Sensitivity analysis of passive CAN bus components to investigate signal integrity of CAN network physical layer

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ABSTRACT

This paper shows the application of sensitivity analysis to identify the most important network parameters impacting overshoot, undershoot and ringing of signals in CAN networks. Checking all worst case combinations of n network parameters would require 2^n simulations or measurements which is not feasible for realistic CAN networks. Using results from sensitivity analysis, not only the number of simulations or measurements can be reduced thus saving time and cost, but also the ringing in CAN networks can be minimized to improve signal integrity. Simulation results have been validated using measurements and there is good agreement between simulation and measurement.

Keywords
Sensitivity analysis, CAN physical layer, choke coil, signal integrity

1. INTRODUCTION

Signal integrity problems at the CAN physical layer due to ringing, overshoot, and undershoot have been observed as a phenomenon during the design process of CAN automotive application. Choke coils, split termination circuits and twisted transmission line are among the many solutions to suppress ringing at the CAN physical layer [1-3]. Unfortunately, these components are characterized by their suppliers for general application. Consequently, without a proper simulation method, it is extremely difficult, if not impossible, to determine which parameters have the highest influences on signal integrity.

Two approaches to determine the influence of parameters are measurements and simulation runs. However, checking all worst case combinations of i parameters would require 2^i experiments. Thus, a design of experiments is required that directly reduces this number of experiments on the one hand. On the other hand, the effort can be reduced by investigating only the influence of critical parameters. A lot of work has been done in this field. Nevertheless, the methods are in general not widely applied and often have to be adapted to special application scenarios.

This paper presents the application of parameter sensitivity analysis for CAN automotive application design. By applying this method, one out of sixty five network parameters, with high impact on ringing on CAN physical layer has been isolated. Simulation results were verified by measurements and confirmed by the supplier. The measurements were guided by a verification plan based on sensitivity analysis results.

2. PARAMETER RELATIVE SENSITIVITY ANALYSIS METHODOLOGY

2.1 Basics of parameter relative sensitivity

Sensitivity Analysis (SA) is a technique used to determine the relative sensitivity of output signals against system parameters [6]. If a small change in a system parameter—e.g. due to component tolerances—results in relatively large changes of the output signals, the signals are said to be sensitive to that parameter. Sensitive parameters need to be controlled very precisely leading to higher system cost or design alternatives have to be found. If the parameter tolerance is ε , then parameter relative sensitivity σ is defined as follows:

$$\sigma = \left| \frac{\dfrac{\Theta_t([p_i]_t) - \Theta_n([p_i]_n)}{\Theta_n([p_i]_n)}}{\dfrac{[p_i]_t - [p_i]_n}{[p_i]_n}} \right| = \left| \frac{\dfrac{\Theta_t((1+\varepsilon)\cdot[p_i]_n) - \Theta_n([p_i]_n)}{\Theta_n([p_i]_n)}}{\dfrac{(1+\varepsilon)\cdot[p_i]_n - [p_i]_n}{[p_i]_n}} \right| \tag{1}$$

with $p_t = (1+\varepsilon)\cdot p_n$

where $[p_i]$ is a set of parameters

$[p_i]_n, [p_i]_t$: nominal value and tolerance value of analyzed parameter respectively.

Θ_n, Θ_t : System output of nominal parameter and tolerance parameter.

Output properties monitored can be overshoot, undershoot, min, max, RMS, etc.

Simplifying (1) leads to:

$$\sigma\left(\left[p_i\right]_n,\varepsilon\right)=\left|\frac{1}{\Theta_n\left(\left[p_i\right]_n\right)}\cdot\frac{\Theta_t\left(\left(1+\varepsilon\right)\cdot\left[p_i\right]_n\right)-\Theta_n\left(\left[p_i\right]_n\right)}{\varepsilon}\right| \quad (2)$$

It can be seen from (2) that the parameter sensitivity analysis of a design/system with *i* design parameter will require *i+1* simulation runs. The first simulation run is the simulation of the system/design when all of the design parameters values are at nominal values. Then each of the parameter in the set $\left[p_i\right]$ is simulated with its tolerance value while the rest of parameter is left at their nominal values. Applying sensitivity analysis for design with *i* parameters only requires *i+1* simulation instead of 2^i simulations if all worst case combinations are simulated. The efficiency of the sensitivity analysis becomes obvious when the number of design parameter *i* increases. In this paper 65 design parameters are evaluated which would lead to 2^{65} = 3.7x10^{19} simulations/experiments.

After each simulation, the results are stored so that the parameter relative sensitivity σ can be calculated as shown in equation (2). In order to visualize the parameter relative sensitivity σ, a parameter relative sensitivity bar indicator is constructed. The bar indicator is a plot of the parameter relative sensitivity σ against all the parameter listed in $\left[p_i\right]$ so that the influences of each parameter on each output property can be displayed. This bar indicator will be explained more in details in section 3.1.

2.2 A general approach of parameter relative sensitivity methodology

Based on of sensitivity analysis, we developed a general approach for the Parameter Relative Sensitivity Analysis. The workflow is shown in Figure 1. Corresponding to the design characteristics, the analysis objectives (mentioned in section 2.1) have to be determined first. These analysis objectives are influenced by a set of design parameters $\left[p_i\right]$ (component parameters or system parameters), which are selected by screening design parameters which have direct impact on the analysis objectives. After the set of relevant design parameters $\left[p_i\right]$ with the parameter tolerances is determined, sensitivity analysis simulation runs are performed and stored so that simulation results can be visualized by the parameter sensitivity bar indicator. The bar indicator plot provides information about the impact of parameters. Parameter sweep simulations are applied to the parameters which are found to be sensitive.

The sweep simulation results of each parameter are plotted against the system outputs. By this way, the minimum/maximum can be found. This is the so called parameter design optimization process. The methodology will be further described in the next section based on our particular CAN application.

2.3 Parameter relative sensitivity analysis of passive CAN-Bus components: Methodology and simulation test bench description.

In [7], a CAN network consisting of two nodes with split termination on both transmitter and receiver side has been investigated. The transmitter and receiver communicate via an 8 meter CAN bus—twisted pair transmission line—at a speed of 500 Kbit/second. It has been shown that there is only a small deviation between measurement and simulation demonstrating that the simulation model is accurate.

It can be seen from measurements and simulations that choke coils and termination circuits have a big impact on ringing. When the bus operates from dominant to recessive, the transmitters show more pronounced ringing at transceiver than at the receiver side, as depicted in Figure 2.

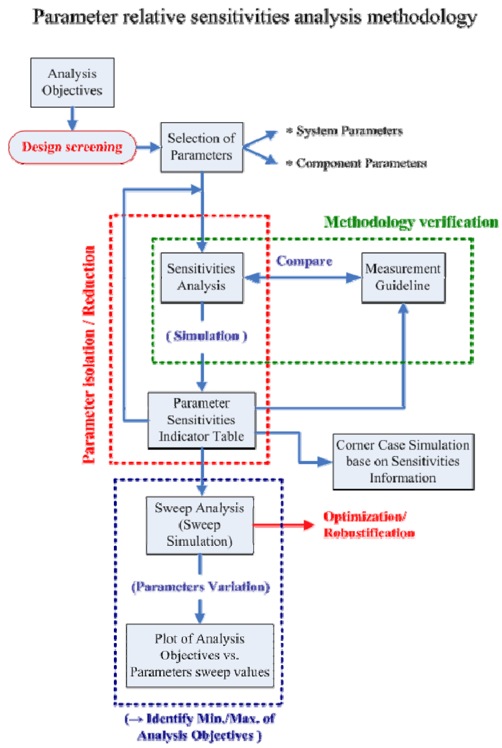

Figure 1: Parameter relative sensitivities analysis methodology

The models used in [7] is very accurate, the sensitivity simulations are therefore based on this model. Sensitivity analysis has been carried out for the overshoot of Lo1 signal (signal at CAN_Lo pin of CAN transmitter), the undershoot of Hi1 signal (signal at CAN_Hi pin of CAN transmitter) and the ringing of these two signals. In this paper, we focus on the passive components of the CAN bus which are choke coils, termination circuits and the transmission line. These components are characterized by the suppliers with different design parameters, which results in a total of 65 parameters with 2% component tolerances.

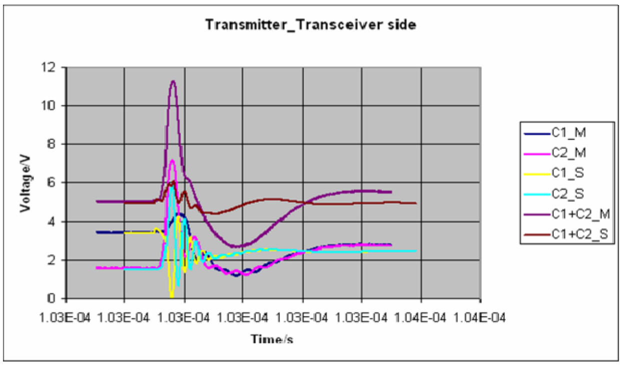

Figure 2: Ringing at transmitter-transceiver side in both measurement and simulation

All of components of the CAN physical layer were modeled with VHDL-AMS. Note that the core model behavior is modeled very closed to the physical structure of the device to guarantee a matching between simulation and real measurement. The details of the model behavior are confidential so that it is not possible to describe them here. The system is simulated in System Vision simulation environment. System Vision is a virtual lab for creating and analyzing analog, digital, and mixed-signal system. Schematics/Designs can be created via schematic entry. System Vision provides a variety of simulation types from basic such as transient (time domain) or AC (small signal) analysis to advance such as Monte Carlo, parameters sensitivity analysis.
The results from simulation were then verified by measurements, guided by sensitivity analysis results in order to reduce the measurement effort.

3. RESULTS AND DISCUSSION

3.1 Sensitivity analysis simulation results

In Figure 3, the signals Hi1 and Lo1 (at transceiver side of the transmitter) of 66 sensitivity simulation results are plotted. In run number 6 undershoot and ringing on Hi1_6 and Lo1_6 are clearly reduced compared to other simulation runs.

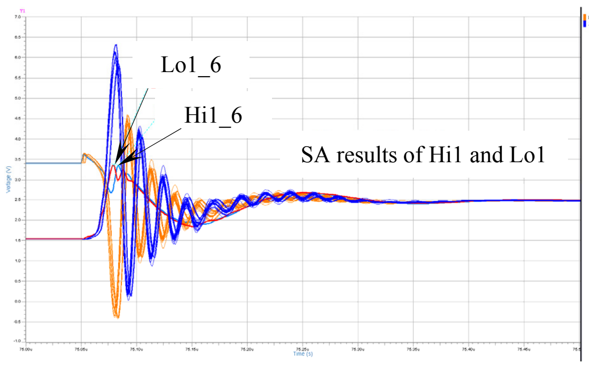

Figure 3: Results of 66 sensitivity simulation runs

Run number 6 simulates the choke coil at the transmitter side modifying *k1a1* (the *k1a1* parameter will be explained in section III.*B*). The nominal value of k1a1 is 0.974; with 2% increase of this parameter to 0.993 the system behavior changes significantly as shown in the Figure 3. In another words, the parameter k1a1 is very sensitive compared to the other 64 parameters. The parameter bar indicator, which is shown in Figure 4, shows the influence of these analyzed parameters against the analysis objectives.

To construct the sensitivity bar indicator the nominal and tolerance values (e.g., in Figure 5 the values 3.6504 and 0.8851) are inserted into equation (2) and the $\sigma -$ values are plotted. The calculation is as follows:

$$\begin{aligned} &\varepsilon = 2\% \; ; \; [p_5]_n = ychoke1, k1a1\_\text{nominal} = 0.974 \\ &\Rightarrow \; [p_5]_t = (1+\varepsilon)\cdot[p_5]_n = ychoke1, k1a1\_tolerance \\ &\qquad = (1+0.02)\cdot 0.974 = 0.993 \end{aligned} \quad (3)$$

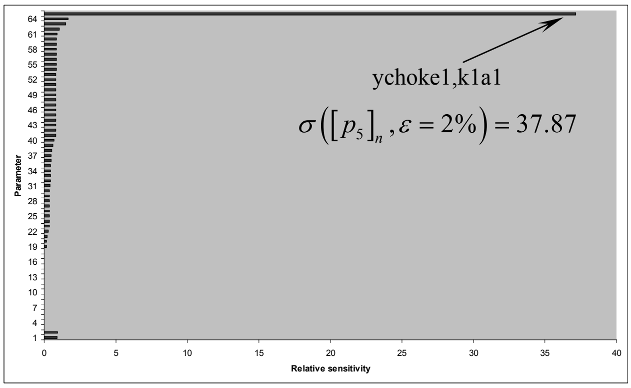

Figure 4: Parameter relative sensitivities bar indicator plot against overshoot of Lo1 signal

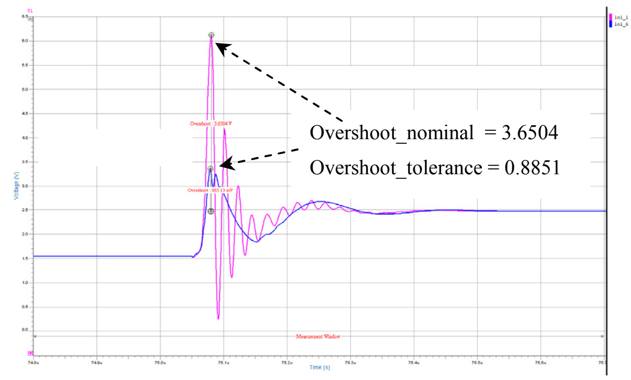

Figure 5: Analysis objective Lo1_Overshoot of the sensitivities simulation results

Inserting (3) into (2) we get:

$$\sigma\left([p_i]_n, \varepsilon\right) = \left(\frac{1}{\Theta_n\left([p_i]_n\right)} \cdot \frac{\Theta_t\left((1+\varepsilon)\cdot[p_i]_n\right) - \Theta_n\left([p_i]_n\right)}{\varepsilon} \right)$$

where $\varepsilon = 2\%$; $[p_5]_n = ychoke1, k1a1\_\text{nominal} = 0.974$

$$\sigma\left([p_5]_n, 2\%\right) = \frac{1}{\Theta_n\left([p_5]_n\right)} \cdot \frac{\Theta_t\left((1+0.02)\cdot[p_5]_n\right) - \Theta_n\left([p_5]_n\right)}{0.02}$$

$$= \frac{1}{3.6504V} \cdot \frac{3.6504V - 0.8851V}{0.02} = 37.87$$

The value $\sigma\left([p_5]_n,\ \varepsilon = 2\%\right) = 37.87$ is the relative sensitivity of the parameter *ychoke1,k1a1* with 2% tolerance. It can be interpreted as follows: a change of 2% in value of parameter *ychoke1,k1a1* leads to 37.87x2 ≈ 75% changes of the overshoot of signal Lo1 in a nominal case. By this way of calculation, the list of parameters $[p_{1...65}]$ will be used to calculate $\sigma\,(p_{1...65})$ as plotted in Figure 4. The longer the bar in the bar indicator, the more sensitive that parameter is. Similarly the parameter relative sensitivity analysis bar indicator of Hi1_undershoot is plotted in Figure 6. Again, it shows in the plot that the parameter *ychoke1,k1a1* is the most sensitive parameter to the undershoot of signal Hi1.

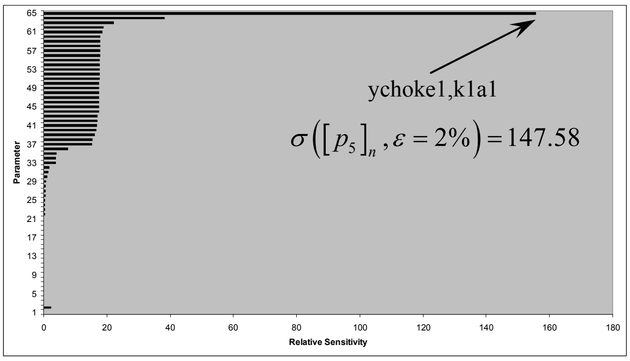

Figure 6: Parameter relative sensitivities bar indicator plot against undershoot of Hi1 signal

From the results shown in the parameter sensitivity bar indicator, it is obvious that out of 65 parameters k1a1 is the most dominant one. It is shown in Figure 7 that with the new value k1a1=0.993 overshoot, undershoot and ringing of signal Hi1 and Lo1 are significantly improved.

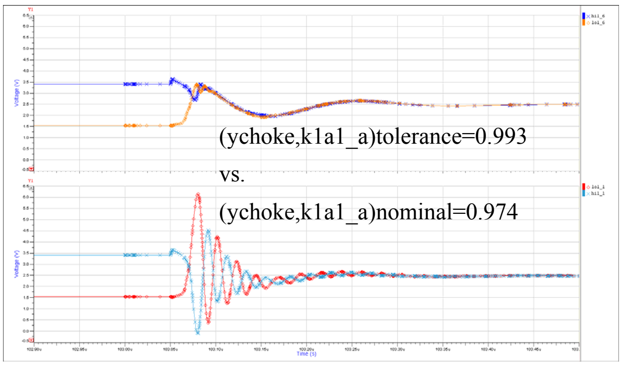

Figure 7: Comparison between nominal and tolerance parameter *ychoke1,k1a1*

3.2 Common mode choke and the parameter k1a1

Electrical and electronic equipment primarily produces common mode interference. Communication system using CAN protocol observe the differential mode current as its normal operating current and the common mode current as disturbance. To minimize EMI, common mode chokes—compensated current choke—are used filtering out the common mode current but passing the differential mode current passes unaffected. The common mode choke is constructed on a high permeability ferrite core with two windings for each direction but on the same core as shown in Figure 8.

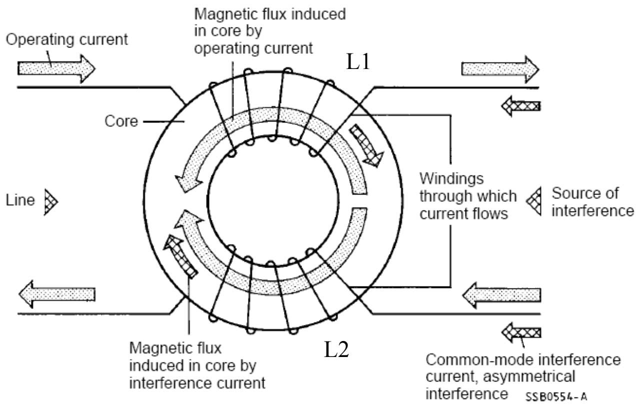

Figure 8: Current-compensated ring core choke

In CAN application, the operating differential mode current flows to the transceiver on the first line and the same current flows to the bus through second winding but in opposite direction. Each of the two currents produces the same flux in the ferrite core. As they show in opposite direction, they compensate each other. If these two winding are coupled ideally (*k1a1=1.0*) the whole flux of *L1* crosses *L2* and vice versa, which results the total flux zero, the stray inductance is also zero and both current pass unaffected. The stray inductance relates to the rated inductance via the following formula:

$$L_{stray} = (1\text{-}k1a1)*(2L_{rated})$$

The stray inductance builds a resonance circuitry with parasitic capacitances leading to resonance effects which become visible in the ringing behavior of the network. Increasing *k1a1* close to 1.0 will decrease the stray inductance and therefore reduce ringing. This has been demonstrated by simulation in the first part of the paper as well as verified by real measurement.

3.3 Parameter k1a1 sweep simulation results

To find further improvements sweep analysis to k1a1 is performed. It is suggested from [8] that *k1a1* value should be chosen as close to 1.0 as possible. The parameter *k1a1* was swept from 0.993219 to 0.997500 with a step of 0.000050, which results in 87 simulation runs.

From sweep simulation results in Figure 9, one can see that *k1a1_66 = 0.996* leads to minimum overshoot of Lo1 signal.

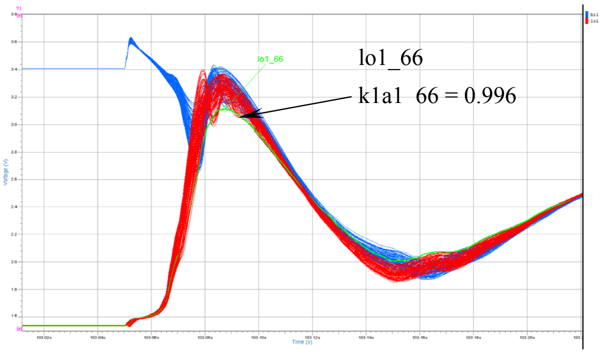

Figure 9: Parameter *k1a1* sweep simulation results plot

Figure 10 plots the variation of parameter *k1a1* against the overshoot of Lo1 signal. From this plot, the minimum in overshoot of Lo1 signal is at the value *k1a1=0.996*, which is exactly as in the observation.

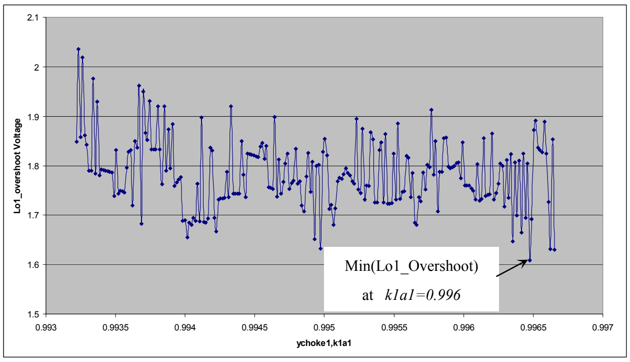

Figure 10: Parameter *k1a1* variation plot against overshoot of Lo1 signal

Figure 11 shows that with the new value found from sweep analysis, the overshoot, undershoot and ringing of signal Lo1 and Hi1 are improved. Increasing *k1a1* closer to 1.0, minimizes ringing.

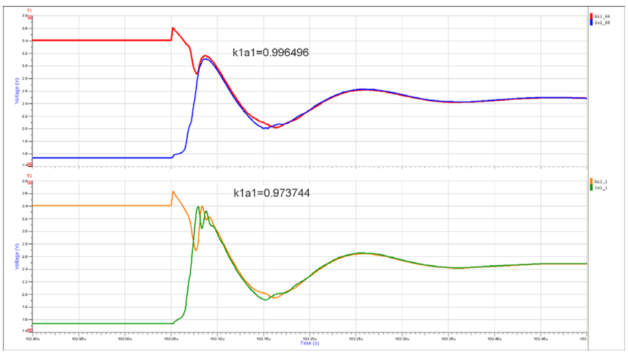

Figure 11: System behaviors comparison of different *k1a1* values

Simulation results have been verified by measurements as shown in the next section.

3.3 Verification of sensitivity analysis methodology

Four different test benches [9] were measured with choke coil values *k1a1=0.973* and *k1a1=0.999*. (The k1a1=0.999-device—close to the ideal value of 1.0—has been manually selected by the manufacturer.)

Figure 12 shows the behavior of signal Hi1 and Lo1 at the transceiver side with the choke (*k1a1=0.974*) in both measurement and simulation when the bus operates from dominant to recessive mode; while Figure 13 shows the behavior of the choke (*k1a1=0.999*).

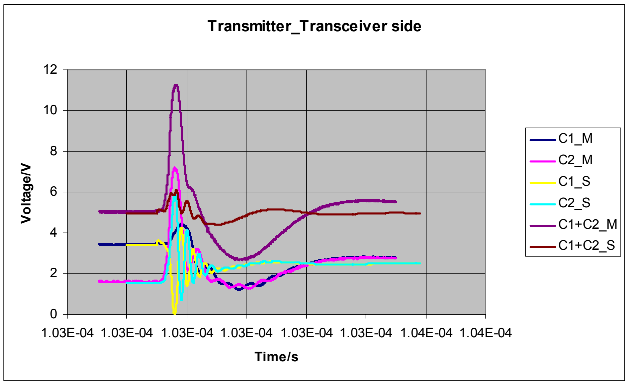

Figure 12: Measurement and simulation of the system behavior with *old* choke coil (with *k1a1=0.974*) – Transmitter – Transceiver side

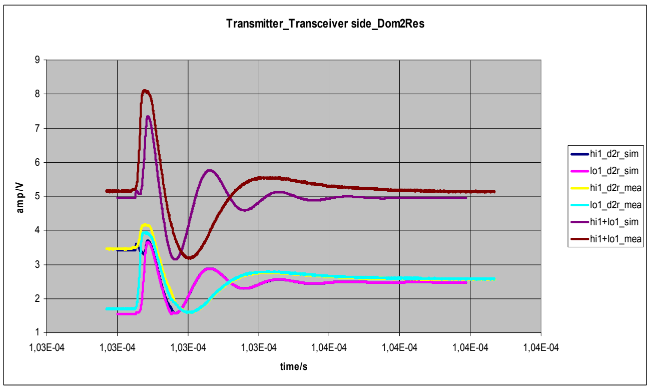

Figure 13: Measurement and simulation of the system behavior with *new* choke coil (with *k1a1=0.999*) – Transmitter – Transceiver side

Overshoot, undershoot and ringing of the signals Lo1 and Hi1 are reduced and the deviation between measurement and simulation is quite small. With choke coil (*k1a1=0.999,* signals at the beginning of the transmission line are also improved with less ringing. This is shown in Figure 14 and Figure 15.

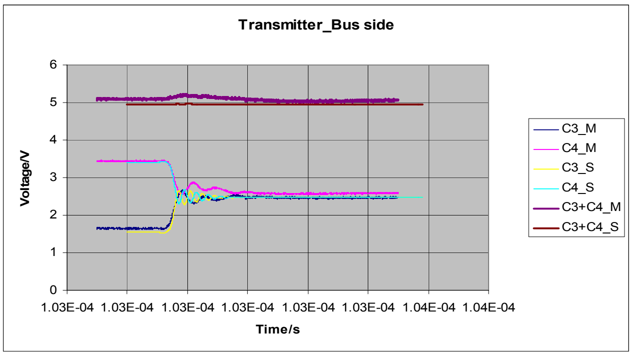

Figure 14: Measurement and simulation of the system behavior with *old* choke coil (with *k1a1=0.974*) – Transmitter Bus side

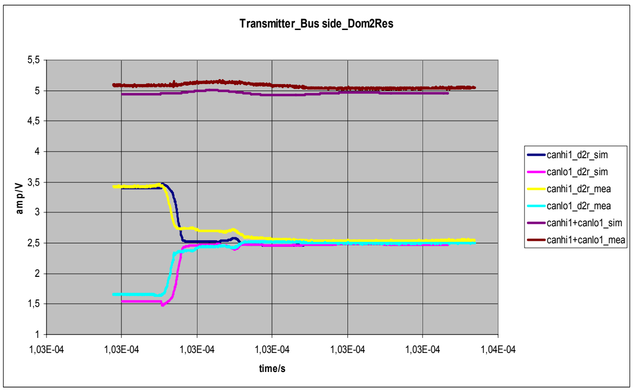

Figure 15: Measurement and simulation of the system behavior with *new* choke coil (with *k1a1=0.999*) – Transmitter – Bus side

4. CONCLUSION AND OUTLOOK

Comparison of measurements and simulations show that the results correspond. Sensitivity analysis helped to find the most sensitive parameter in the network and helped to reduce simulation and measurement effort.

Stray inductance k1a1 is the most influential parameter which needs to be controlled very carefully to maintain signal integrity in CAN-networks.

In a next step (active) CAN transceivers will be included in the sensitivity analysis and more complex CAN networks will be investigated.

5. ACKNOWLEDGMENTS

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