Immunity of Modulation Schemes in Automotive Low Bitrate Power Line Communication Systems

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***Abstract*—In this paper, immunity of commonly employed modulation schemes for low data rate transmission over power line (PLC) are investigated. Transmitter and receiver models for Amplitude Shift Keying (ASK), Frequency Shift Keying (FSK) and Binary Phase Shift Keying (BPSK) are implemented. Virtual automotive EMC tests, including Direct Power Injection (DPI), Bulk Current Injection (BCI) and plane wave field coupling (ALSE) were performed to investigate the immunity of the modulation schemes. Furthermore, selected pulse disturbances were tested. For method validation DPI measurements of a real PLC transceiver for automotive applications were carried out and failure behavior was compared to the virtual DPI test results. The pros and cons are discussed.**

***Keywords*—Low bit rate PLC, in-vehicle power line communication (PLC), immunity test.**

I. INTRODUCTION

Anti-Break System (ABS), Electronic Stability Program (ESP) or Automatic Cruise Control (ACC) are state of the art in today's mid-size class vehicles. This trend leads to a higher number of electronic systems like ECU's and sensors. These systems are distributed over the entire vehicle body. Apart from the power supply the systems need one or more communication cables, usually using bus protocols like LIN, CAN or FlexRay. Due to the increasing number of systems, the wiring harness complexity, weight, and volume increase.

To reduce the complexity and to optimize the weight of the wiring harness in modern vehicles, simultaneous use of supply cables for power and communication is an interesting option. The Power Line Communication (PLC) has its origin in industrial application for data transmission and internet access over the AC low voltage grid. A relatively new application for PLC are vehicles [1] or spacecrafts. PLC is facing different challenges when implemented in a vehicle energy supply network.

Several publications are dealing with integration of PLC in DC power supply systems. In [2] the authors investigate the conducted immunity against noise, generated by terminal units of the power line, from theoretical point of view by using multi-conductor transmission line theory and modal decomposition. A typical power supply system used for application in spacecraft, which includes a twisted pair cable over ground was analyzed. The conversion of common mode to differential mode noise for balanced and unbalanced systems is mathematically derived. A system using differential mode signaling on twisted pair cables shows a flat channel transfer function. The cable system differs from typical automotive power supplies, where single wires over ground are used. According to this difference and considering the branched structure of a DC supply wiring with a large number of electrical systems, the channel properties are less well defined, and radiation of electromagnetic fields is more problematic. In [3] and [4] the cable transfer characteristics of an in-vehicle power distribution system were analyzed and modeled. It is shown in [3] that the transfer function is frequency selective and is subjected to strong fluctuations. Furthermore, the input impedance at the connection point of the PLC transceivers is dependent on the loads that are connected in the entire power supply network. The randomly switching loads during operation cause variation of input impedance. In [5] and [6] the statistical properties of typical impulsive noise as a result of switching loads in vehicular power lines were analyzed and modeled. An approach for an improved design of power distribution systems to overcome the mismatch of characteristic impedances is given in [7].

The challenging channel properties are as important as the used modulation schemes in an automotive power supply system. In [8] a comparison of modulation schemes in presence of impulsive noise was done. The Bit Error Rate (BER) performance of Amplitude Shift Keying (ASK), Binary Phase Shift Keying (BPSK) and Differential BPSK (DBPSK) under impulsive noise environment was analyzed.

Impulsive noise is one of many disturbance mechanisms. The cable harness can operate as an antenna. An incident field can induce a RF signal at the interface of a receiver input and disturb the communication. Commonly used immunity tests for automotive ICs are Direct Power Injection (DPI), Bulk Current Injection (BCI) reproduce the coupling of an electromagnetic wave to the cable harness. In our work a virtual DPI, BCI and field coupling test for Continuous Wave (CW) investigation were performed, to evaluate the immunity of ASK, BPSK and Frequency Shift Keying (FSK) to narrowband noise. Moreover, a real DPI test of a PLC transceiver chip for automotive applications [9] was carried out and compared to the simulation results using VHDL-AMS. Furthermore, a virtual pulse disturbance test was carried out.

The structure of this paper is as follows. Section II gives a short overview of the investigated modulation schemes. In section III the impedance model, the demodulation techniques, and the bit detection mechanisms are described. Section IV deals with the performed CW test setups and presents simulation and measurement results. Pulse disturbance results are presented in section V . Conclusions and further discussions are given in section VI.

II. Modulation Methods

Traditional bus systems like LIN, CAN or Flexray apply baseband signals to transmit digital data. Using DC power supply system as a channel for transmission of baseband signal is problematic due to energy transportation of DC current and low frequency noise from power electronics. An unallocated and low noise frequency band is required. Therefore, the digital baseband signal has to be shifted to a higher frequency band by modulation. Common used modulation methods for low bit rate communication systems are introduced in this section to give a short overview [10].

ASK is a simple modulation scheme. The magnitude of a sinusoidal carrier signal is variable to encode the binary state. For a simple one bit encoding the carrier signal can be switched on and off, also called on-off-keying (OOK). The demodulation is done incoherent with an envelope detector. The FSK method uses the frequency to encode the binary state. In that method one bit encoding uses two sine carriers with variant frequencies, which are switching in between. The FSK method can be demodulated incoherent as simple as the ASK with two envelope detectors but previously the frequencies need to be separated by band pass filters. The method for encoding the bit state in the phase of a carrier is called BPSK. Two carrier signals with the same frequency but a constant phase shift are switched in dependence to the bit state. For one bit encoding a phase shift of 180° is used. Demodulation can be done coherent. Therefor a synchronic sine is required and can be generated by a Phase Locked Loop (PLL).

More complex modulation methods like Quadrature Phase Shift Keying (QPSK) or application of different channels for Orthogonal Frequency Domain Multiplexing (OFDM) are commonly employed for high data rates. The focus of this work are low bit rate communication systems thus the simple modulation schemes (ASK, FSK and BPSK) are investigated. Next section deals with the model generation of the described modulation methods.

III. Transceiver and Receiver Modeling

The main goal in this paper is to investigate the behavior of a transceiver under several immunity tests. In this section the modeling procedure of a power line transmitter and receiver is described.

A. Transmitter Source and Receiver Impedance Model

Both impedances of transmitter and receiver are modeled as shown in Fig. 1 with a linear equivalent circuit where TxD denotes the digital data Signal, V_{Tx} represents the voltage at the transmitter output, V_{Rx} is the voltage at the receiver input and RxD is the received digital data signal. The signal propagation and reflection depends on the characteristic impedance of the transmission line. Usually a coupling network is used to connect the transmitter and receiver to the power line, which should be considered separately.

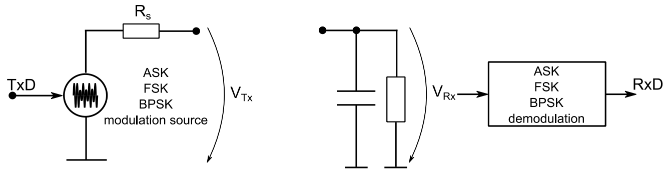

Fig. 1. Equivalent transmitter (left) and receiver (right) model

The transmitter is assumed as an ideal voltage source and an internal source resistance R_s with 90 Ω. The source mathematically generates a modulated carrier signal (ASK, FSK or BPSK) which is depending on the binary TxD signal connected to the source. The voltage magnitude of 1 V and frequency of 6.5 MHz for the carrier signal was chosen according to an available PLC transceiver for automotive applications [9].

The input impedance is assumed as a combination of a resistor and a capacitor in parallel. The resistor represents the high impedance input (here 1 MΩ) of an amplifier inside the transceiver chip with a parasitic capacitance of 10 pF.

B. Demodulation Methods

Three demodulation methods for the investigated modulation schemes (ASK, FSK, and BPSK) were implemented in the receiver model. The structures are kept as simple as possible. The received voltage V_{Rx} will be post processed by each demodulation method to detect the binary data in V_{demod}. Non-coherent demodulation is used in the models of ASK and FSK as depicted in Fig. 2 (a) and (b). The models are composed of an envelope detector and band pass filters (BP).

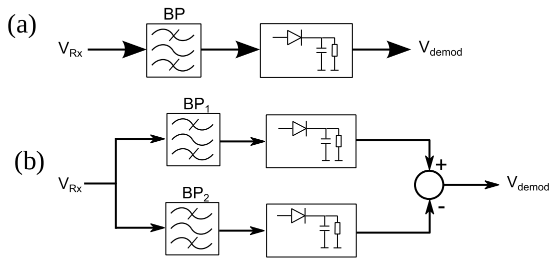

Fig. 2. Incoherent demodulation methods for ASK (a), FSK (b) as implemented in the analog receiver front end

The envelope detector is a circuit containing a diode and a RC network. In FSK the band pass filters are used to separate the frequencies. The filters are expressed as a second order transfer function in frequency domain:

$$H(s) = \frac{s\frac{2D}{\omega_0}}{1 + s\frac{2D}{\omega_0} + s^2\frac{1}{\omega_0^2}} \qquad (1)$$

where ω_0 denotes the center frequency and D represents the dumping factor. The bandwidth can be calculated with:

$$B = 2D\frac{\omega_0}{2\pi} \tag{2}$$

Coherent demodulation is necessary for BPSK (see Fig. 3). A Costas Loop [11] was implemented in the model to synchronize the internal Voltage Controlled Oscillator (VCO) with the carrier signal.

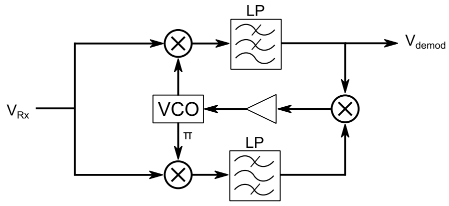

Fig. 3. Coherent demodulation method for BPSK to extract the actual transmitted data from received voltage at receiver input pin (V_{Rx})

The low pass filters are implemented with following transfer function:

$$H(s) = \frac{1+\frac{s}{\omega_1}}{1+\frac{s}{\omega_2}} \tag{3}$$

The described methods are simple and cost-effective to be implemented in an analog front end of a real transceiver.

C. Bit Detection Model

For detection of the digital bit stream from the demodulated signal V_{demod} a simple RC circuit is attached as an integrator to the analog front end of the receiver as illustrated in Fig. 4. The switch discharges the capacitor periodically at the beginning of a bit. During the bit duration the capacitor integrates the current from the demodulation circuit. Consequently, at the end of a bit duration the voltage at the capacitor can be sampled to decide the bit state.

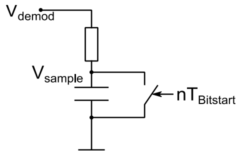

Fig. 4. Integration circuit designed for sampling the demodulated signal containing a switch for periodic discharge of capacitor.

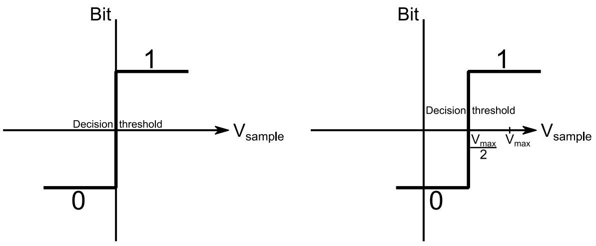

Fig. 5. Bit detection thresholds for FSK, BPSK (left) and ASK (right) applied to detect the bit state from the sampling voltage (V_{sample})

A decision threshold at 0 V for FSK and BPSK sets the digital output of the receiver to the detected bit state. Since during the carrier off states in the modulation scheme (also called on-off-keying, OOK) the demodulator output voltage is zero, the ASK threshold needs to be set to a nonzero voltage. The bit rate for the models is set to 20 kBit/s.

D. Transmission Line Model

To consider the line properties a transmission line (TL) model was implemented. Accurate simulation of signal propagation require a TL with frequency dependent losses. The presented model involves a single wire over ground.

The voltage and current conditions at the beginning and the end of the TL can be expressed in the frequency domain by the following equation [16], [17]:

$$\begin{bmatrix} V_2 \\ I_2 \end{bmatrix} = \begin{bmatrix} \cosh(\gamma(s)l) & -Z_0(s)\sinh(\gamma(s)l) \\ -\frac{1}{Z_0(s)}\sinh(\gamma(s)l) & \cosh(\gamma(s)l) \end{bmatrix} \begin{bmatrix} V_1 \\ I_1 \end{bmatrix} \tag{4}$$

In the frequency dependent propagation constant $\gamma(s)$ and characteristic impedance $Z_0(s)$, the per-unit-length parameters like DC resistance R'_{DC}, the skin effect R'_s, the line capacitance C' and the line inductance L'_e are taken into account by following equations [16]:

$$Z_0(s) = \sqrt{\frac{R'_{DC} + R'_S\sqrt{s}\sqrt{2} + sL'_e}{sC'}} \tag{5}$$

$$\gamma(s) = \sqrt{(R'_{DC} + R'_S\sqrt{s}\sqrt{2} + sL'_e)sC'} \tag{6}$$

Z_0 and γ have to be approximated by rational functions for time domain simulation. A linear differential equation can be formed directly. In a simulation environment, several TL models of any length and in any configuration can be combined.

The frequency dependend characteristic impedance and propagation constant of the applied TL in the simulation are depicted in Fig. 6.

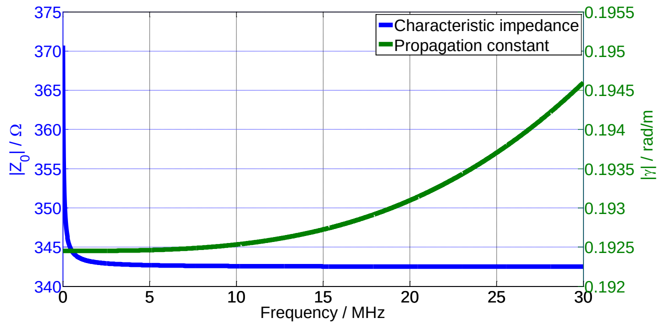

Fig. 6. Characteristic impedance and propagation constant of TL model

IV. CW (Continuous Wave) Investigations

The aim of the CW test is to evaluate the immunity of the communication system to narrow band noise. A sine wave generator with variable frequency and output voltage is implemented in the test setup. Here no additional modulation is assumed. DPI test for capacitive coupling and BCI test for inductive coupling can be performed for communication disturbances. Furthermore, a field coupling test setup complete the test procedure. A principal drawing of the DPI and BCI test setup is shown in Fig. 7. The transceiver models under test are connected via capacitors to the TL. Besides DPI and BCI direct field coupling into the transmission cable is investigated in this chapter.

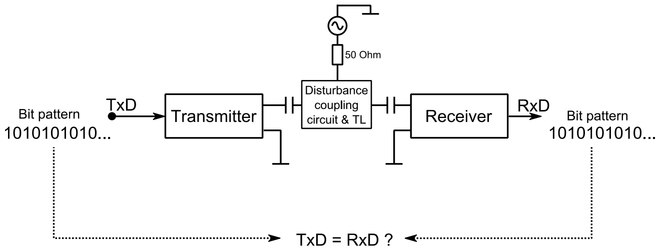

Fig. 7. DPI test setup to evaluate the transceiver models with different modulation schemes

In the test procedure a sweep of frequency and voltage is performed. At every step of frequency and voltage a bit pattern is transmitted. The received bit pattern is compared to the transmitted one. In case of a mismatch, maximum immunity level at achieved frequency and voltage is exceeded. In the presented simulations the virtual test is performed in the frequency range from 500 kHz to 30 MHz. A pattern of 32 bits is transmitted to evaluate the communication system.

A. DPI Test Results

According to section III the virtual DPI test is performed for each modulation separately up to a maximum source voltage of 10 V. Additionally, a real DPI immunity test is performed for a Yamar transceiver [9]. The setup includes transmitter and receiver connected together with 1 m twisted pair cable over ground (see Fig. 8). The power supply was attached with a second 1 m cable at the transmitter terminal. DC power supply and periphery on the PLC evaluation boards were not considered in the simulation setup. The noise signal is directly injected at receiver evaluation board terminal. The digital output of the receiver is monitored by a PC connected to the measurement setup via a serial connection.

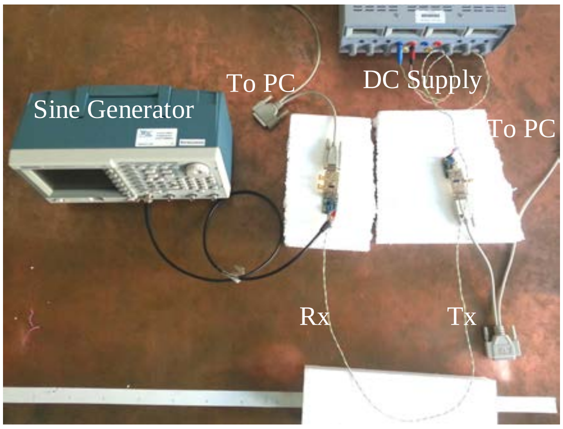

Fig. 8. DPI immunity measurement setup with PLC transceiver evaluation boards from [9]

The comparison results achieved for the BPSK transceiver model and the direct DPI immunity test are illustrated in Fig. 9. Measurement results show an expected higher sensitivity against disturbances at the carrier frequency. Three further significant sensitive frequencies (5 MHz, 13 MHz and 19.5 MHz) can be observed in the measurement results. Harmonic frequencies in the local oscillator of the receiver for coherent demodulation could have impact on the immunity level. A non-ideal VCO (see Fig. 3) was implemented in the BPSK receiver model for reproduction of the real transceiver behavior. Apart from some deviations close to 5 MHz and 6.5 MHz simulation can reproduce well the measurement results (Fig. 9). Simulation models are verified this way.

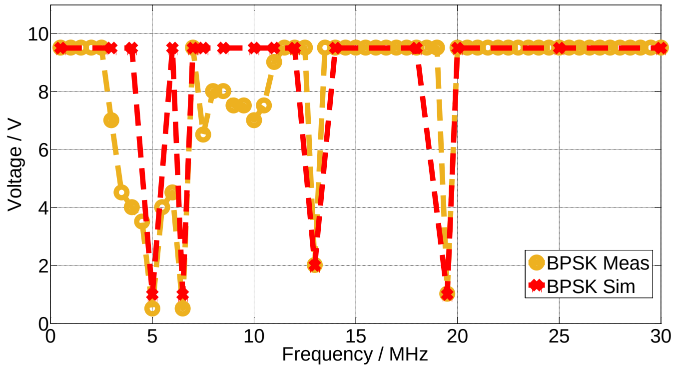

Fig. 9. Comparison of DPI immunity test result achieved by simulation of BPSK transceiver model and actual measurement

Using different modulation schemes in simulation environment are compared and the results are illustrated in Fig. 10. Results show a significant drop of robustness for each curve due to narrowband noise at the carrier frequency.

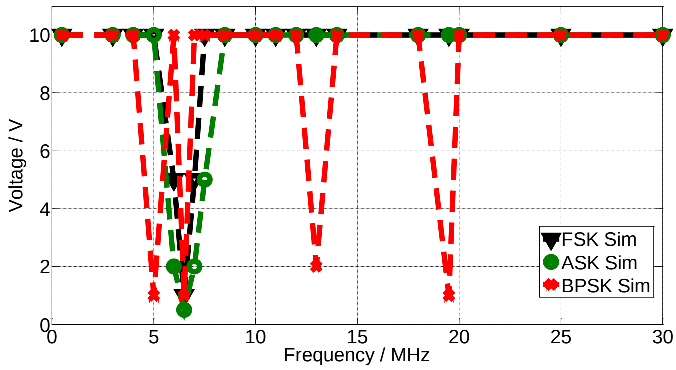

Fig. 10. DPI immunity test result achieved by simulation of different digital modulation in VHDL-AMS

The ASK and FSK modulation show no immunity reduction up to the maximum test level outside the carrier frequency band due to the non-coherent demodulation. This modulations show good robustness to direct power injection in the observed frequency range. Nevertheless, real implementations of the modulation schemes might inhibit problems not visible with ideal simulation models.

B. BCI Test Results

A BCI model composed of lumped elements [19] is used for inductive disturbance coupling. The used simple linear equivalent circuit (Fig. 11) of the BCI current clamp is valid for simulations up to 30 MHz.

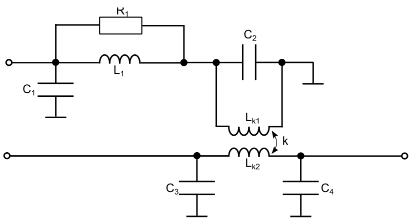

Fig. 11. BCI model circuit

The comparison of BCI simulation results are depicted in Fig. 12. The simulations were carried out with a 50 Ω sine source connected to the BCI input terminal. The maximum Voltage was set to 25 V.

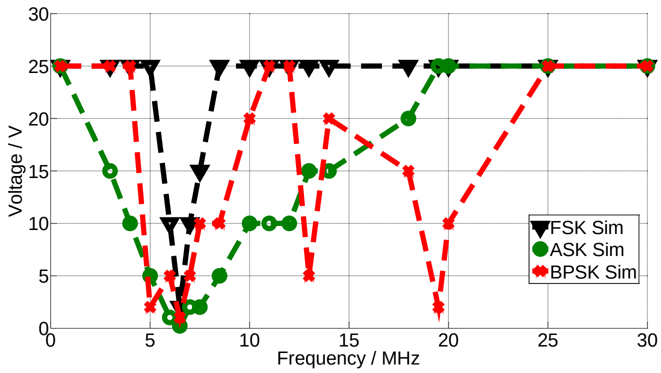

Fig. 12. BCI simulation results of the transceiver models

Immunity drops at the carrier frequency occurs in all models. The drops outside the carrier frequency band observed in DPI simulation with the BPSK model are also visible in the BCI test. The ASK Model is sensitive to frequencies from 3 MHz to 18 MHz. The FSK model has best performance in the BCI immunity test.

C. Field Coupling Test

This test reproduces the coupling of an incident plane wave to a parallel wire structure as depicted in Fig. 13. The field coupling can be modeled as a combination of a voltage and current source. The model is valid for a short TL relative to the wavelength ($l \ll \lambda$). Signal propagation effects are not considered in this model.

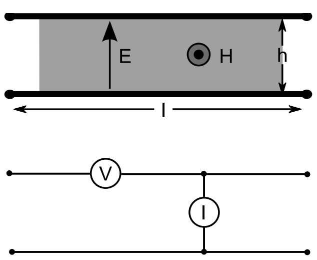

Fig. 13. Field coupling to a TL of length *l=1m* and high *h=0.05m* represented by equivalent circuit consists of a voltage and current source

The voltage and current can be found using by following equations [18]:

$$
\begin{aligned}
V(\omega) &= -j\omega\mu_0 lhH \\
I(\omega) &= j\omega\frac{\pi\epsilon_0}{ln(h/r)}lhE
\end{aligned} \tag{6}
$$

with TL length $l = 1m$, distance between the lines $h = 0.05m$ and wire radius $r = 2mm$. The height and length have impact to the induced voltage and current on the TL and were choosen according to typical antenna tests performed in anaechonic chamers. The test was carried out with a maximum electric field strength of 200 V/m. The simulation results are shown in Fig. 14.

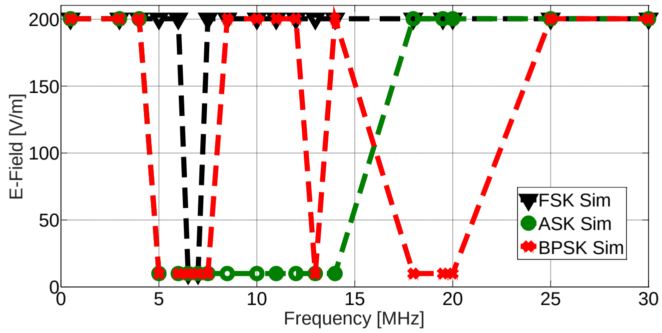

Fig. 14. Immunity simulation results from field coupling test with the transceiver models

The typical immunity drop at the carrier frequency is also visible in these results. Moreover, the ASK model is sensitive to frequencies in a wide band around the carrier frequency.

V. Pulse Disturbance Investigations

A virtual pulse disturbance test was performed in a similar way to the DPI test with a capacitive coupling. A pulse generator instead of a continuous sine generator was implemented for simulation. Besides, the pulse with was chosen fix to 50% of the period duration. The simulations were carried out in a pulse frequency range of 20 kHz to 8 MHz with a maximum pulse height of 25 V and pulse rise time of 10 ns. The results are shown in Fig. 15. The compared transceiver models have different behavior in case of pulse disturbance. The ASK and FSK models are sensitive to pulse frequencies at 500 kHz, 2 MHz, 4 MHz and 5 MHz. Furthermore, the BPSK model has a high immunity performance, except the drops at 1 MHz and 5 MHz.

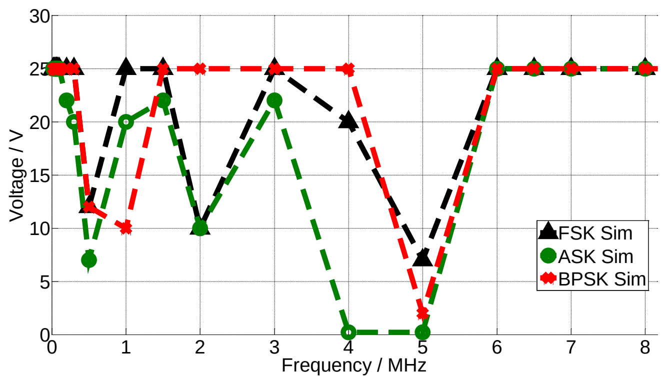

Fig. 15. Immunity simulation results from pulse disturbance test

For additional analysis of ASK model failure at 5 MHz, time domain simulation results are shown in Fig. 16. The demodulated voltage is drawn in comparison with a 100 kHz and 5 MHz pulse disturbance at 10 V magnitude.

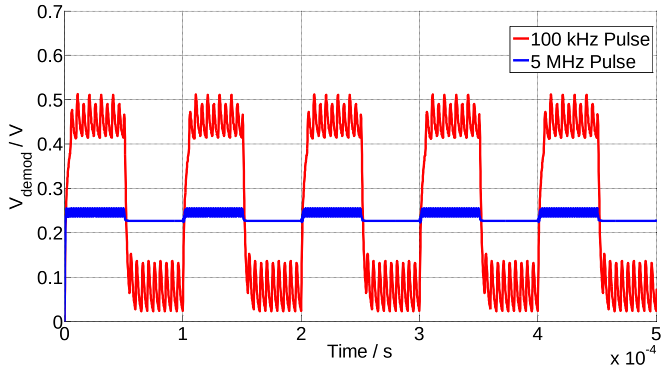

Fig. 16. Demodulated voltage of ASK receiver model compared with 100 kHz and 2 MHz pulse disturbance

The high frequency part of the 100 kHz pulse edges is noticeable as a ripple in the demodulated voltage but bit detection is still possible. The 5 MHz pulse interferes with the carrier signal and cause a dumping of V_{demod}. Due to the dumping the bit decision threshold is not reached (see sec. III). The FSK and BPSK models fail under these conditions too.

VI. Conclusion

Cost-effective modulation techniques were implemented for transmitter and receiver models and automotive EMC performance was analyzed. Virtual DPI, BCI and field coupling test were performed to investigate the immunity of the structure to narrowband disturbances. Furthermore, for model validation a real DPI test was done and compared to the simulation results. The simulation results agree well with behavior of the actual transceiver. Furthermore, pulse disturbance investigations were performed with the presented models in a simulation environment and time domain results were analyzed to point out the reason for immunity drop to pulses at 5 MHz.

The virtual CW investigations are pointing out, that the immunity level for frequencies near to the carrier frequency is low for the compared transceiver models. Furthermore, a real transceiver was tested with the DPI test and results were compared to the virtual test. The BPSK model is realized with a non-ideal local oscillator (VCO) and comparison of simulation results to measurements show a very good model quality. Simulations show immunity drops at 5 MHz, 13 MHz and 19.5 MHz. In contrast, the pulse disturbance investigations issued a different behavior of the models. The best performance between the implemented models is achieved by the BPSK model, which shows the best immunity to pulse disturbances in the considered frequency range. Further investigations at higher frequencies will be done to extract more accurate behavioral model parameters. Model based method will be used first to improve EMC behavior of the different modulation schemes. Finally the best modulation scheme from EMC point of view will be selected and limitations compared to existing methods like LIN will be analyzed.

VII. Acknowledgment

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