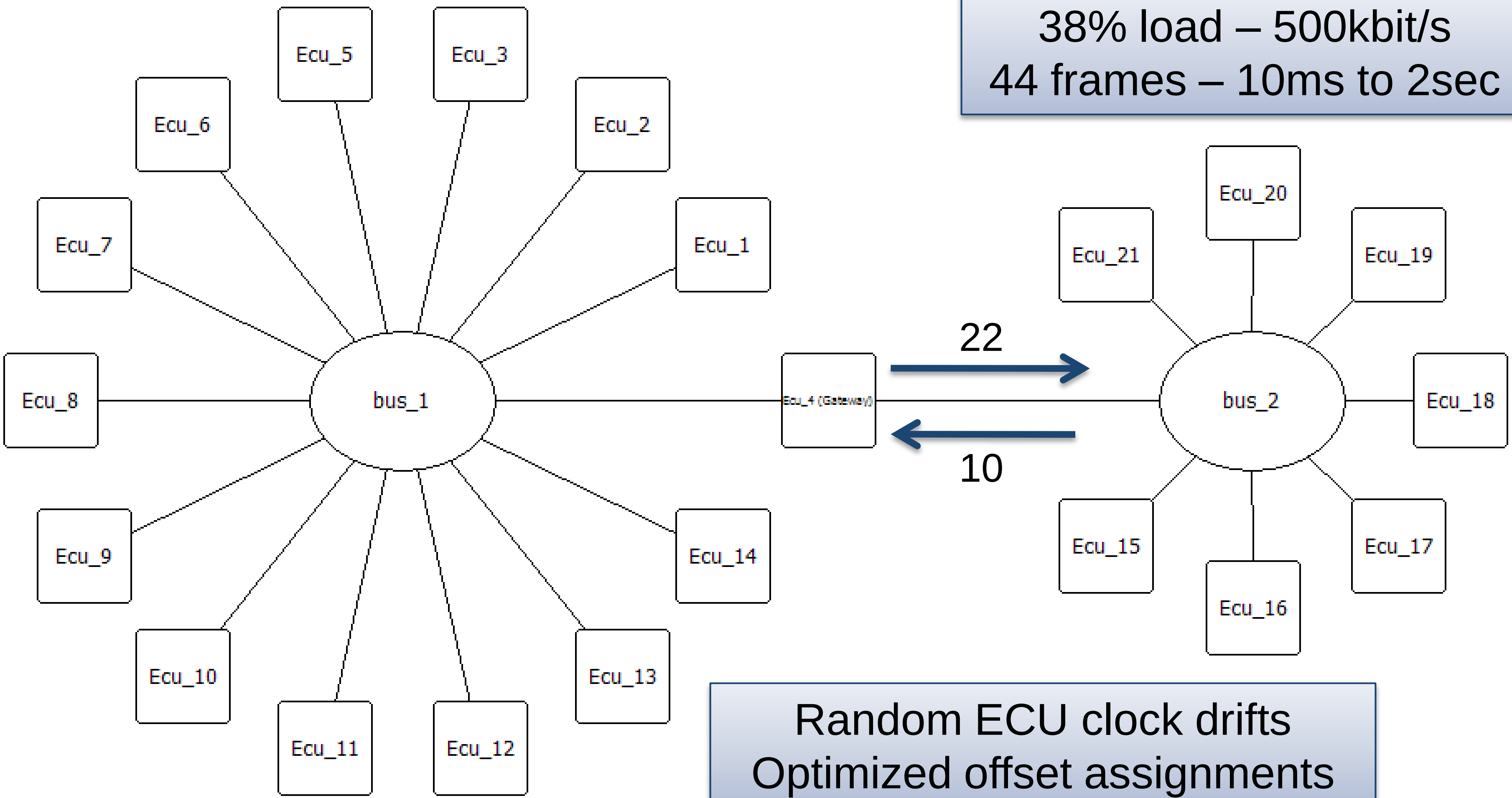
"Simulation cannot provide firm guarantees"
Our view: it might not be so…

4. It is possible to verify correctness of simulation models
5. User- chosen guarantees can be enforced with proper methodology, e.g. with quantiles

Typical CAN-based automotive system

49% load – 500kbit/s
72 frames – 10ms to 2sec

38% load – 500kbit/s
44 frames – 10ms to 2sec



Random ECU clock drifts
Optimized offset assignments

[RTaW-sim screenshot]

Performance metric: frame response time ≈ communication latency

“Time from transmission request until frame received by consuming nodes”

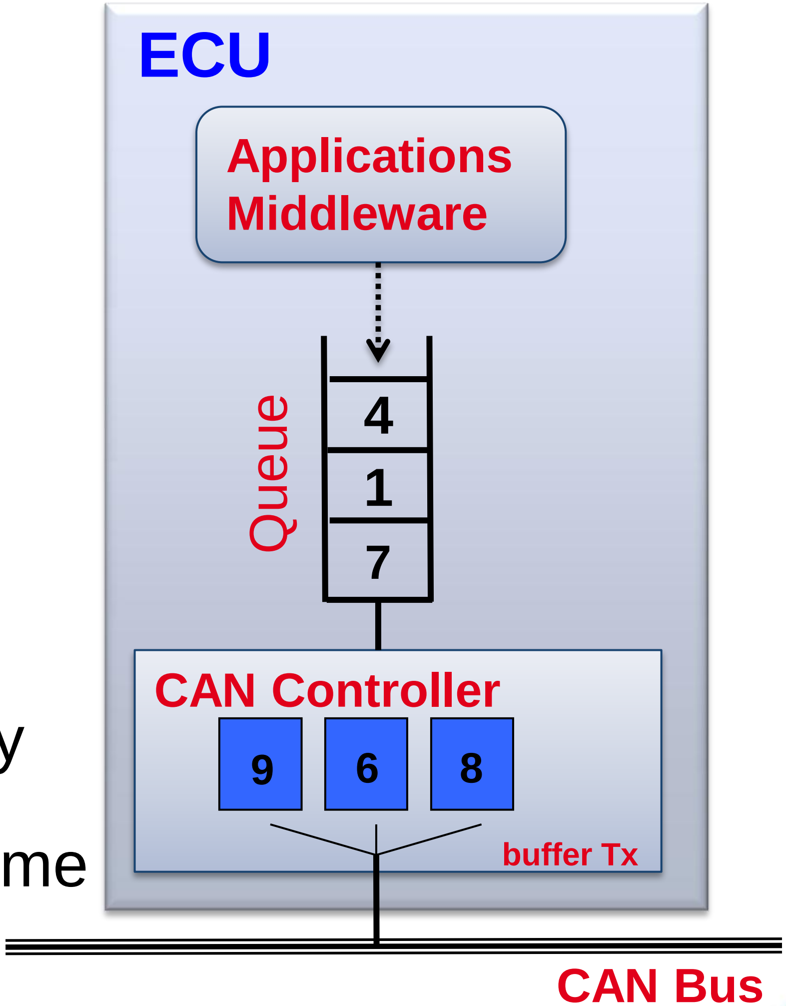
Ideal CAN = *“whenever message arbitration starts on the bus, the highest priority message queued on each node is entered into arbitration”*

Software delay

Waiting time in software queue

Arbitration delay

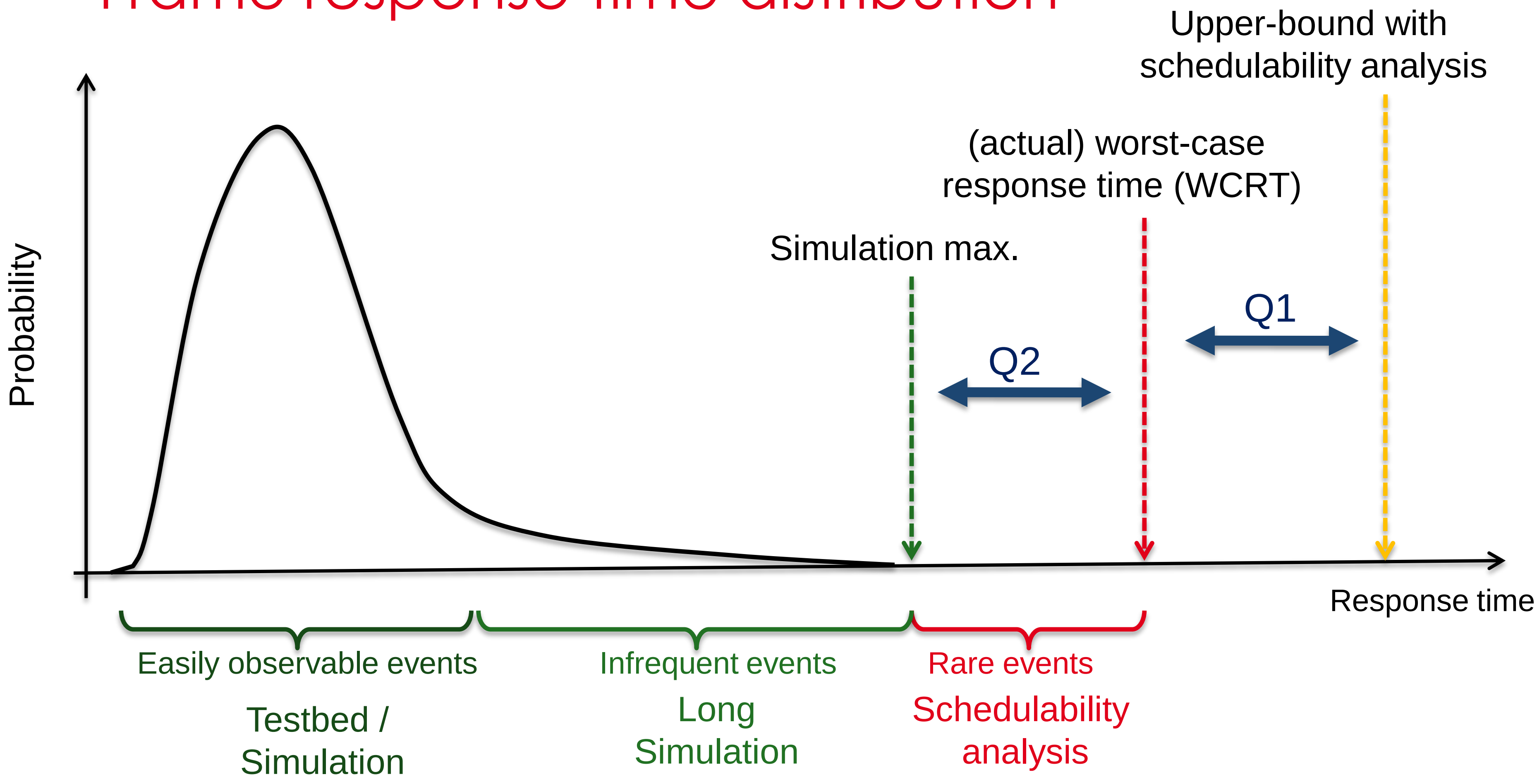
Transmission time



1

Analytic models are pessimistic (except in the “ideal” case)

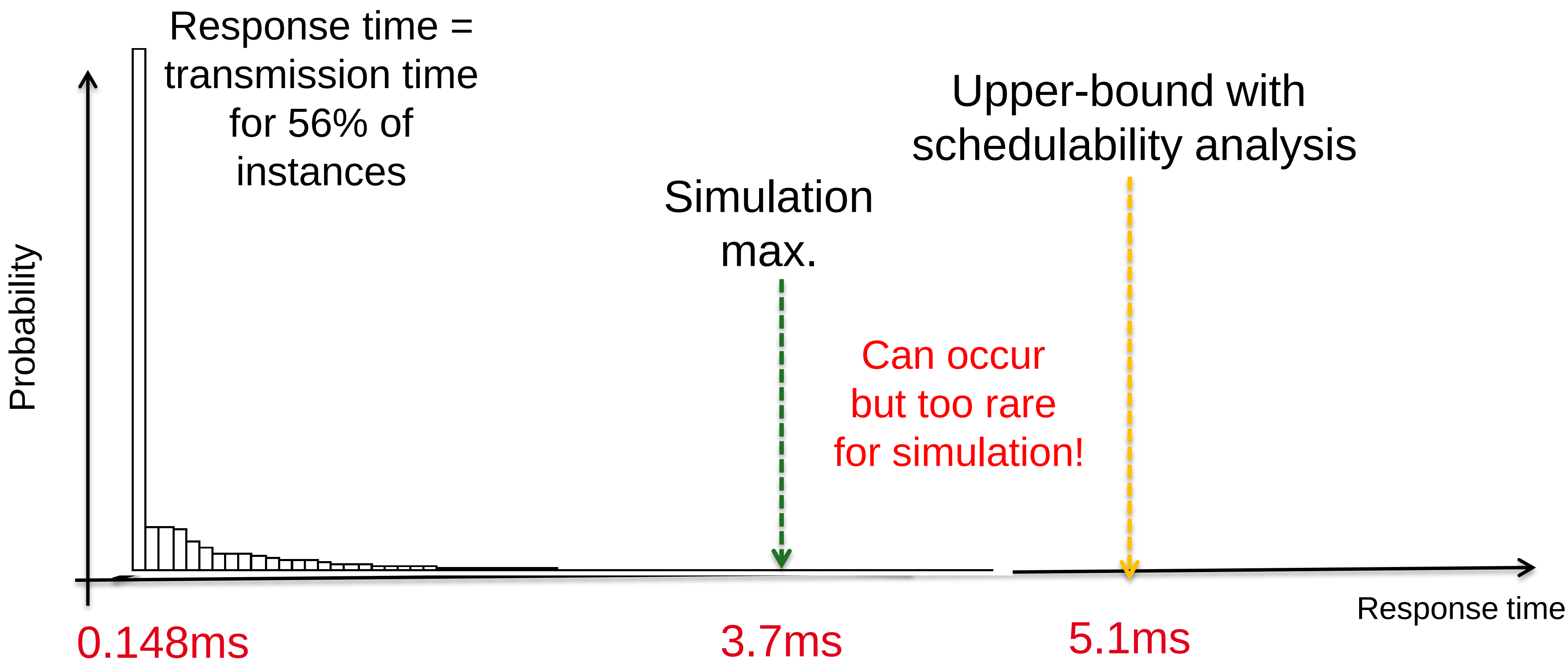
Frame response time distribution



Q1: pessimism of schedulability analysis ?!

Q2: distance between simulation max. and WCRT ?!

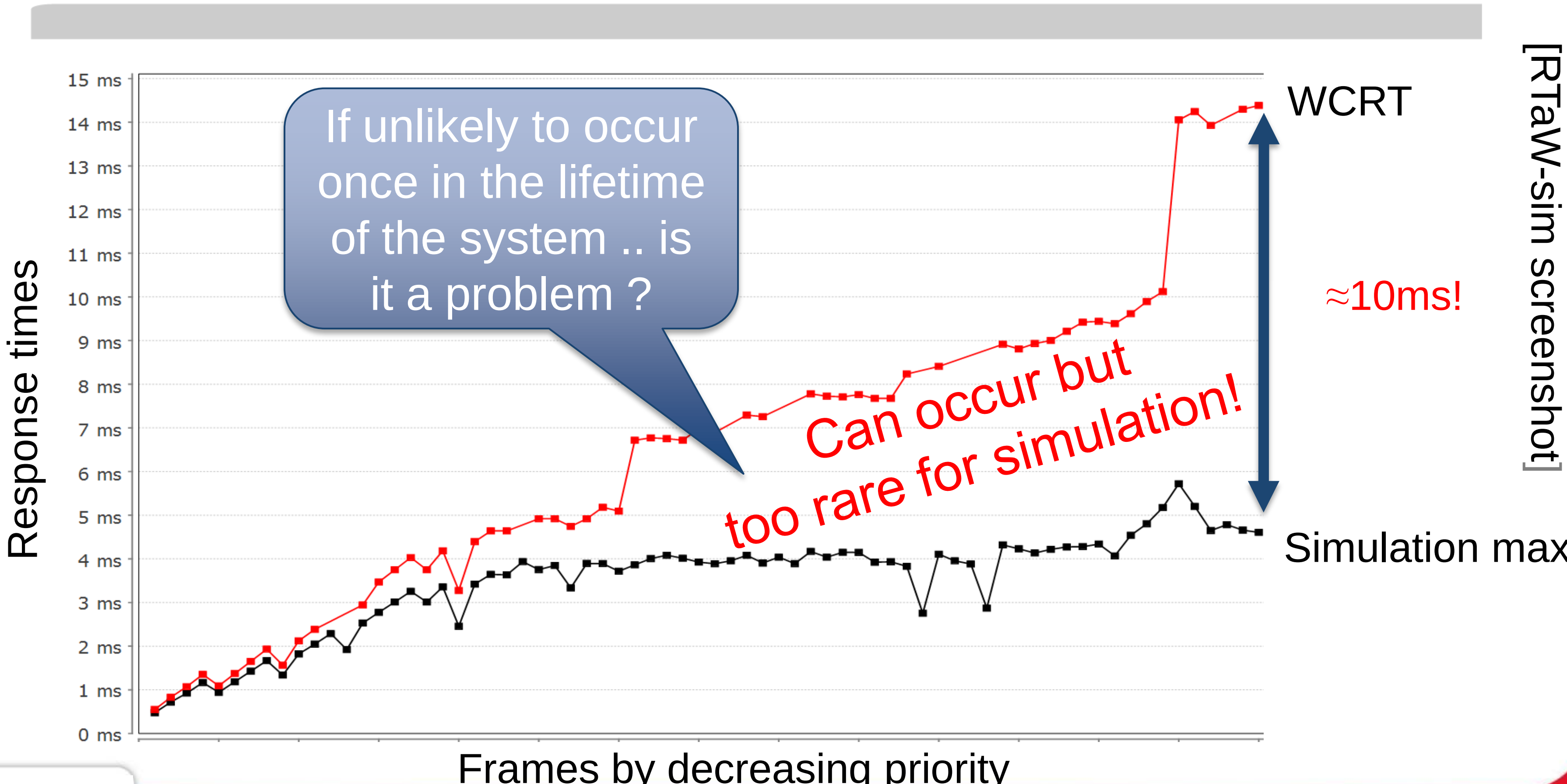
(Typical) Frame response time distribution



Medium priority frame on a 50% loaded 500kbits/bus with offsets

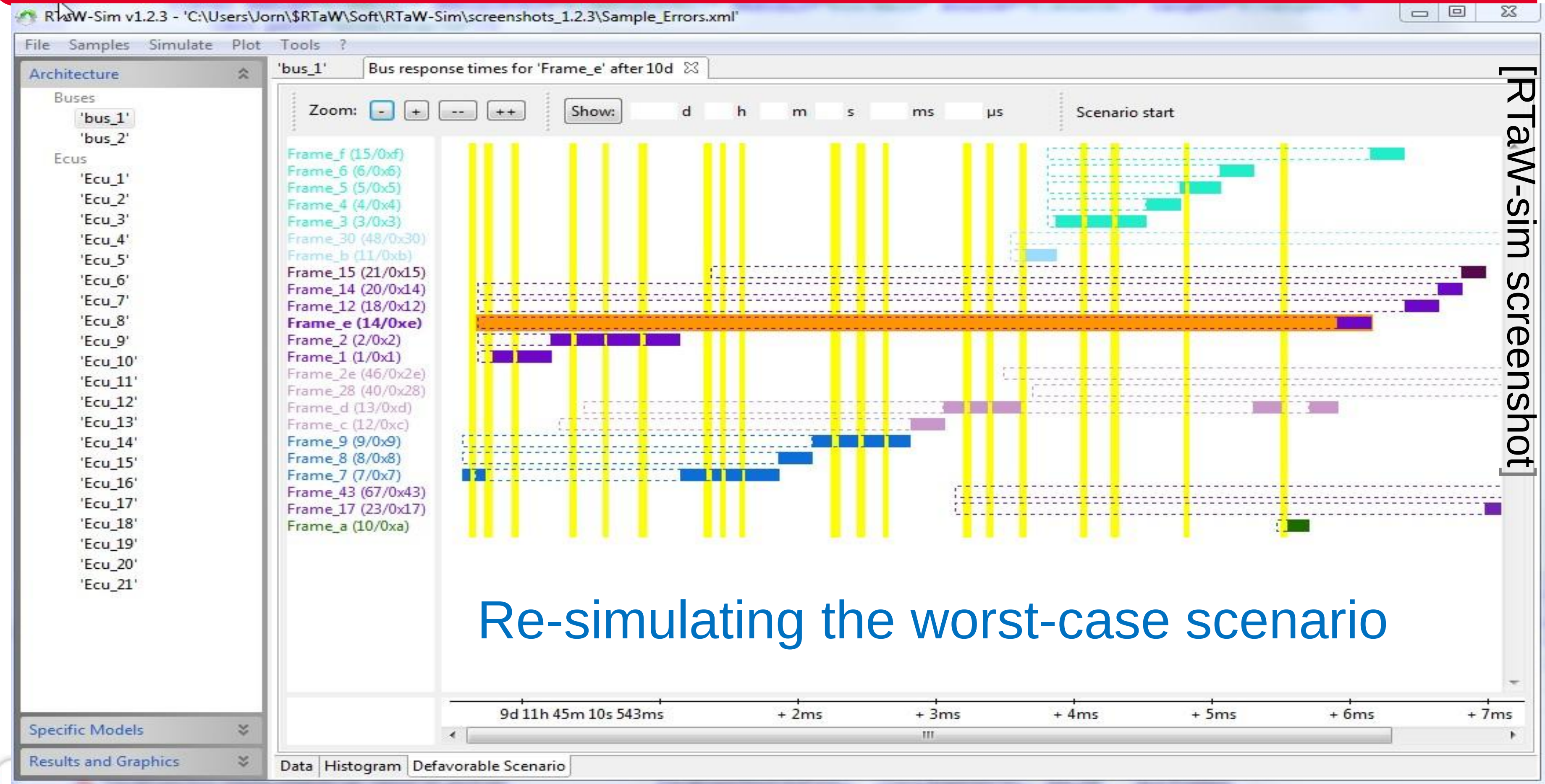
Q1 : Pessimism of CAN schedulability analysis ?
Q2: distance with simulation ?

Case 1: ideal communication stacks + no gateway →
the computed upper-bound can occur (and be re-simulated)



Q1 : Pessimism of CAN schedulability analysis ? Q2: distance with simulation ?

Case 1: ideal communication stacks + no gateway → the computed upper-bound can occur (and be re-simulated)

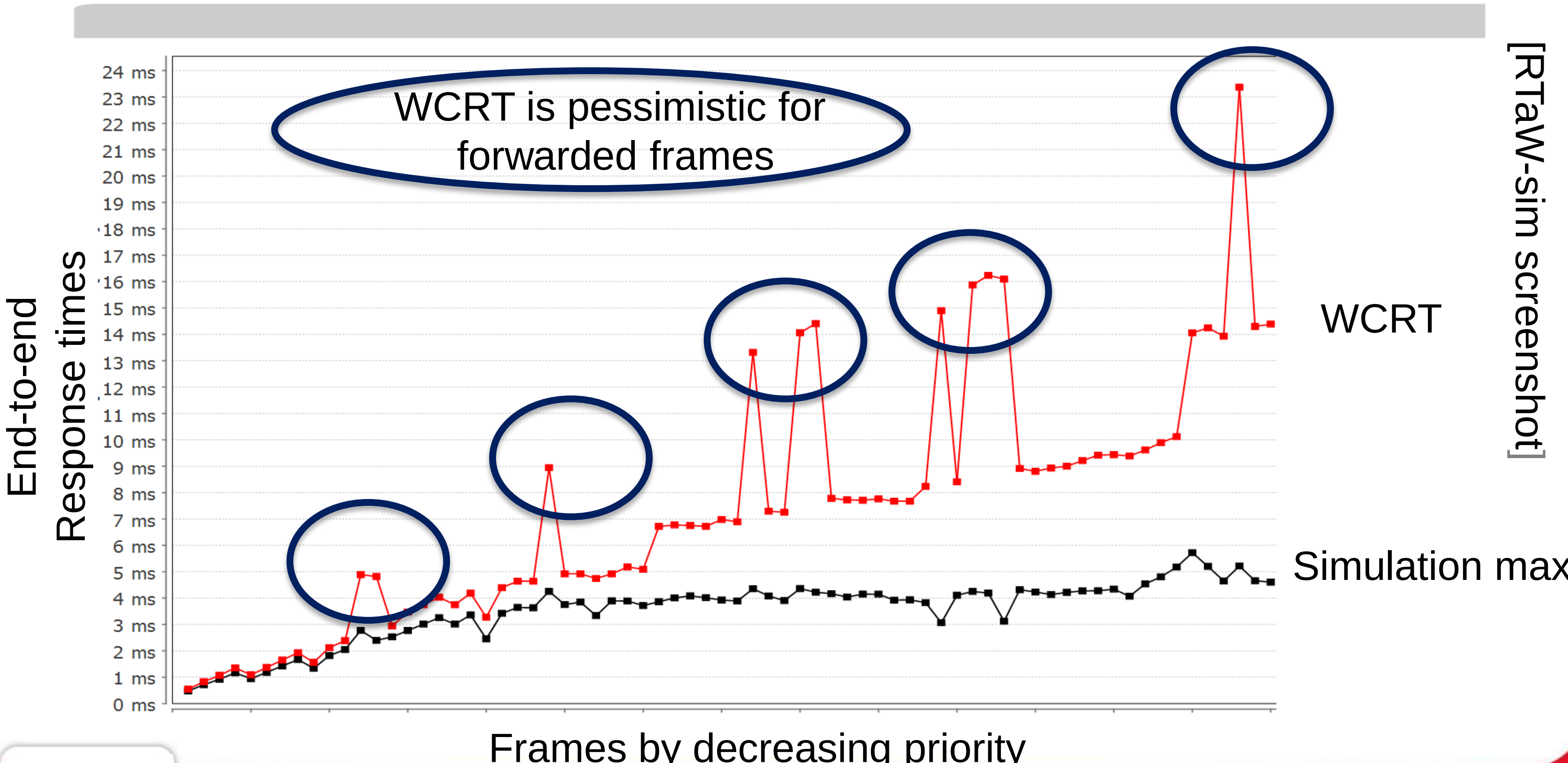


[RTaW-sim screenshot]

Re-simulating the worst-case scenario

Q1 : Pessimism of CAN schedulability analysis ?
Q2: distance with simulation ?

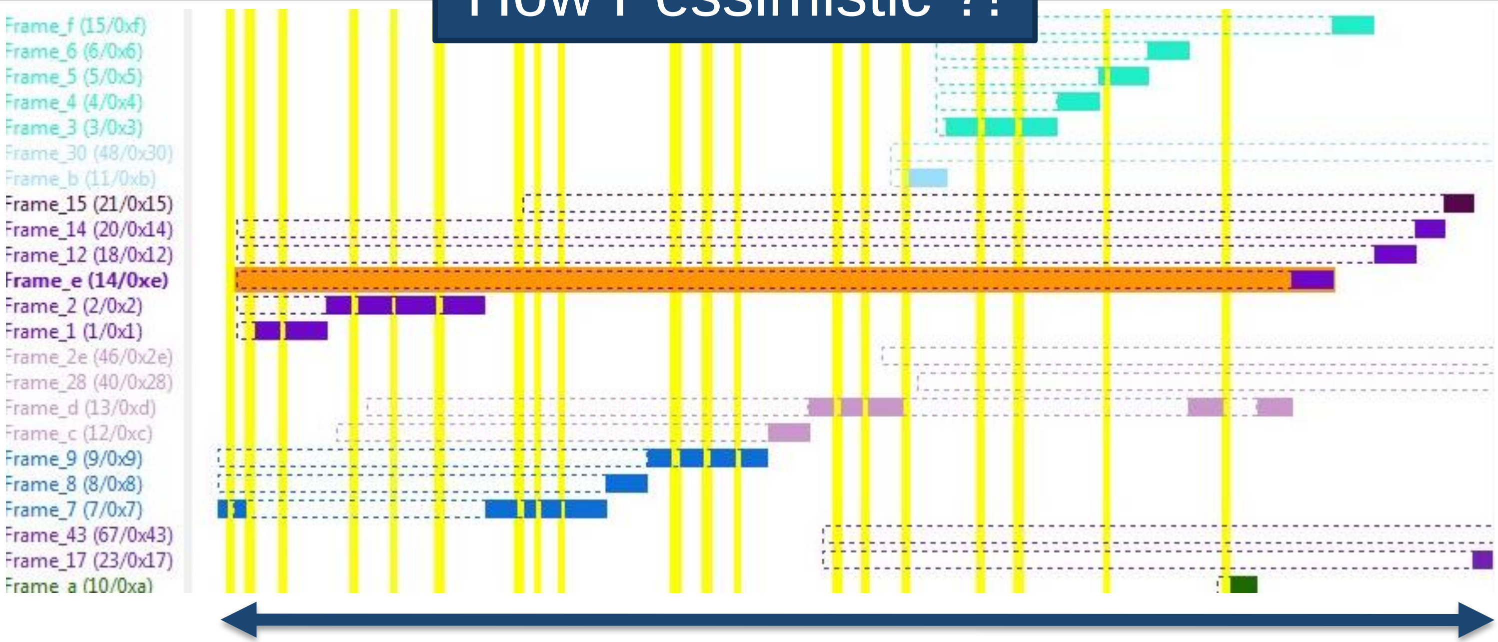
Case 2: perfect communication stacks + **gateway** → the computed upper-bounds do not occur for forwarded frames in the general case



Q1 : Pessimism of CAN schedulability analysis ?
Q2: distance with simulation ?

Case 3: non-ideal communication stacks
the computed upper-bounds do not occur
in the general case – analysis are in general very pessimistic !

How Pessimistic ?!



[RTaW-sim screenshot]

Up to the longest possible busy-period on the bus

≈ Worst-case response time of lowest priority frame in the ideal case

2

Analytic models are not realistic

(it the system has not been conceived with schedulability in mind)

Departure from ideal CAN: HW and SW

1 Non-HPF waiting queues [5,6]

2 Frame queuing not done in priority order by communication task

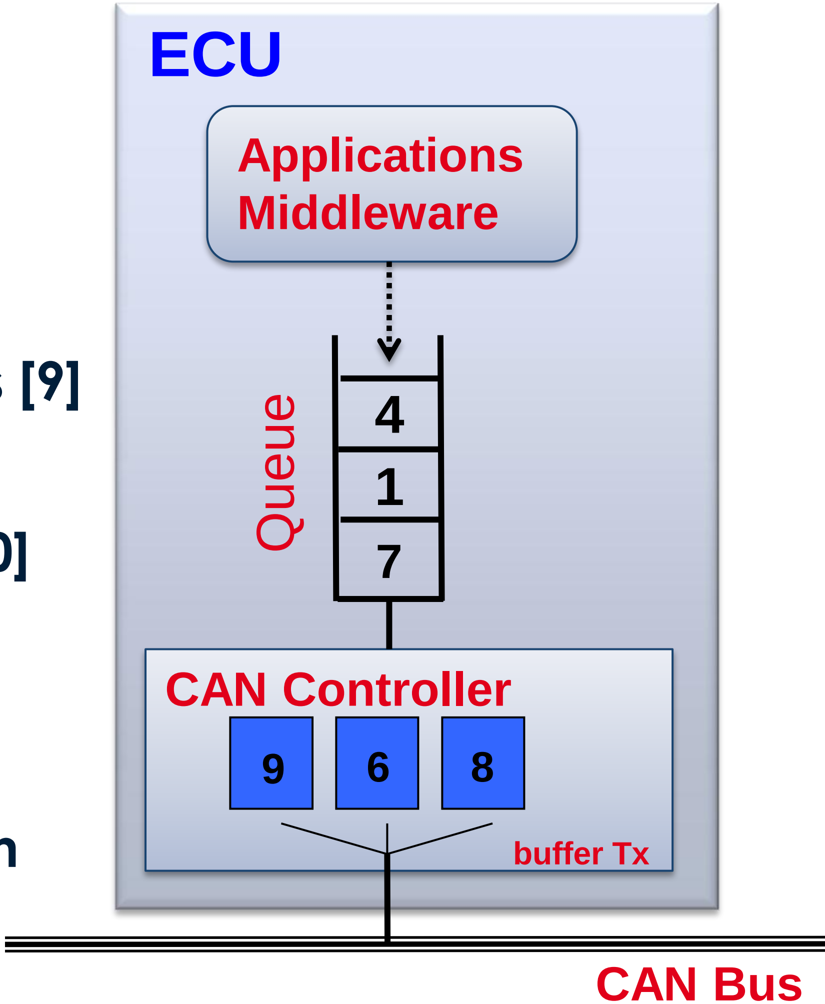
3 Non abortable transmission requests [9]

4 Not enough transmission buffers [8,10]

5 Delays in refilling the buffers [11]

6 Delay data production / transmission request

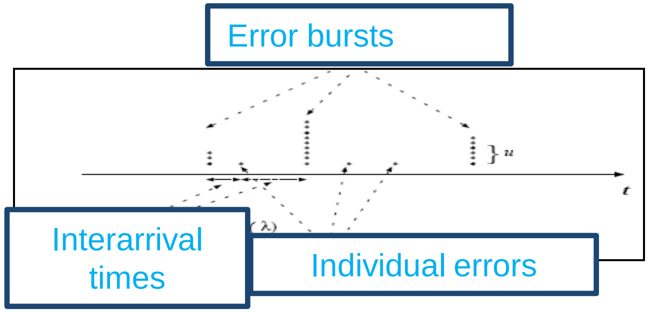
• • •



Departure from ideal CAN: frame transmission patterns

7 **code upload or segmented messages**

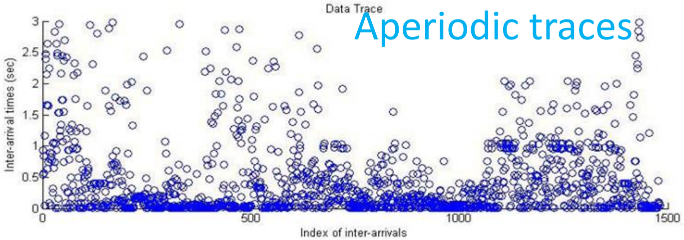
8 **Autosar-like mixed transmission models**



9 **Diagnostic requests**

10 **Transmission errors (probabilistic model ?! [1])**

11 **Aperiodic traffic (probabilistic model ?! [2])**

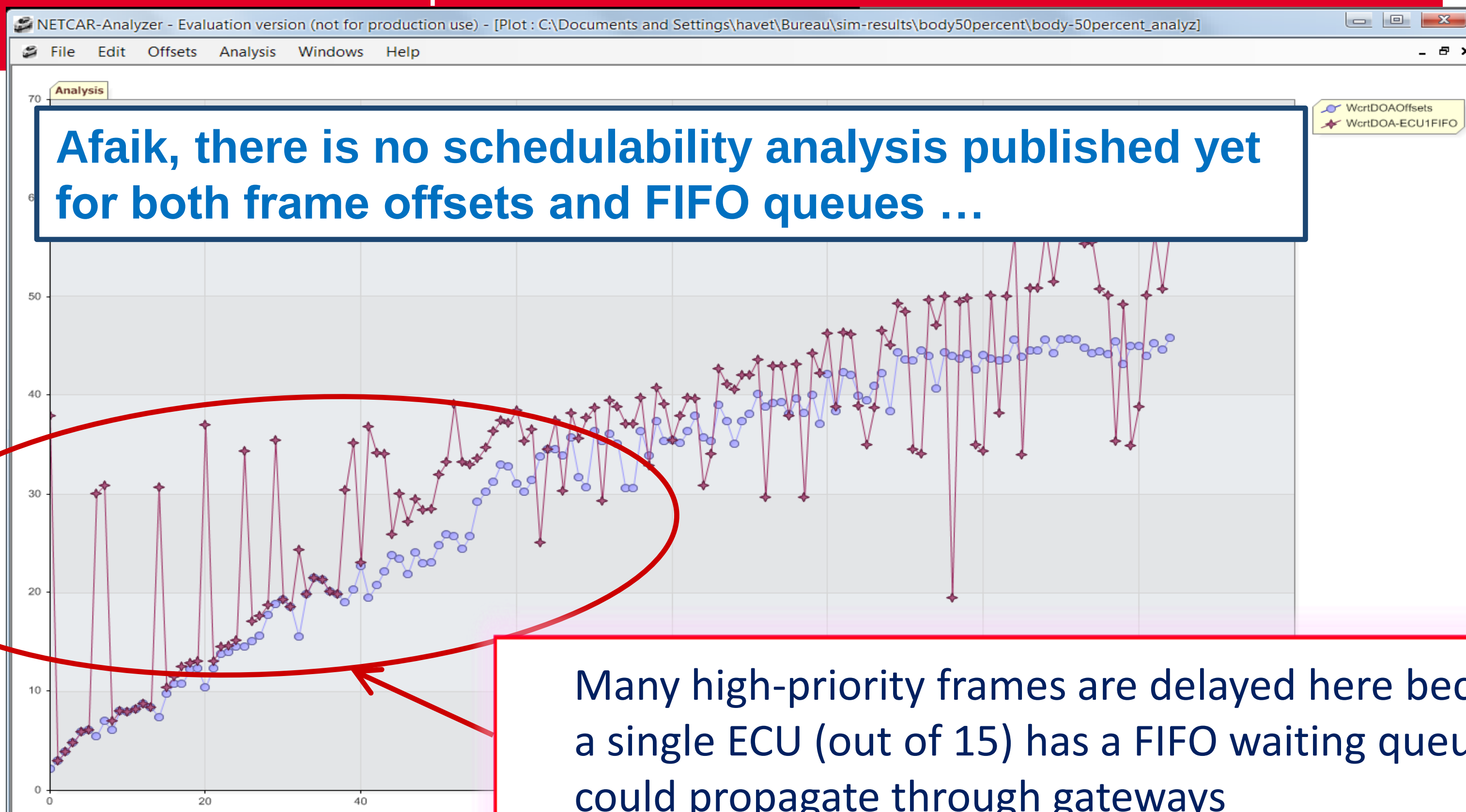


12 **Gatewayed traffic**

…

Higher load level calls for more realistic models

If the analytic model does not capture accurately all the characteristics of the system, then the results will be wrong … in an unpredictable manner



Afaik, there is no schedulability analysis published yet for both frame offsets and FIFO queues …

Many high-priority frames are delayed here because a single ECU (out of 15) has a FIFO waiting queue … could propagate through gateways

Response times

NETCAR-Analyzer screenshot

Frames by decreasing priority

About the suitability of schedulability analysis for non-ideal architectures..

- ✓ Good news: many works try to bridge the gap between analytic models and real systems [Ref.1 to 12]
- ✓ Bad news #1: not everything is covered, no integrated framework (first step in [6])
- ✓ Bad news #2: many existing analyses are conservative (= inaccurate), thus hardly usable for highly-loaded systems.
- ✓ Bad news #3: comprehensive and exact analysis would be overly complex (e.g. as in [9]) and intractable!

Personal view : both accurate and comprehensive analyses are out of reach … if you need analysis, you have to conceive the systems accordingly

3

And, schedulability analysis can be flawed …

What's different from other software (e.g. a simulator) ?

- ✓ Analysis are complex and error prone. remember "CAN analysis refuted, revisited, etc" [14] ?!
- ✓ Implementations are error prone: analyses complexity, floating-point arithmetic !, how to check correctness ?, not many end-users, cost-pressure, etc …
- ✓ Solutions ?
  - peer-review of the WCRT analyses is needed
  - coarse-grained / conservative but simple as far as possible: e.g., [5,6] vs [9]
  - no black-box software – documentation of implemented analyses and <u>underlying hypotheses</u>
  - rational arithmetic (w. float for Design Space Exploration)
  - cross-validation between tools / techniques on benchmarks

4

Simulation models validity can be questioned as well, after all …

Validating a network simulator ?

- ✓ Cross-validation by re-simulating worst-case situation from schedulability analysis (when possible)
- ✓ Cross-validation by comparison with real communication traces : e.g., comparing inter-arrival times distribution
- ✓ Checking a set of correctness properties on simulation traces

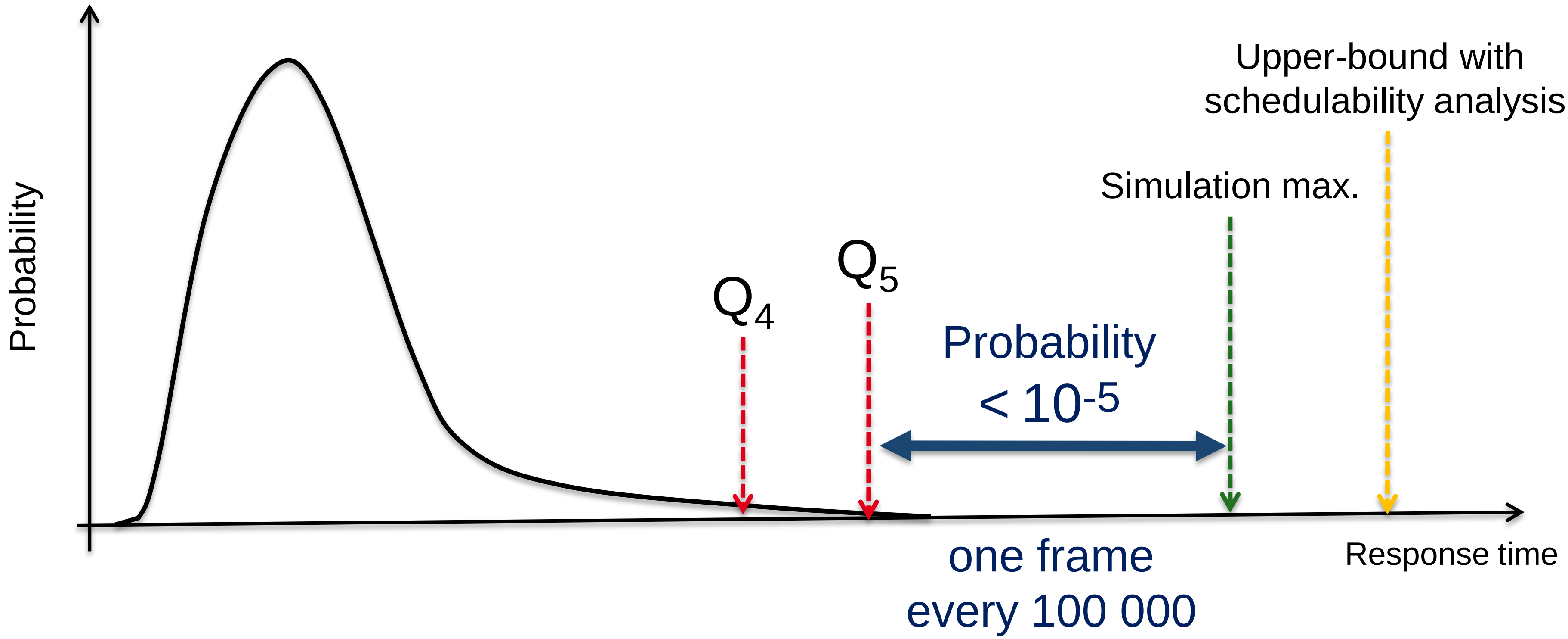
And model parameters must be realistic: transmission patterns, transmission errors, clock drifts, communication stacks, etc → analysis of communication traces is helpful here

5

Simulation can provide guarantees with proper methodology

Using quantiles means accepting a ***controlled*** risk

Quantile Q_n: $P[\text{ response time} > Q_n] < 10^{-n}$



✓ Convergence unlike max → reproducibility & controllability
✓ No extrapolation here, won't help to say anything about what is too rare to be in simulation traces

1) How often performance objectives can be violated ?

Quantile	One frame every …	Mean time to failure Frame period = 10ms	Mean time to failure Frame period = 500ms
Q3	1000	10 s	8mn 20s
Q4	10 000	1mn 40s	≈ 1h 23mn
Q5	100 000	≈ 17mn	≈ 13h 53mn
Q6	1000 000	≈ 2h 46mn	≈ 5d 19h
…	…	…	

Warning : successive failures in some cases might be temporally correlated, this must be ruled out …

2) Determine the minimum simulation length

- ✓ not obvious because non-Gaussian and possibly non i.i.d.
- ✓ time needed for quantile convergence
- ✓ reasonable # of values: a few tens …

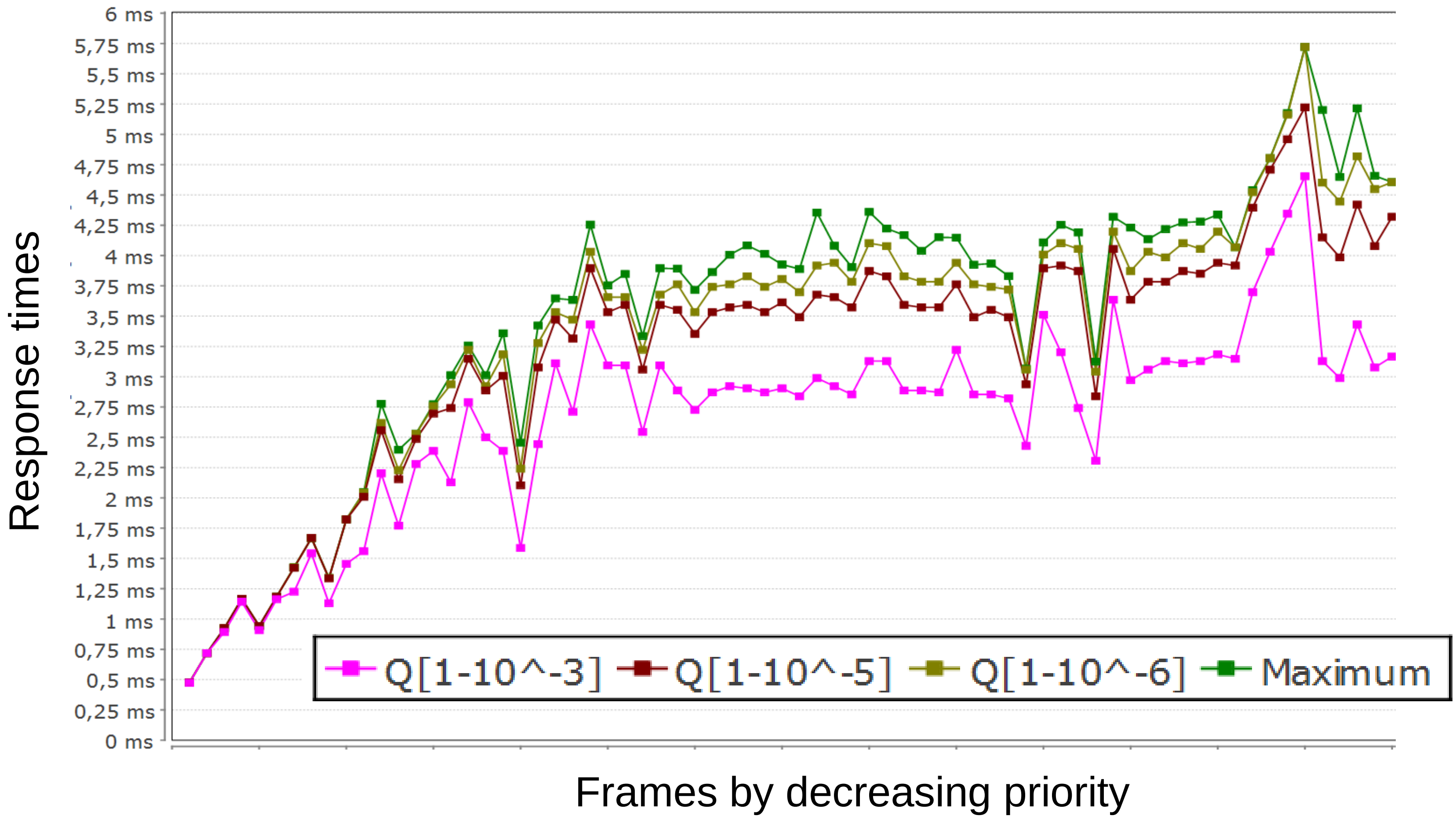
Tool support can help here: e.g. numbers in gray should not be trusted

Min	Average	Q2	Q3	Q4	Q5	Q6	Max	Bound
0,236 ms	0,272 ms	0,466 ms	0,474 ms	0,477 ms	0,477 ms	0,477 ms	[illegible]	0,550 ms
				[illegible]	0,719 ms	0,719 ms	[illegible]	0,830 ms
				[illegible]	0,925 ms	0,925 ms	[illegible]	1,074 ms
				[illegible]	1,167 ms	1,167 ms	[illegible]	1,354 ms
				[illegible]	0,943 ms	0,943 ms	[illegible]	1,092 ms
				[illegible]	1,185 ms	1,185 ms	[illegible]	1,372 ms
				[illegible]	1,414 ms	1,427 ms	[illegible]	1,652 ms
				[illegible]	1,669 ms	1,669 ms	[illegible]	1,932 ms
				[illegible]	1,328 ms	1,339 ms	[illegible]	1,564 ms
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	1,791 ms	1,811 ms	[illegible]	2,124 ms
0,218 ms	0,313 ms	1,061 ms	1,481 ms	1,750 ms	1,875 ms	2,009 ms	[illegible]	2,386 ms
0,522 ms	0,686 ms	1,490 ms	1,897 ms	2,116 ms	2,267 ms	2,388 ms	[illegible]	4,890 ms
0,450 ms	0,615 ms	1,398 ms	1,811 ms	2,104 ms	2,293 ms	2,402 ms	[illegible]	4,818 ms
0,720 ms	0,929 ms	1,832 ms	2,128 ms	2,280 ms	2,374 ms	2,486 ms	[illegible]	2,946 ms
					2,573 ms	2,710 ms	[illegible]	3,470 ms
					2,618 ms	2,710 ms	[illegible]	3,750 ms
					2,989 ms	3,166 ms	[illegible]	4,030 ms
					2,773 ms	2,854 ms	[illegible]	3,750 ms
					2,854 ms	2,989 ms	[illegible]	4,186 ms
					2,092 ms	2,153 ms	[illegible]	3,276 ms
					2,854 ms	2,971 ms	[illegible]	4,396 ms
					3,277 ms	3,373 ms	3,460 ms	4,640 ms
					3,076 ms	[illegible]	3,239 ms	4,640 ms
					3,698 ms	[illegible]	3,871 ms	8,946 ms
					3,412 ms	3,483 ms	3,483 ms	4,920 ms
					3,491 ms	3,864 ms	3,864 ms	4,920 ms
					3,129 ms	3,181 ms	3,181 ms	4,744 ms
					3,451 ms	3,548 ms	3,548 ms	4,920 ms
					3,392 ms	3,532 ms	3,532 ms	5,182 ms
					3,315 ms	3,336 ms	3,336 ms	5,094 ms
					3,431 ms	3,817 ms	3,817 ms	6,718 ms
					3,511 ms	3,733 ms	3,733 ms	6,772 ms
					3,471 ms	3,587 ms	3,587 ms	6,754 ms
0,182 ms	0,391 ms	2,068 ms	2,726 ms	3,148 ms	3,412 ms	3,578 ms	3,578 ms	6,718 ms
0,166 ms	0,383 ms	2,080 ms	2,805 ms	3,184 ms	3,416 ms		3,416 ms	6,982 ms

[RTaW-sim screenshot]

Reasonable values for Q5 and Q6 (with periods <500ms) are obtained in a few hours of simulation (with a high-speed simulation engine) – e.g. 2 hours for a typical automotive setup

Max, Q6, Q5, Q3 on our example…



[RTaW-sim screenshot]

Concluding remarks

1 There is gap between analytic models and real (non-ideal) systems

✓ pessimistic at best, unsafe if assumptions not met
✓ no dramatic improvements in sight
✓"analyzability" should be a design constraint if needed

2 Simulation is a practical alternative even for critical systems .. some precautions needed

✓ Determine quantile wrt criticality, and simulation length wrt to quantile
✓ Simulator and models validation
✓ High-performance simulation engine needed for higher quantiles

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