Modeling of Automotive Bus Transceivers and ESD Protection Circuits for Immunity Simulations of Extended Networks

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Abstract—**To establish a stable communication between electronic control units in vehicles special bus systems were developed. CAN and FlexRay are safe data buses with high immunity against electromagnetic disturbances. To ensure the safety, the systems should be qualified with special RF immunity tests, e.g. BCI, within the development process. EMC simulations can help to calculate the effect of electromagnetic disturbances coupled to the bus system cable network. To protect the transceiver on PCB level against ESD, additional overvoltage protection elements are often used. However, the non linear ESD protection circuits and high disturbance levels can change the shape of the bus signal and the transceivers may not be able to detect the bus information. For simulation based EMC investigations using large BCI setups exact models of the wires, the ESD protection elements, the behavior of the transceivers, and the BCI injection clamp are necessary. These models were developed and verified with measurements. The simulation results are in good agreement with measurements.**

I. INTRODUCTION

In today's vehicles modern bus systems with powerful EMC protection circuits are in use. Testing of immunity against electromagnetic interferences in laboratory is time consuming; only several cases can be investigated and special hardware is required. Simulations can help to overcome a part of the problems and give a deeper understanding of system behavior. In the past there were several investigations conducted concerning the signal integrity (SI) of CAN [1], [2] and FlexRay [3]. Immunity models of LIN, CAN and FlexRay transceivers were presented in [4], [5]. Combining transceiver models with models of other bus components, EMC simulations of the complete FlexRay topology can be done.

In [6] behavioral models of ESD protection circuits written in VHDL-AMS were presented. These models are used here for EMC investigations in combination with CAN and FlexRay transceiver models presented in [5]. If the FlexRay nodes are equipped with external ESD protection elements and in case of EM field coupling into the bus wires, the amplitudes of the bus signals may be limited to the cut off voltage and the transceiver can't detect the differential bus signal [5]. For low frequencies in the range of the operational frequency of the bus system a sinusoidal wave can disturb one or more bits of the communication signal and e.g. the FlexRay transceiver might detect the Idle Mode.

In the following paper improved behavioral models of bus transceivers valid up to 100 MHz are presented.

An extended network of four FlexRay nodes with a passive star structure was investigated in order to show applicability to realistic test cases. A BCI clamp model was integrated and positioned next to low ohmic terminated node. The maximum input power without any bus failure can be calculated.

II. SIMULATION MODELS

A. *Models of the ESD protection circuits*

ESD protection elements in circuits are used to protect sensitive semiconductors against high voltage transients, e.g. ESD. The response time of SMD varistors and TVS diode arrays is in the range of < 1 ns due to low inductances. The investigated varistors have a capacitance of 18 or 150 pF. A capacitance value of ≈1 pF was measured for the diode arrays.

In [6] methods for parameter determination and generation of VHDL-AMS models of ESD-protection elements are presented. The V/I characteristic is determined by static and transmission line pulse measurements (TLP). The maximum permitted power can be found in data sheets. The determination of the RF parameters can be done by reflection measurements with a network analyzer (NWA) [7], [8]. The components are modeled in VHDL-AMS as a parallel circuit of a capacitor and a current dependent resistance, a serial inductance is connected to the parallel circuit.

The breakdown voltage, the maximum current through the protection element and the parasitic capacitance are important parameters. These parameters are very accurately depicted in ESD models of [6].

ESD protection elements are intended for the protection against rarely occurring pulse currents. A permanent operation with CW-coupling above the breakdown voltage is not possible. The thermal power, generated by the current, can not be lead off and leads to destruction. The immunity simulations with sinusoidal disturbances were exemplarily done with a TVS diode array from Protek, type GBLCS05C, two equal

SEMTECH TVS diodes of type SD12 (interconnected as an array) and two Epcos Varistors, type CT0603K14G and CT0603L25HSG. Table I shows the main characteristics of the investigated elements.

TABLE I. CHARACTERISTICS OF PROTECTION ELEMENTS

Protection element	Breakdown voltage @ 1 mA	Maximum power losses	Equivalent impedance
Protek TVS-Array GBLCS05	6 V	--	1,4 pF ll 100 kΩ
SEMTECH TVS-Diode SD12	13,3 V (DC)	--	12 pF ll 100 kΩ
Epcos Varistor CT0603K14G	14 V (RMS) 22 V (DC)	3 mW	150 pF ll 30 kΩ
Epcos Varistor CT0603L25HSG	25 V (RMS) 32 V (DC)	3 mW	18 pF ll 70 kΩ

B. Behavioral Models of FlexRay Transceivers

Because of the nonlinear behavior of the transceivers for EMC modeling, not only the determination of the stationary impedance is important, but also the dynamic behavior in case of bus communication failure [4], [5]. In other investigations the input impedance of IC's were mostly determined by the reflection measurements of the input pins and potential ESD protection elements were implemented as simple diode models [9]. The nonlinear effects near or over critical values are not considered in these examinations. In [5] investigations on modeling of CAN and FlexRay transceivers were made and very simple equivalent impedance models for EMC simulations were presented. However the behavior in case of transient disturbances or the partial destruction of bits by amplitude modulated signals in combination with ESD protection circuits and the transceiver internal signal processing is not considered. The receiver unit of a differential bus transceiver can be modeled as ideal high impedance comparator with low pass filter. High frequencies or fast transient pulses may not affect the correct detection of the signal and pulse width. In Table II the equivalent RC-circuits of investigated bus transceivers are shown.

TABLE II. EQUIVALENT IMPEDANCES OF INVESTIGATED BUS DRIVERS

Transceiver	CAN Type A	FlexRay Type A	FlexRay Type B
Equivalent Impedance	12 pF ll 450 Ω	10 pF ll 2 kΩ	42 pF ll 20 kΩ

Figure 1 shows a simple behavioral model of the bus receiver with equivalent impedance bus load, comparator and low pass filter.

The comparator detects and amplifies the differential bus voltage. The connected low pass will filter all high frequency parts of the signal and the digital unit is modeled as ideal A/D-D/A converter.

In VHDL-AMS the transceiver behavior can be modeled as combination of discrete elements and variable input impedances (V/I- and f/Z- tables) which can be found by measuring the DC V/I characteristic and the impedance in failure point in frequency domain.

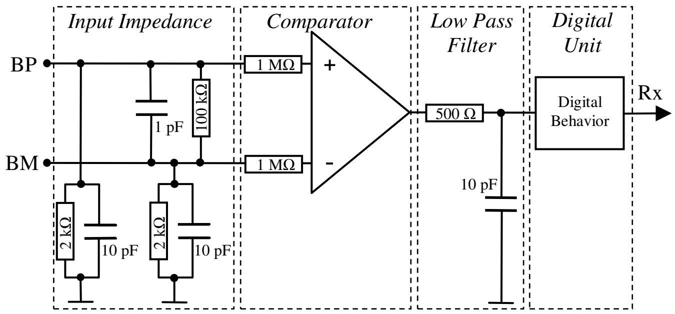

Figure 1. Behavioral model of FlexRay receiver input

Figure 2 shows sample V/I-measurement results done with HPPI TLP [10] of two typical FlexRay transceivers. At levels over 45 – 50 V internal ESD circuits may switch and the current increases critically. Below 45 V both transceivers have high impedances.

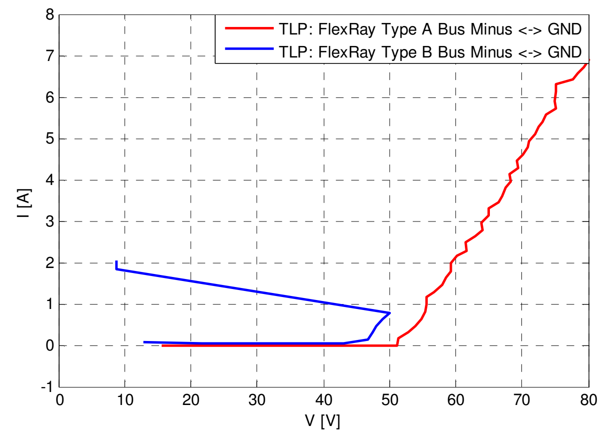

Figure 2. TLP measurement, V/I characteristic of tested FlexRay transceivers

In Figure 3 the frequency dependent critical failure voltages of the FlexRay transceivers are presented. Because of constructive variations and internal signal processing the transceivers have different immunity levels.

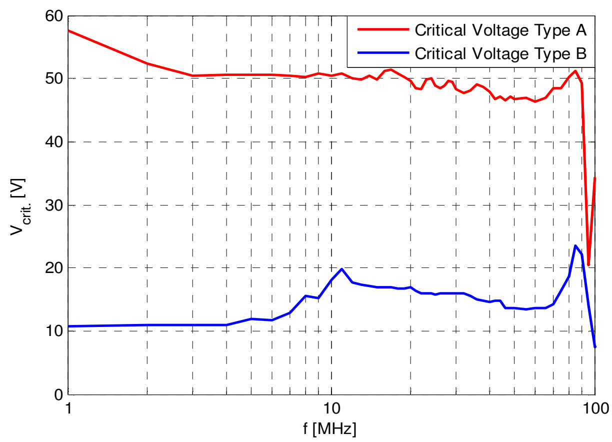

Figure 3. Critical failure voltage of tested FlexRay transceivers

The voltage change between 90 and 100 MHz are caused by resonances in the measurement setup.

C. *Physical Model of the BCI Clamp*

For simulating a BCI setup an exact model of the BCI clamp is essential. The BCI model couples the disturbance power through the wires to the EUT and adds an additional inductance. The used BCI model [12] is show in Figure 4. P1 is the power injection port of the clamp. The input impedance is modeled by inductances, capacitors and resistors. Between P2 and P3 the cable of the EUT is connected.

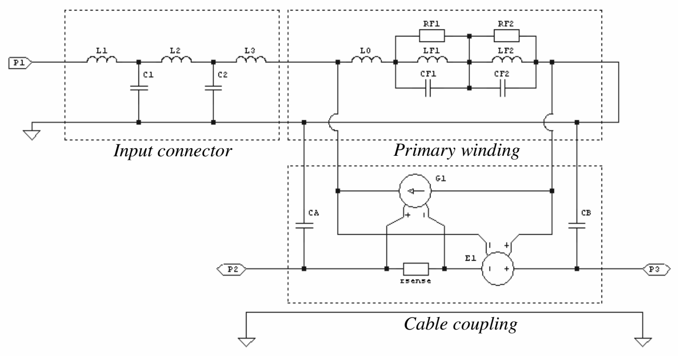

Figure 4. Equivalent circuit model of the BCI clamp

D. *Cable model*

In [13] a time domain model of a multiconductor transmission line considering frequency dependent losses, e.g. skin effect, for VHDL-AMS was developed. The model can be used for linear and nonlinear time and frequency domain simulations. The given approach implements analytical approximations of the attenuation and the characteristic admittance functions directly in VHDL-AMS by using a transfer function described by a rational function approximated using Padé's method. These models were tested in several setups and the matching of simulation and measurement results is good.

III. INVESTIGATIONS OF FLEXRAY TRANSCEIVERS IN COMBINATION WITH ESD PROTECTION CIRCUITS

CAN and FlexRay are operating with differential bus levels and signal transmission is realized via twisted pair wires. The transceivers evaluate the differential voltage between the bus lines and decide whether "logical zero" or "logical one" is present. Since the pair twisted cable is used it can be assumed that mainly common mode disturbances may affect the transceiver. The disturbance is coupled to both bus lines symmetrically, the differential bus levels are not affected.

Wrongly dimensioned ESD protection elements may cut off the bus voltages on both lines and thus the differential bus voltage might be affected. In the FlexRay protocol a differential bus voltage of zero for data communication introduces the idle mode. In this case the communications will stop.

A. *Disturbances at low frequencies*

To perform EMC simulations of the overall system, the transceiver models described in chapter II.B can be modularly extended with VHDL-AMS models of protection elements. According to the DPI method [16] the noise voltage will be coupled to both bus lines through the termination resistors and a capacitor. In Figure 5 the simulation and measurement setup is shown.

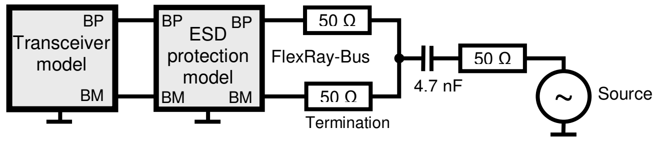

Figure 5. Test setup incoupling with DPI method

In the following the protection elements of Table I are further investigated. The models are stimulated with a typical AM modulated test signal with carrier wave frequency of 1 MHz and a modulation frequency of 1 kHz. The modulation factor is 80%. Figure 6 shows the simulated FlexRay Bus Plus signal in combination with the model of a TVS diode array. The limiting effect of the protection element can be seen.

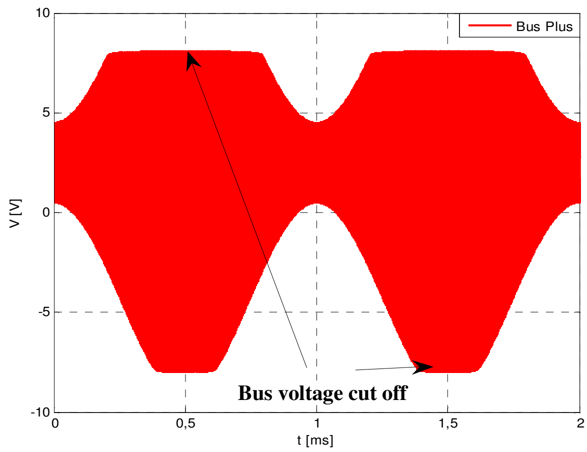

Figure 6. Simulation of disturbed FlexRay bus voltage in combination with a TVS Diode Array

A comparison between simulation and measurement is given in Figure 7. The upper curves are a zoomed part of the signal levels of BP and BM of Figure 6.

The voltages are limited by the protection element. At disturbance amplitude of about 8 V, the transceiver can not detect the differential voltage anymore. The disturbed differential bus signal with the resulting bit errors can be seen below. The correlation between simulation and measurement results correlate very good.

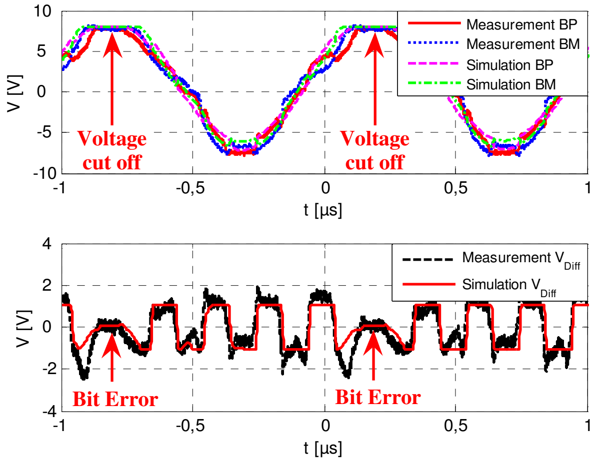

Figure 7. Simulated and measured differential bus voltage, interference frequency 1 MHz with FlexRay Type A and Protek TVS Array

B. *Behavior at high frequency interferences*

At lower frequencies the sinusoidal wave may disturb directly one or more bits. In this case the transceiver isn't able to send the correct data on the Rx pin.

At frequencies > 20 MHz a half of the differential signal may be limited. In this case the comparator is able to detect positive and negative edges. In combination with the connected low pass filter the high frequency contents of the signal is eliminated. Figure 8 shows the differential bus signal at BP and BM, disturbed by a 50 MHz sinusoidal wave. In comparison the undisturbed bus signal is given by the green curve.

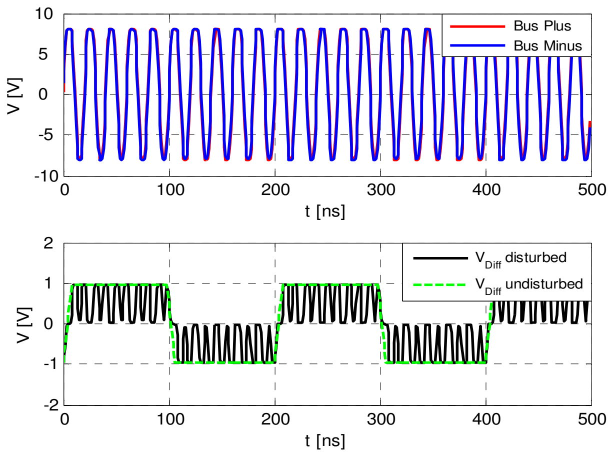

Figure 8. Disturbed differential bus voltage, cutted off by Protek GBLCS05C TVS Array, interference frequency 50 MHz

C. *Verification of low pass characteristic by measurements*

To verify the low pass filter characteristics and the digital behavioral model in combination with ESD protection circuits measurements at high and low frequencies were done. The sample results are given for 1 MHz and 50 MHz with a Protek TVS array in Figure 9. At higher frequencies the low pass filter and the A/D-D/A converter will remove the RF-components from the signal and the partial drop outs of differential bus signal by protection circuits don't affect the Rx output of the transceiver.

In Figure 10 a comparison between the simulation with the behavioral model and a measured signal of the FlexRay transceiver can be seen. The transceiver is combined with the Protek TVS array. Interference frequency is 50 MHz and the injected amplitude is 20 V. The correlation of presented curves is good.

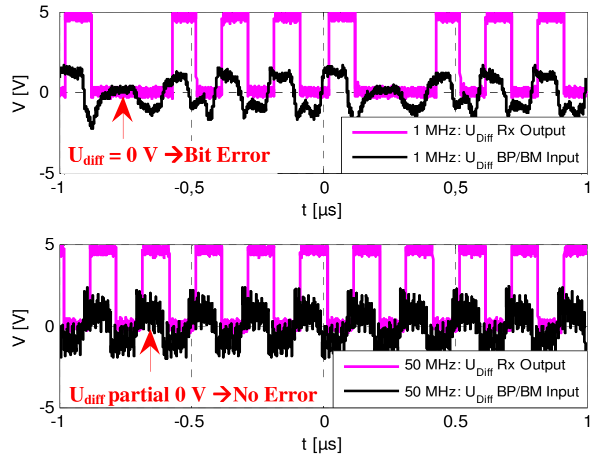

Figure 9. Measurements of disturbed FlexRay bus signals at 1 MHz and 50 MHz with FlexRay Type A and Protek GBLCS05C TVS array

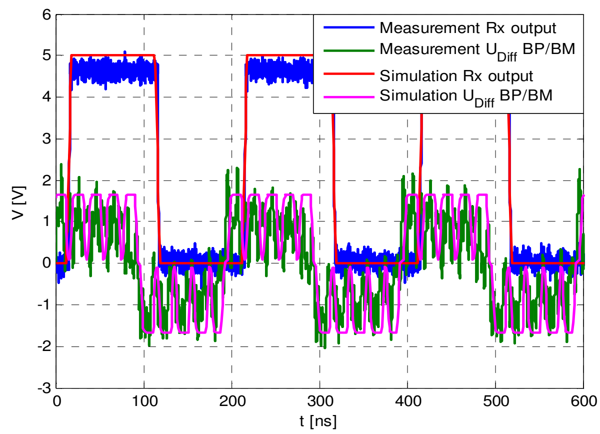

Figure 10. Comparison between simulated and measured signal of a FlexRay transceiver

IV. SIMULATION OF BCI TEST AT FOUR NODE FLEXRAY NETWORK

With the presented VHDL-AMS model of the BCI clamp it is possible to make virtual CAN or FlexRay network EMC tests. In combination with the cable and the transceiver models an overall simulation can be created. To investigate extended networks 4 FlexRay nodes are interconnected with cable models of twisted pair cables. In Figure 11 the BCI test setup is shown. According to [15] all nodes are split terminated. Nodes 1 and 4 with two 1.3 kΩ resistors, nodes 2 and 3 with two 47 Ω resistors and each with 4.7 nF to GND. Common mode chokes or other protection elements are not used in this setup. The BCI clamp is positioned on the cable of node 2 in a distance of 0.2 m.

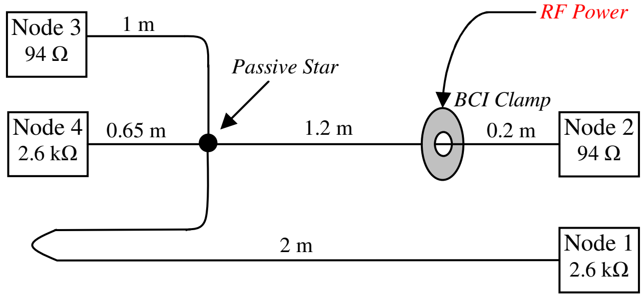

Figure 11. BCI test setup with passive star and four nodes

Figure 12 shows a comparison between the simulated and measured voltages at different FlexRay nodes. The measurements were done in the frequency domain with a network analyzer and in the time domain with a signal generator and oscilloscope. Here higher input power and active voltage probes were used. The BCI clamp was supplied with constant power of 10 dBm over all frequencies. The parasitic effects of connectors, the PCB and discrete elements, like resistors and capacitors, were considered in the model. The model shows very good correlation up to 200 MHz between simulated and measured results.

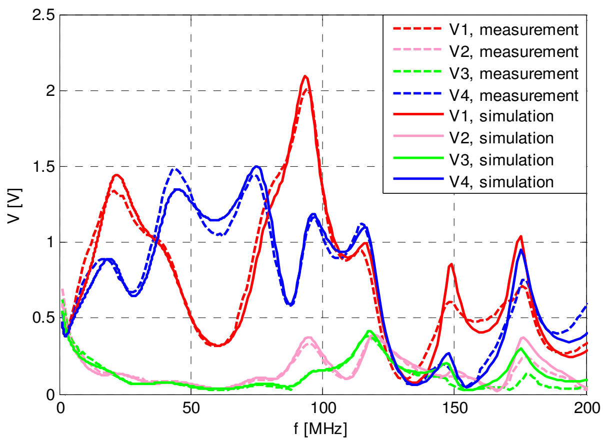

Figure 12. Comparison between simulated and measured amplitudes at the four FlexRay nodes

V. Results

A. *RF Immunity with ESD Protection Circuits*

Depending on the breakdown voltage the sinusoidal noise amplitude will be limited on the bus and this can lead to communication errors. Figure 13 shows the simulated voltages of the investigated protection elements.

According to [16] in Table III the maximum breakdown voltages and the maximum calculated pulse power injected into the transceiver depending on used protection element are given. In case of using CT0603L25HSG the FlexRay transceiver would be thermally destroyed before the critical value is reached. Even most protection circuits are designed only to keep transient pulses. In case of CW disturbances over breakdown voltage, the protection element will be destroyed.

If the breakdown voltage of the ESD circuit is too high the transceivers may be damaged by ESD pulses.

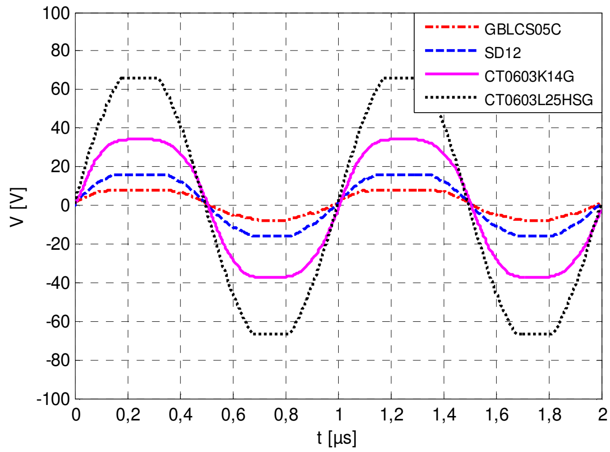

Figure 13. Comparison of breakdown voltages

TABLE III. BREAKDOWN VOLTAGES AND MAXIMUM INPUT POWER DEPENDIG ON INVESTIGATED PROTECTION ELEMENTS

Protection elements	**Break-down voltage**	**Max. calculated power dissipation of used transceiver depending on protection circuit**		
		CAN Type A	**FlexRay Type A**	**FlexRay Type B**
Protek TVS GBLCS05C	≈ 8 V	< 140 mW 1)	< 32 mW 1)	< 17 mW 1)
SEMTECH TVS SD12	≈ 16 V	< 560 mW 1)	< 128 mW 1)	< 68mW 1)
EPCOS CT0603K14G	≈ 32 V	< 2240 mW 1)	< 512 mW 1)	< 272 mW 1)
EPCOS CT0603L25HSG	≈ 65 V	< 8960 mW 1)	< 2048 mW 1)	< 1088 mW 1)
1) Pulse power only (sample calculation at 1 MHz) Modeling of transceivers with equivalent impedances				

B. *BCI Simulations of extended FlexRay Networks*

Based on laboratory measurements an overall model for BCI testing was developed. Including the transceiver model and the characteristic values of Figure 2 and Figure 3 the critical forward input power by using the FlexRay transceiver Type A can be calculated and is given in Figure 14.

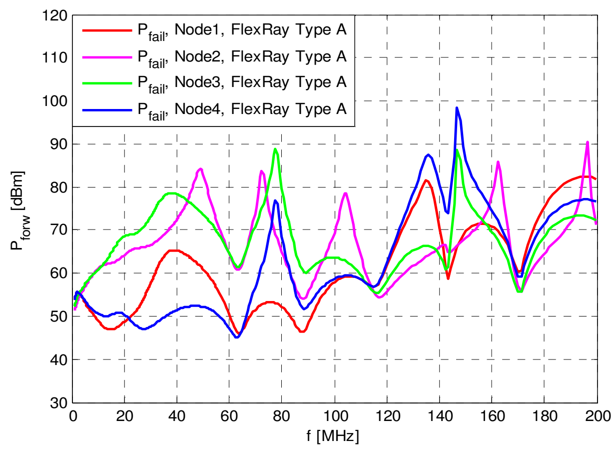

Figure 14. Critical BCI Input Power for interconnected FlexRay nodes using transceiver Type A

The critical values for transceiver Type B are shown in Figure 15.

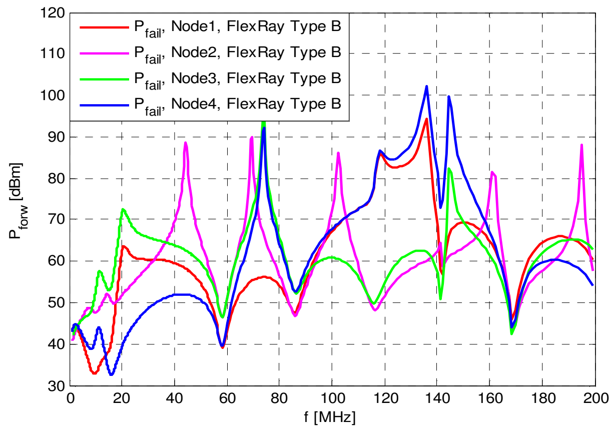

Figure 15. Critical BCI Input Power for interconnected FlexRay nodes using transceiver Type B

Because of different transceiver types and depending on the impedance the critical values may vary. Transceiver Type B has got a lower failure voltage than Type A but higher impedance. Depending on resonances of the harness the minimum BCI failure input power is higher than Type A. The curves in Figure 16 show the critical forward power supplied to the BCI clamp necessary for bus failure of the whole network depending on critical failure voltage at the nodes. Values over 40 – 50 dBm are improbable in those networks.

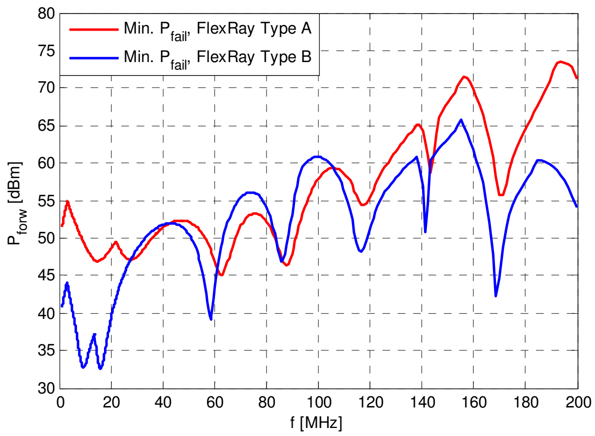

Figure 16. Minimum critical BCI input power for interconnected FlexRay nodes depending on used transceiver type

Because of high ohmic terminations the voltages levels will exceed the critical values of node 1 and 4 in the frequency range until 100 MHz. Over 100 MHz the voltage levels will be dominated by resonances depending on the cable length, the termination and transceiver capacitances.

VI. Conclusion

Behavioral models of bus transceivers for EMC investigations were developed. Due to the usage of VHDL-AMS as modeling language the model can be interfaced easily with other circuit models, e.g. of protection elements. Complex simulations are possible. In combination with the developed BCI and cable models EMC simulations of large systems can be performed.

Because of an exact consideration of all important components like cable, BCI, PCB, and transceiver models, a good matching between measurement and simulation results is obtained.

ESD protection circuits can reduce the immunity against sinusoidal disturbances, especially when the breakdown voltage of used elements is too low. A compromise between immunity against high energy transient pulses and RF disturbances is recommended.

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