Workflow of topology simulation in automotive communication focused on frequency dependent cable modelling procedures.

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ABSTRACT
The transmission of automotive communication-signals in mass production is based mainly on electrical cables used in topologies which do not meet technical schoolbook requirements perfectly. For evaluating their signal quality and their communication robustness time-domain based simulation tools are essential. One of the key elements hereby is an adjustable cable model. Unfortunately real cables show frequency-dependent behaviours which are not covered by time-domain simulation tools usually. The paper points out some summarizing results of various projects which enable a workflow beginning with (noisy) cable measurements going via approximation procedures up to frequency and time domain qualified models.
Keywords: twisted-pair cable, cable parameter

1. INTRODUCTION

Modern cars use various communication systems in parallel; each of them shall be implemented functional robust and cost-efficient. During the early development phase several architecture and topology variants compete against each other. Supporting usage of simulation tools is essential: e.g. for getting the system costs, the overall weight or the signal quality. The paper is focused on two aspects:

- Behaviour and modelling of cables as one of the key elements influencing the communication properties.
- Work-flow to integrate cable-properties into the simulation.

The succeeding example shows a topology consisting of five CAN-nodes communicating among each other.

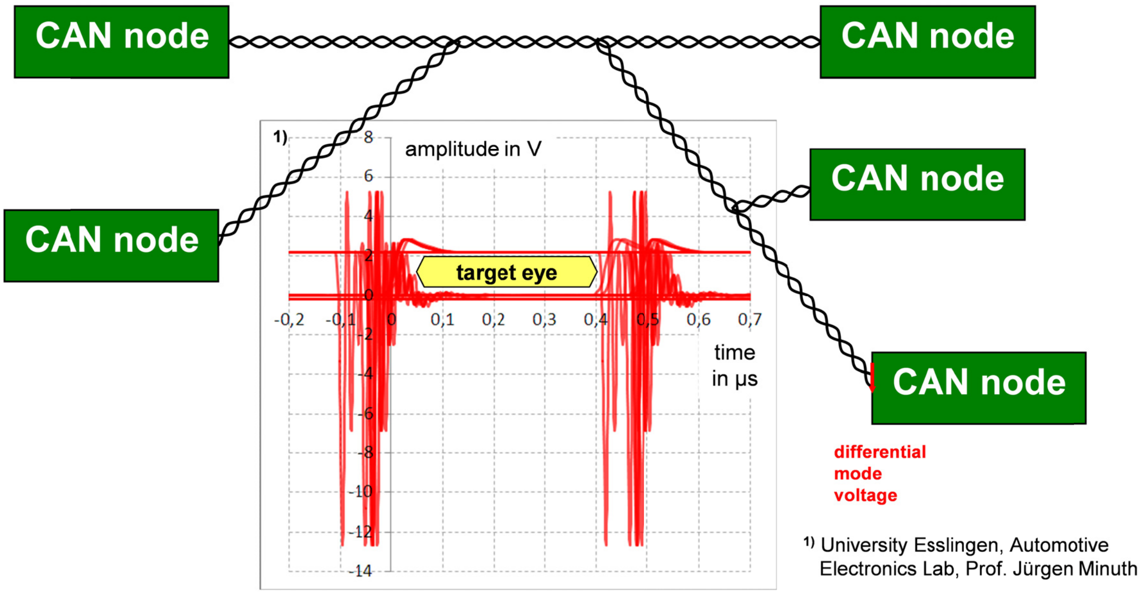


Figure 1: Topology simulation with five CAN nodes at 2 Mbit/sec[1], the simulation results are superposed to an eye chart.

For topology evaluation several properties of the signals are determined and voted against limits:

- Eye chart got by the superposition of all bits of a selected data stream.
- Rising and falling edge timings like propagation delay and slew-rate.
- Duration of ringing.
- etc.

A proper simulation requires the availability of models like transceivers (CAN) or bus-drivers (FlexRay™), common mode coils, ESD protection elements, ferrite beads, termination circuits and last but not least cables:

- A single cable-model shall guarantee a practically perfect matching between measurement and time-domain simulation from <<10 kbit/sec up to >10 Mbit/sec at least.

[1] supported by "CAN flexible data rate"

- The propagation delay of edges shall be covered.
- The damping shall be covered (steady state and edges' slew-rate).
- Reflections and ringing shall be shown.

The standard cable-model available in most SPICE-compliant tools offers constant losses (constant for all frequencies). Therefor two main behaviours are covered (simulation and measurement fit):

- Edges' propagation delay.
- The steady state level of "long bits".

Further essential properties are not covered, in other words simulation does not fit with measurement:

- Ringing amplitudes and ringing duration.
- Slew rate modifications (when a pulse travels along a cable).

The required new extended cable-model has to meet several requirements, so that simulation and measurement match practically perfect from engineer's point of view.

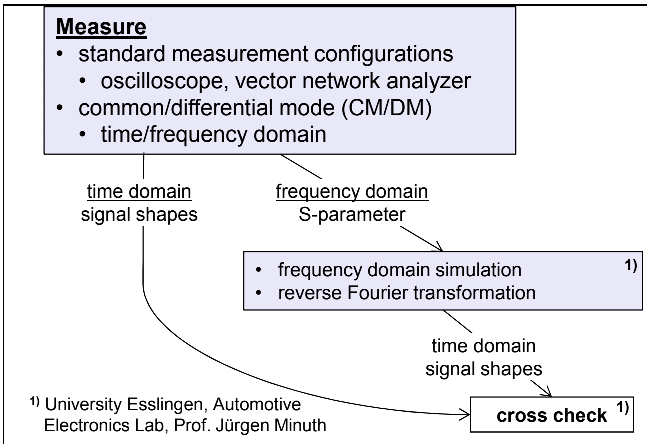
- Common mode and differential mode (because twisted pair cables are used).
- Impedances and delays.
- Frequency dependent losses (which influence slew-rate, damping etc.).

The development of the workflow to get satisfying cable-models was done in two main approaches: a 1st pragmatic approach (less successful) where measured S-parameter were directly used for time domain simulation and a 2nd more successful approach: a generic physical cable-model is parameterized according measurements; a succeeding mathematical approximation enables a time domain simulation.

2. MODELLING OF CABLES

2.1 Measurement and Simulation Results (1st Approach)

When thinking about how to enable frequency dependant behaviour to simulation the obvious answer is: "Measure the S-parameter and use them as simulation input": a vector network analyser with a four-terminal-pair S-parameter measure set-up was used for getting common mode and differential mode S-parameter.



1st measurement		1600 logarithmic steps	from 9 kHz up to 500 MHz	A
2nd measurement		1600 linear steps	from 9 kHz up to 200 MHz	B
	∑	3200 steps	from 9 kHz up to 500 MHz	C

Figure 2: Workflow overview 1st approach "measurement → simulation".

A simulation was done for getting the signal shapes for a single 100 ns bit in a 50 Ω environment. The succeeding figure shows the differential mode results only:

- Measurement and simulation seem to fit perfect in all three cases A, B and C.
- Unmotivated ringing appears.

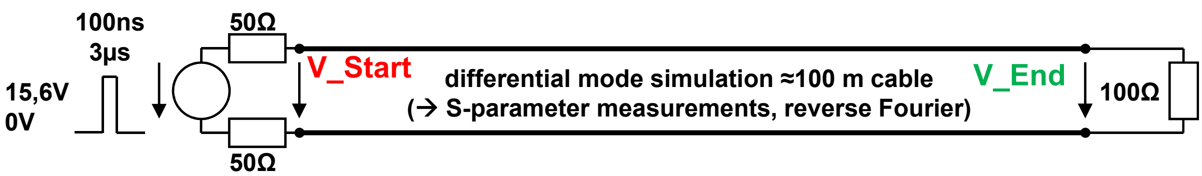


Figure 3: Measurement and simulation set-up (100 ns and 3 µs bit).

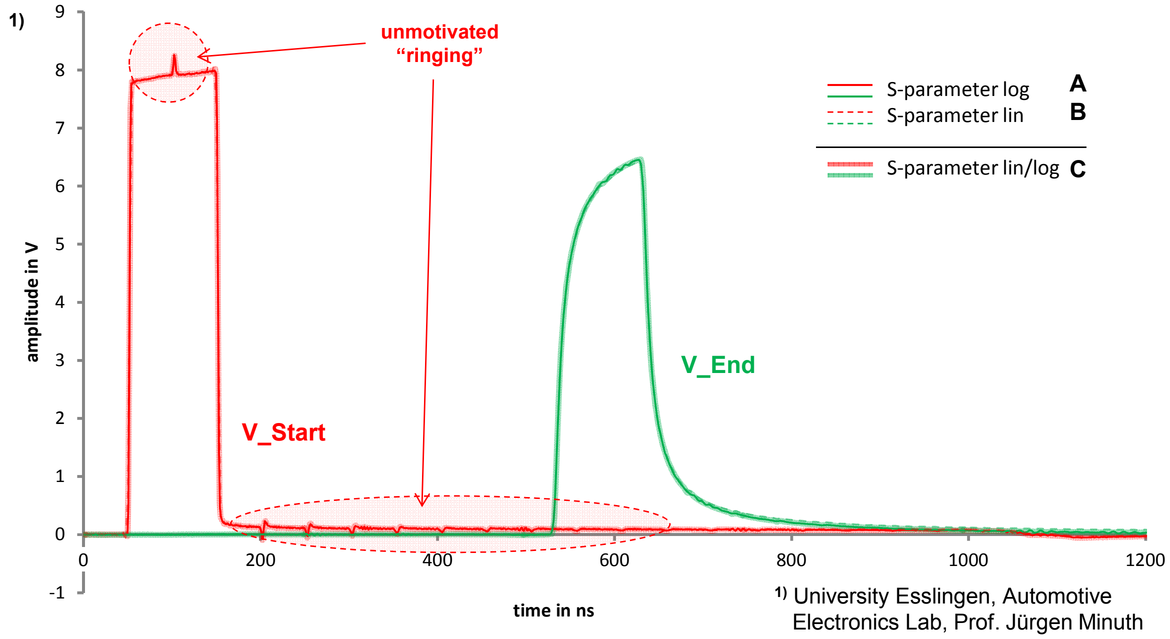


Figure 4: Using S-parameter measurement results in simulation (100 ns bit).

The next example checks the behaviour when applying a "long" 3 µs bit. All three cases are far away from acceptable results:

- Unmotivated ringing appears.
- Completely faulty signal shapes appear (→ linear measure).
- The steady state symmetry enforced by the set-up is not available.

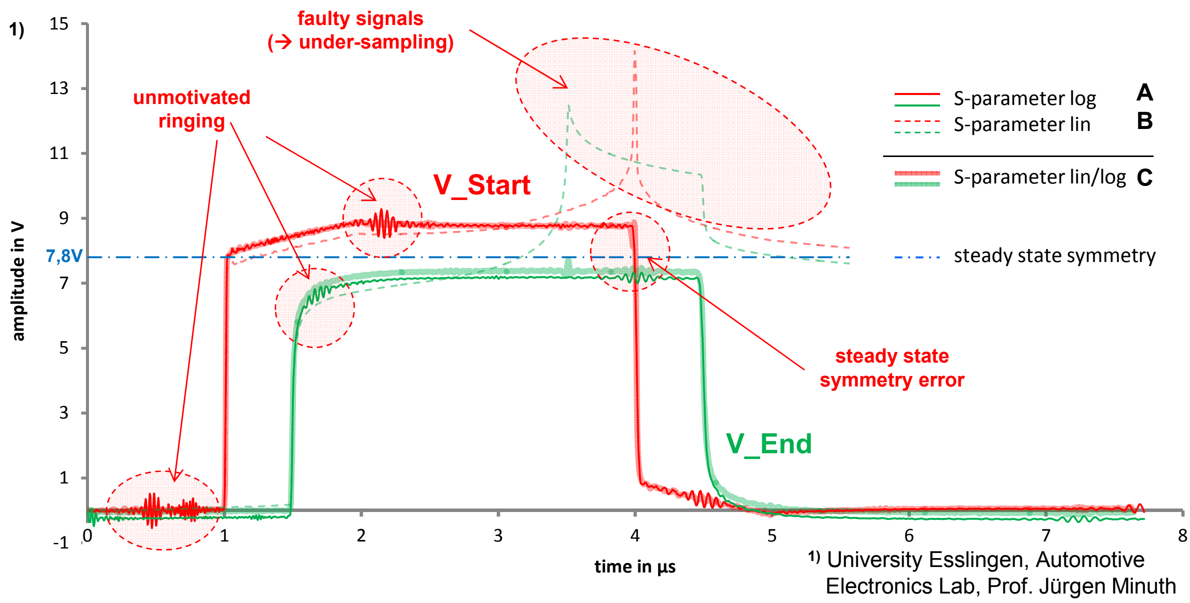


Figure 5: Using S-parameter measurement results in simulation (3 µs bit).

The reasons for this deviation are known, their elimination is difficult or impossible:

- Parasitic components generated by the set-up itself.
- Poor measurement accuracy especially at low frequencies (phase and attenuation).
- Under-sampling at low frequencies in the linear case.

2.2 Measurement and Simulation Results (2nd Approach)

The deviation between simulation and measured signal shapes in the 1st approach is not acceptable[2]. A modified 2nd approach separated into an approximation phase and a simulation phase is necessary:

– Approximation phase
  1: Measure signal shapes in time domain and S-parameter in frequency domain.
  2: Parameterize a generic physical cable-model[3] for best matching (simulation ⇔ measurement).
  3: Approximate[4] the output of the generic model with broken rational functions for several cable lengths.
– Simulation phase:
  A dedicated cable-model[5] uses the rational functions for user's simulation of network architectures or topologies in time domain.

The succeeding figure illustrates the complete work-flow (including the cross-check procedures during the development process).

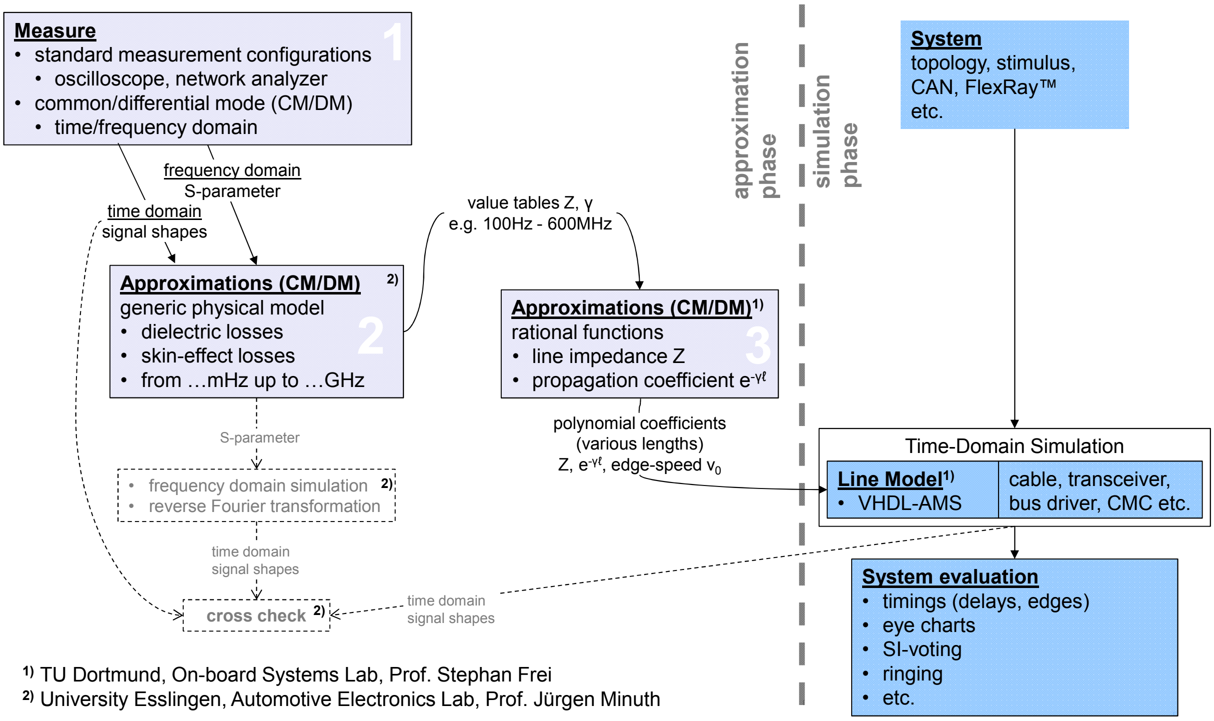


Figure 6: Workflow overview 2nd approach "measurement → approximation → simulation".

When applying the generic physical model to the example according figure 3 practically perfect results are generated (black lines in the succeeding figure):

– The unmotivated ringing is eliminated.
– The symmetry error is eliminated.
– Self-inductive effect due to cable's inner inductivity appears.
– Simulation and measurement fits practically perfect (not shown in the figure).

[2] Phase and attenuation error especially at low frequencies, parasitics which cannot be eliminated by recalibration.
[3] The model allows adjusting the properties of real cables like DC-resistor, capacitive and inductive loads per unit length, frequency dependant skin-effect and last but not least frequency dependant dielectric losses (designed by Prof. Jürgen Minuth, University of Esslingen, Automotive Electronics Lab).
[4] designed by TU Dortmund, On-board Systems Lab, Prof. Stephan Frei
[5] designed by TU Dortmund, On-board Systems Lab, Prof. Stephan Frei

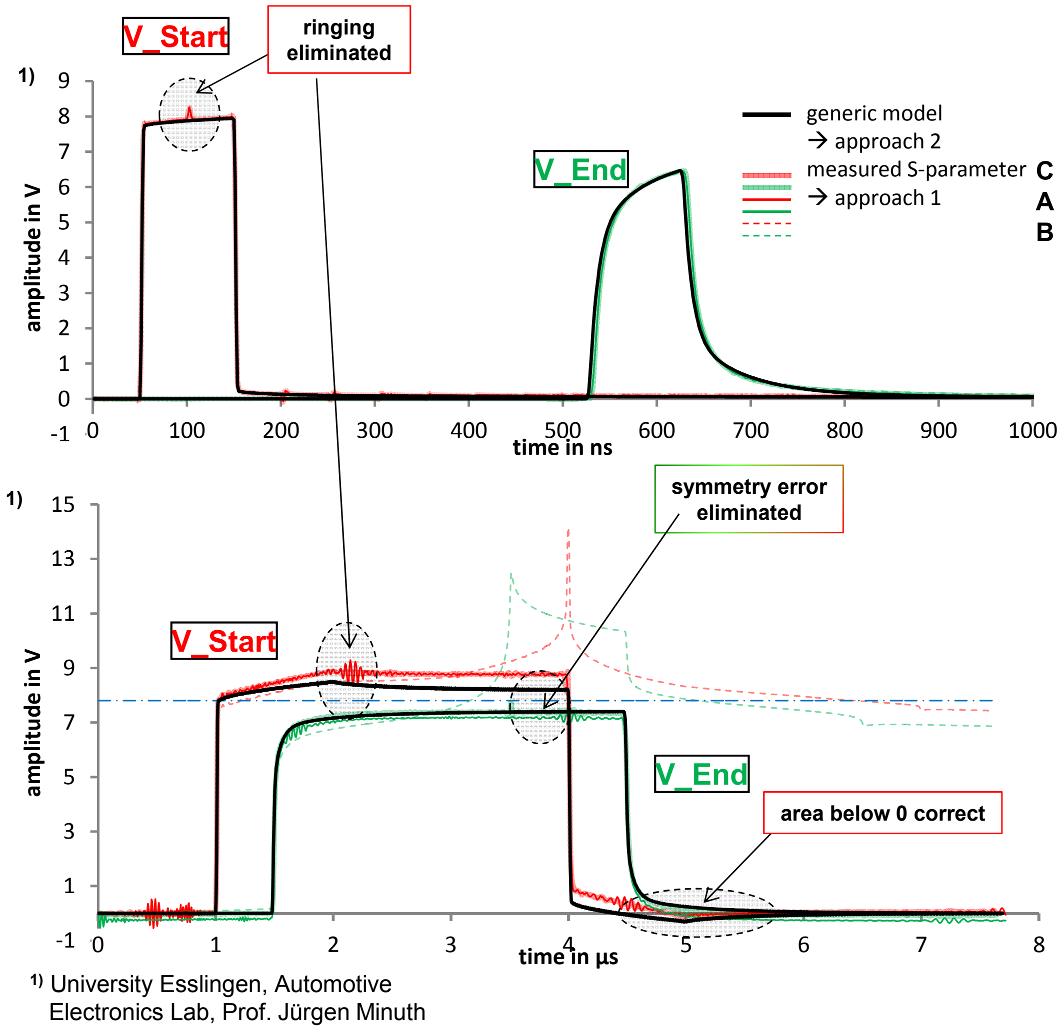


Figure 7: Using S-parameter measurements and approximation results (generic model) in simulation (100 ns and 3 µs bit).

2.2.1 Details to the Approximation Phase Step 3

The generic physical model is able to generate data available from DC up to several GHz. Knowing the simulation sceneries allows to limit the frequency area which shall be covered by the approximation step 3 to e.g. a few Hz up to a few 100 MHz. The approximation tool[6] fits rational functions best:

- INPUT
  - cable impedance Z as value table
  - propagation coefficient γ as value table
  - required lengths ℓ
- OUTPUT
  - polynomial coefficients a_k; b_k for the cable impedance $$Z(\omega)=\frac{\sum_{k=0}^{N} a_k (j\omega)^k}{\sum_{k=0}^{N} b_k (j\omega)^k}$$
  - edge-speed v_0
  - polynomial coefficients c_k; d_k for the propagation coefficient $$e^{-\gamma(\omega)\cdot\ell}=\frac{\sum_{k=0}^{M} c_k (j\omega)^k}{\sum_{k=0}^{M} d_k (j\omega)^k}\cdot e^{-j\frac{\omega}{v_0}\cdot\ell}$$
  - Hints
    The coefficients a_k, b_k, c_k and d_k are real numbers, the polynomial orders M and N are typically between 8 and 12.
    Cable lengths ℓ can be chosen (length from a few centimetres up to some 10 meters are typical).

[6] designed by TU Dortmund, On-board Systems Lab, Prof. Stephan Frei

The succeeding example visualizes the approximation quality using a typical automotive twisted pair cable:

- CABLE
  - uncoated twisted pair
  - specified differential mode cable impedance app. 98 Ω
  - generic physical model available from 0 Hz up to 2 GHz
- INPUT
  - cable impedance Z as value table from 100 Hz up to 600 MHz
  - propagation coefficient γ as value table from 100 Hz up to 600 MHz
  - length of the cable 10 m
- OUTPUT (differential mode only here)
  - polynomial coefficients for the cable impedance (order 11)
  - polynomial coefficients for the propagation coefficient $e^{-\gamma\ell}$ (order 11)
  - edge-speed v_0 (20 $^{cm}/_{ns}$)

Inside the approximation area the matching between generic physical model and the rational functions is practically perfect (see succeeding figures: lines ⇔ dotted lines). From automotive communication point of view the model covers the area from DC up to the speed of FlexRay™ (10 Mbit/sec) perfectly. The deviation of the cable impedance for low frequency does not influence the results if using cable lengths available in passenger cars or trucks.

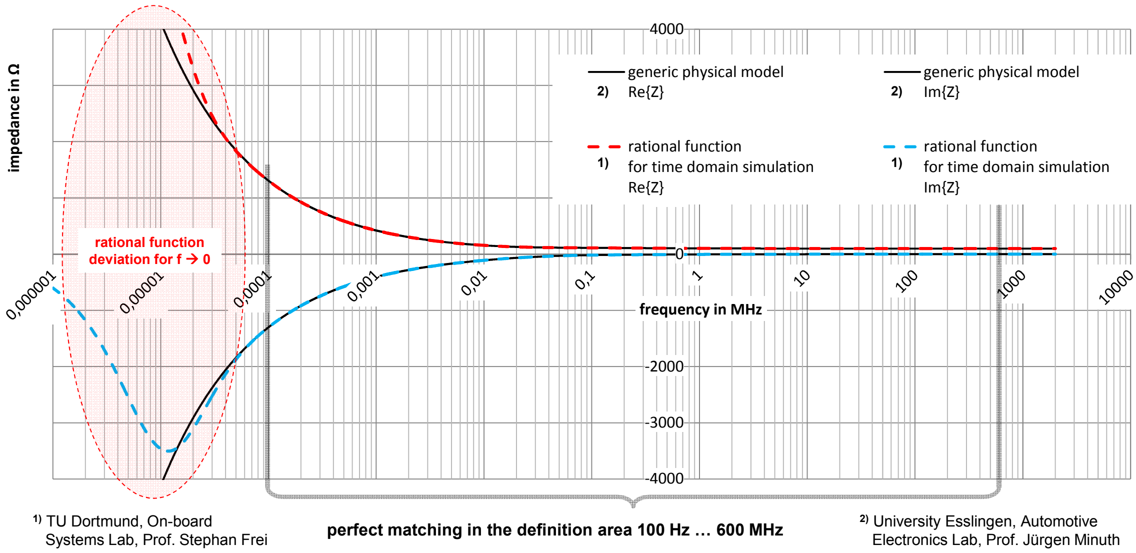


Figure 8: Matching cable impedance Z "generic model" ⇔ "rational function model".

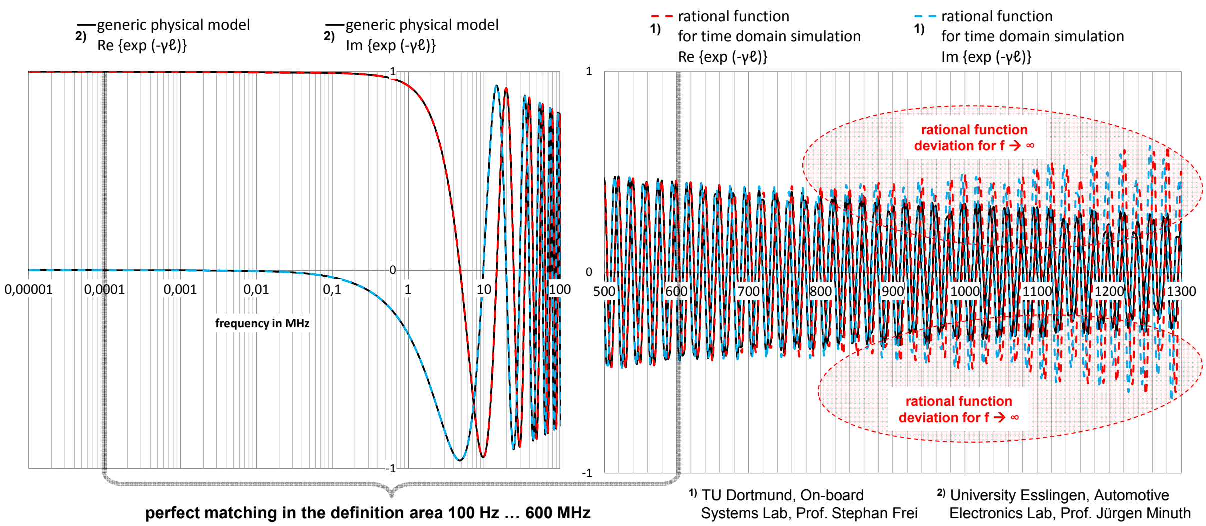


Figure 9: Matching propagation coefficient $e^{-\gamma\ell}$ "generic model" ⇔ "rational function model".
length ℓ = 10 m; edge speed v_0 = 20 $^{cm}/_{ns}$

2.3 Simulation in time domain

The On-board Systems Lab team[7] designed a cable-model (rational function approach) in VHDL-AMS enabling time domain simulation. The matching between measurement and simulation is practically perfect from low-speed CAN via CAN-FD up to FlexRay™. Topology simulations generate results which meet the accuracy requirements to support system evaluations. Post processes are available e.g. for generating eye charts, measuring slew-rates or ringing durations.

2.4 Application Example

Often topologies generate ringing when switching bus-interfaces from a driven state to a high-ohmic state. In case of CAN this corresponds to the change from any dominant bit to any recessive bit; in case of FlexRay™ this corresponds to the change of the EOF-bit to the idle state at the end of each frame. For evaluating the sampling properties it is essential knowing the ringing duration. The succeeding figure illustrates the ringing effect of four different cables in the use-case of a passive star with five nodes.

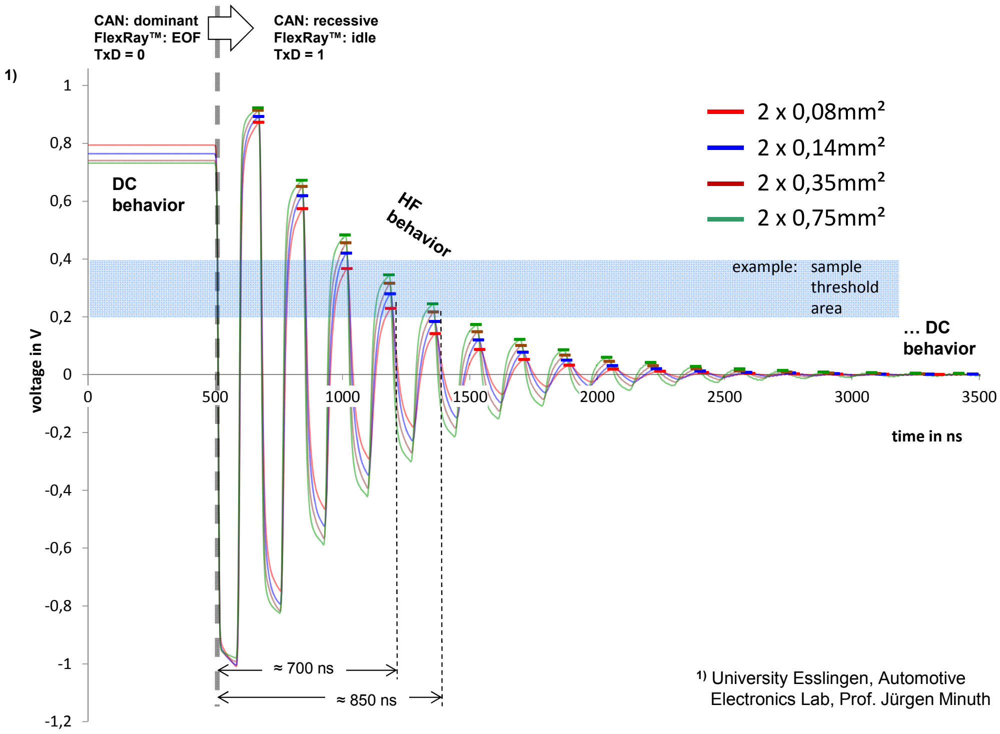


Figure 10: Effect of frequency dependant losses: ringing in CAN and FlexRay™.

The time constant of ringing's envelop curve is linked strongly with the type of cable, in other words: with their frequency dependant losses. The complete area from DC op to "high frequencies" with reflections is covered. The question of a system designer: "How is the earliest possible sample-point influenced by the cable type?" can be answered. Assuming the blue area shows the threshold variations, we get: "case red/blue: ≈ 700 ns" and "green/brown: ≈ 850 ns". The example would support a CAN application up to a few 100 kBit/sec.

3. CONCLUSION

The presented workflow offers a straight forward approach for of a time-domain simulation of topologies; the cable-models are parameterized based on measurement results. The simulation covers the DC-area up to the speed of FlexRay™ signals; however the new models can be parameterized for being used with much higher baud-rates. The matching between measurement and simulation meets engineer's accuracy requirements. The achievable simulation speed is high enough to do topology simulations with e.g. 32 nodes where each node may transmit round robin messages.

ABBREVIATIONS

CM	common mode
CMC	common mode coil
DM	differential mode
EOF	end of frame bit, followed by a high ohmic phase on the cables
ESD	electro static discharge
SI-voting	a procedure defined in FlexRay™ for estimating the signal quality

[7] TU Dortmund University, Prof. Stephan Frei