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Electromagnetic Susceptibility Assessment of Controller Area Networks

Michele Fontana*, Flavio G. Canavero* and Richard Perraud†

*Dipartimento di Elettronica e Telecomunicazioni, Politecnico di Torino
10129 Torino, Italy, Email: {michele.fontana,flavio.canavero}@polito.it
†Airbus Group Innovation, 92152 Suresnes, France, Email: richard.perraud@eads.net

Abstract—**Mixed signal communication networks are used in electromagnetically noisy environment to establish a stable link between local systems. The ability to predict their EMC compliance to standard immunity tests in design phase is required. The paper focuses on an AMS modeling procedure allowing to describe the CAN bus behaviour when affected by disturbances. The network is simulated combining mixed-signal models of CAN transceiver, cables and noise injection circuits, correctly assessing at system level the relationship between analog and digital signals. The obtained model efficiently predicts the influence of a continuous wave disturbance and estimates the immunity graph obtained through standard testing in a design phase. An application example on a real CAN network concludes the paper and confirms its ability to assess EMC problems.**

Index Terms—**Direct Power Injection test; Immunity Model; Controller Area Network; Electromagnetic Conductive Interference; Integrated Circuit**

I. Introduction

Today, in automotive, avionic or industrial environments, well-designed communication networks are able to provide data integrity and performance requirements of safety critical systems at a reasonable effort. These network-based systems offer a significant weight reduction, lower development cost and maintenance savings compared to dedicated communication systems. This is mainly achieved using a network backbone which serves as a shared resource for the communication between multiple modules.

In CAN bus [1], every module communicates using a transceiver as an interface between the local digital signaling and the analog differential signaling through the network. In order to be used in noisy environments, the network has to be qualified with special immunity tests during the design process. Hence, the evaluation of the network performance when affected by disturbances is one of the main factors that guarantees the EM immunity of the whole equipment. Simulations are used to evaluate the effect of electromagnetic noise coupled to the communication network, to forecast the immunity test results for compliance and to avoid costly redesign issues.

In literature, several contributions on bus networks were published analyzing functional faults [2], signal integrity [3]-[4] and EMC issues due to ESD protection circuits [5]. In this contribution the Analog-Mixed Signal transceiver model presented in [6] is used together with a cable model to predict the behaviour of a real CAN network and to assess its performance in a noisy environment. Analog and digital waveforms measured along the network during a noise injection test are predicted accurately in time domain and the resulting immunity graph is built in a simulation environment.

The next section describes the testing procedure of immunity against RF narrow-band disturbances in CAN networks. Section III presents the CAN transceiver model together with the cable characterization. Section IV validates the proposed network model with measurements carried out at system level and shows the immunity test results using the proposed modeling procedure, explaining how to obtain the immunity graph from noise injection simulation in time domain. The paper is summarized in the last section.

II. EMC Evaluation of CAN networks

The operation of CAN transceivers can be affected by EMI because cables that connect network nodes behave like unintentional antennas, so that the signals at CAN ports are affected by conducted interferences leading to potential failures. In order to investigate noise effects, an immunity analysis to conducted disturbances is carried over according to IEC/TS 62228 test method [7]; the test standard is used as a standardized common scale for EMC evaluation of CAN transceivers, where failures can be analyzed by means of the IEC 62132-4 DPI test method [8], directly injecting a RF disturbance into the EMI affected CAN ports and characterizing the susceptibility in terms of the incident power of the EM disturbance causing the failure.

To test the EMC behavior of a transceiver, a simple CAN network consisting of 2 powered nodes is used, as shown in Fig. 1, where a communication test function is run and analog and digital port signals are observed to verify send-and-receive functionality and to detect any errors. The bus central termination consists of a resistor R = 60 Ω to comply with CAN physical layer specification [9], while cable length is kept as short as possible to minimize propagation delay between transceivers. The disturbance source is constituted by a RF continuous wave signal generator with an output impedance of 50 Ω and interferences are injected in the network with a pair of RC-serial circuits (R = 120 Ω, C = 4.7 nF) which symmetrically couples the RF signal on CAN ports as common-mode noise.
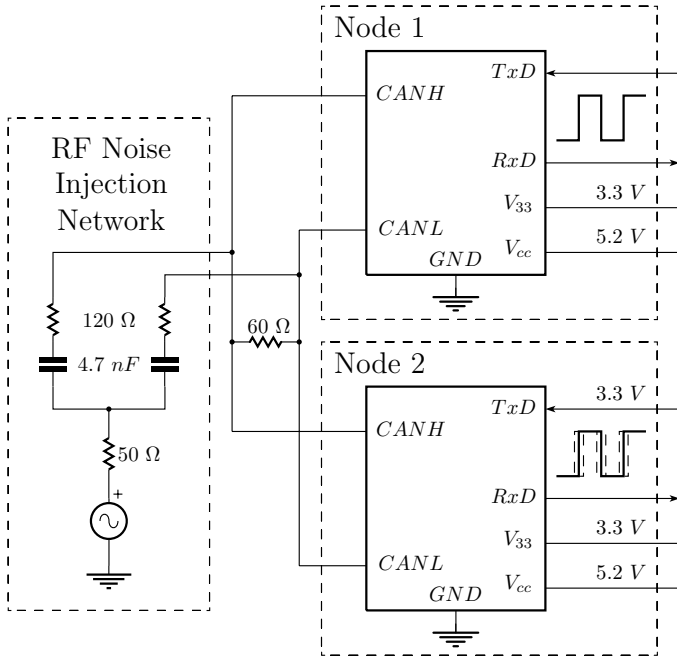
Figure 1. Schematic view of Direct Power Injection test for evaluation of transceiver susceptibility to RF disturbances in CAN networks
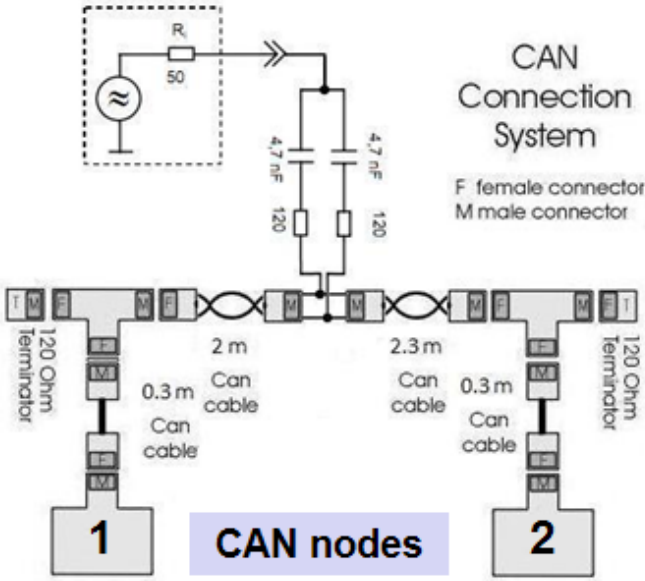

Figure 2. Network topology with two nodes

A CAN node consists of a transceiver and decoupling networks for monitored pins. Node 1 operates as a transmitter for a bit pattern, which simulates a CAN message to be received and monitored at the RxD output ports of all nodes in the configured network. A test communication signal with 0-1-0-1 data alternation is sent to Node 1 TxD port, with a bit rate equal to 1 Mbps (T_{Bit} = 1 μs), equivalent to a square wave signal with a frequency equal to 500 kHz, the maximum

possible bit rate on a CAN network.

To determine the immunity of the transceiver against RF narrow-band disturbances for each frequency, starting from 1 MHz onwards, disturbances are injected in the network increasing noise power level up to 36 dBm until a fault is detected. Although the noise power level is defined from the forward power generated by the disturbance source [8], only a fraction is transferred to the transceiver, depending on the IC port impedances at the corresponding noise frequency. As a fault criterion for immunity evaluation the maximum voltage variation on the RxD signal of every transceiver is checked: if a voltage variation equal or higher than 0.9 V is detected, a glitch occurred and a error event for this test is recorded. The bit period T_{Bit} is also monitored: a time variation equal or higher than 10% T_{Bit} (0.1 μs) fulfills the susceptibility criterion.

An analysis at network level regards the combination of equipment, integrated circuits, wiring and its load, in a standardized test equipment configuration. Thus, the IEC test method has been extended to measure the immunity towards RF disturbances on a CAN bus. A 2-node CAN network was assembled, whose topology is shown in Fig. 2. The network is based on a main bus, whose lengths is 4.3 meters, and the two TLE6250G33V transceivers [10] are connected through wire stubs 0.3 meter long, linked with 3-way T connectors. The wires are shielded twisted pairs designed for CAN bus [13]; on both ends of the main bus, two 120 Ω resistors are placed between CANH and CANL wires, to match the characteristic impedance of CAN twisted wires [9]. RF noise is generated by the voltage source and injected through the DPI RC subcircuit (R = 120 Ω, C = 4.7 nF) with a maximum noise power level equal to 38 dBm; CANH and CANL wires are connected to RC branches while wire shields are connected to ground, therefore the noise is injected directly into the wires without being attenuated by the shield. Immunity criteria [7] is checked on RxD signal of node 2 while node is transmitting a 0-1-0-1 signal with 1 Mbps bit rate.

III. COMMUNICATION NETWORK MODELING

In order to simulate the operation of a CAN network for the assessment of EMC problems, suitable models of CAN transceivers and wires are needed. The models must be efficient to yield reliable predictions of CAN differential transmission through the cables and to correctly assess their relationship with the local I/O digital signaling. The models are implemented in VHDL-AMS language [11], a modeling environment created with the intent of enabling designers of analog/digital mixed systems (AMS) to create and use modules that encapsulate high-level behavioral descriptions as well as structural descriptions of systems and components. It provides both continuous-time and event-driven modeling semantics, particularly well suited for verification of mixed-signal integrated circuits.

A. CAN Transceiver

In a CAN network, a transceiver is responsible for translating digital I/O data into CAN signaling on the bus. TXD and RXD ports carry the digital I/O data, while CANH and CANL have adjusted analog voltage levels to ensure communication based on differential signaling. The VCC port is connected to a 5 V power supply, while GND connects to the ground reference for both analog and digital ports. When describing CAN signals, the terms recessive and dominant are used to describe the state of the bus, corresponding to a logic '1' and '0' value respectively on digital I/O ports. In a twisted wire differential bus the recessive bus state occurs when the CANL and CANH lines are at the same voltage level, while the dominant bus state occurs when there is a difference in potential; the CAN bus remains in the recessive state when it is idle. Therefore the AMS model has to emulate all the CAN physical layer features included in the transceiver and the relationship between digital I/O data and CAN bus signals as well; thus signal propagation delay from TXD to CAN ports and from CAN ports to RXD has to be properly modeled, along with the correct differential voltage level required to switch from recessive to dominant state and vice versa.

The proposed approach to the modeling of active devices is via simplified circuit blocks, in which the information on the internal structure of the device is used to derive a simplified equivalent circuit for each port. The model is developed to be used in time-domain simulation, as the I/O ports of ICs are highly non-linear and the electrical properties are linked to their switching behaviour. In a CAN communication system, disturbances are typically injected in the bus network or through power supply, therefore in VHDL-AMS modeling environment the transceiver ports that could be affected by noise are modeled as analog ports, while other pins carrying control signals for the IC can be defined as digital ports.
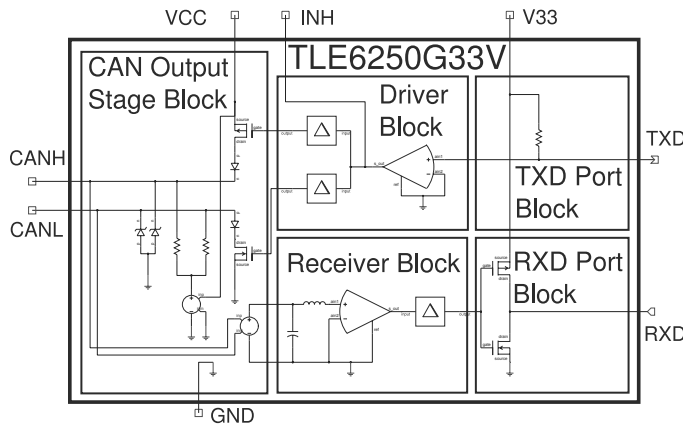

Figure 3.   TLE6250G33V CAN transceiver AMS model

The CAN transceiver block model is shown in Fig. 3 and its constituting blocks can be divided in two types:

1) *Port circuit block*: it physically describes the electrical connection between the corresponding port and the local
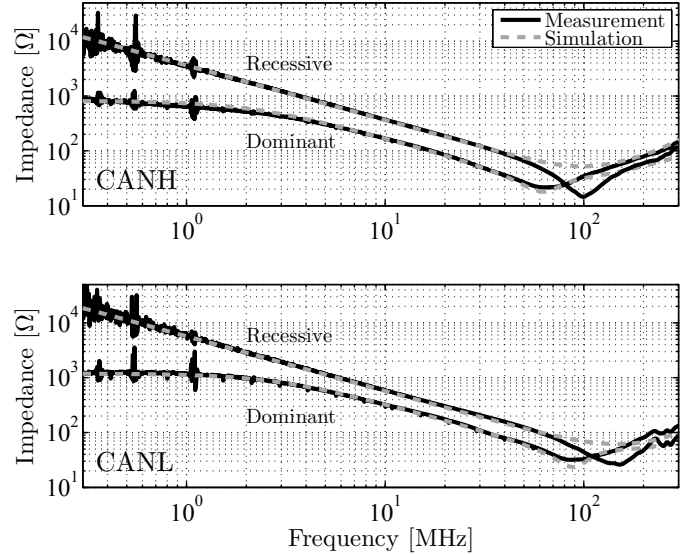

Figure 4.   CANH (top panel) and CANL (bottom panel) port impedances in dominant and recessive state. Solid lines: real measurement carried out on the transceiver; dashed lines: prediction obtained via the equivalent circuit of Fig. 3.

ground and power supply pins. The port schematic are taken from the transceiver datasheet [10]; TXD is a high-impedance port and RXD is a CMOS stage. CANH and CANL port circuits are branches made of transistors and diodes [12] linked to VCC and GND ports respectively. Transistors are turned on in dominant state and off in recessive state, in which the ports are put in a high-impedance state. Furthermore, ESD protection diodes connects CANH and CANL to GND port to protect the IC from transient noise. Together with LC parasitic elements, not depicted in Fig. 3 for picture readability, the block circuit is able to describe the port impedance up to 300 MHz in both logic state, as shown in Fig. 4, and any non-linear effect in order to correctly assess the noise coupling in a system-level EM analysis.

2) *Internal connection block*: it describes the IC inner structure and the link between different I/O ports. The characterization of the internal switching structure is done using a behavioural model, as the physical structure of the IC logic core is protected by Intellectual Property of the producer and not disclosed. The block is composed of AMS elements, such as comparators, filters and digital delays, and it has to model the internal propagation delay between different I/O ports. and the correct switching behaviour when driven by a noisy signal. The block parameters, such as comparator voltage threshold and internal propagation delay, have to be assessed from IC switching and DPI measurements in time domain. For further details about the AMS modeling procedure and the parameter estimation, the reader is referred to [6] and reference therein.

B. Cable Characterization

CAN cables [13] are shielded twisted wires compliant to CAN standard [9]. CAN analog signals are transmitted along
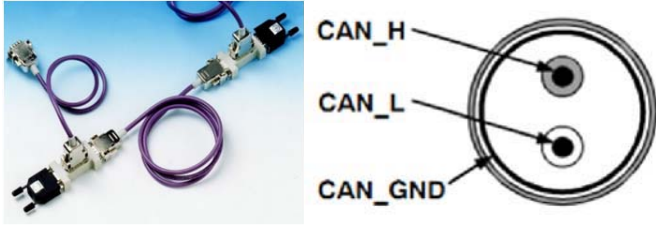
Figure 5.   Left: CAN shielded twisted cable [13]. Right: wire inner structure

CANH and CANL twisted wires, while CAN_GND shield is used as ground reference; therefore a 3 conductor structure has to be characterized.

The model is realized by means of an equivalent circuit composed of three transmission lines [14]; each line is modeled as lossless Branin model [15], where voltages v and currents i are calculated using the following equations, with T_d defined as transmission delay and Z_0 characteristic impedance:

$$v_1(t) = Z_0 i_1(t) + v_2(t - T_d) + Z_0 i_2(t - T_d)$$
$$v_2(t) = Z_0 i_2(t) + v_1(t - T_d) + Z_0 i_1(t - T_d)$$

The three transmission lines have the same propagation speed v, physical length l and relative dielectric constant $\epsilon_r = 2.5$, but their characteristic impedance is different: the two transmission lines between CANH and CAN_GND and between CANL and CAN_GND show a common mode impedance $Z_0 = Z_c = 60\ \Omega$, while the line between CANH and CANL has a differential mode impedance $Z_0 = Z_d = 120\ \Omega$ [9].

The multi-transmission line model [15] does not include losses or any frequency-dependent phenomena, but it is accurate enough to simulate these small CAN networks, as it is shown in the next section. If any higher-order effects have to be included to simulate longer network, a more accurate cable model has to used.

IV. NOISE IMMUNITY SIMULATION

The 2-node CAN network shown in Fig. 2 is simulated connecting the CAN transceiver and cable models developed in this paper to digital I/O signal sources.

Before simulating DPI test, a comparison between measurements and simulation results is done to validate the proposed model on a undisturbed communication test on the 2-node network. A good accuracy is obtained between measurements and simulations on digital signals and analog waveforms, proving that transceiver and wire models are able to correctly estimate, in time domain, both IC internal delays and cable transmission line behaviors, such as reflections and propagation delays.

After validating the network model, a single-frequency DPI test on 2-node CAN network is run in simulation, as described in section II. A 31.5 dBm 5 MHz noise is injected in the network from the RF signal generator through the DPI circuit; IEC susceptibility criterion [7] is fulfilled because a 10% jitter is detected on Node 2 RXD digital output signal. As shown
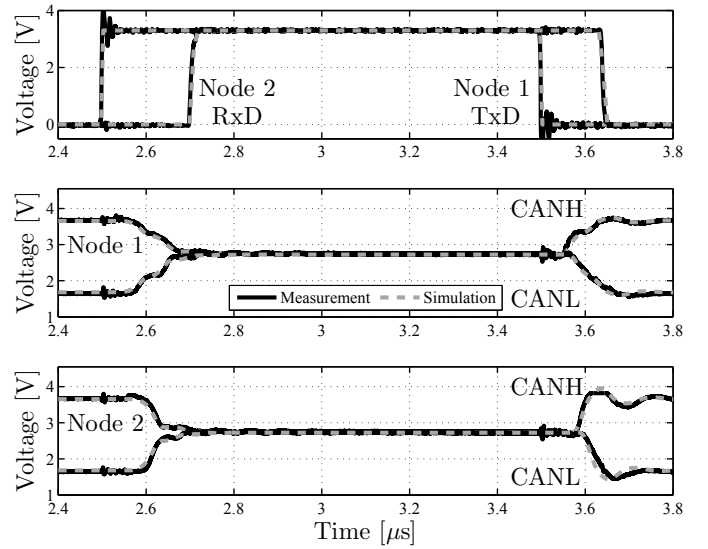

Figure 6.   Transmission test waveforms on a 2-node CAN network without noise injection

in Fig. 7, CAN analog waveforms (middle graphs - Node 1; bottom graphs; Node 2) from measurements and simulation are in good agreement and the susceptibility criterion is verified on digital signals (top graph), proving that the proposed models are able to perform a DPI test procedure in a simulation environment, as long as the injected noise frequency is included in a bandwidth where models were validated. It is relevant to remark that the simulation is able to assess the conversion of injected common-mode disturbance to differential noise, correctly evaluating its impact on communication between transceivers. The simulation time required to obtain these waveforms is 9.8 s on a commercial laptop, proving a good computational efficiency.

At last, the complete model of the 2-node CAN network is used to carry out a DPI immunity test at system level. For each frequency point starting from 1 MHz onwards, disturbances are injected in the network increasing the noise power level up to 38 dBm. In order to obtain a complete immunity graph, the parameters of the RF noise source have to be varied in the DPI circuit, therefore time-domain simulations are run in three nested loops: noise frequency, amplitude and phase.

The simulation results of a single-frequency DPI test on the TLE6250G33V transceiver are shown in Fig. 8 (top graph). On each graph the pulse width of the positive bit of the node 2 RXD signal is plotted with the corresponding RF noise power: an immunity criteria violation is found when the pulse width is lower than 900 ns, as the node 1 TXD input signal has a $T_{Bit} = 1\ \mu s$ and therefore a 10% variation is detected. The effect of the noise phase on the test results can be clearly seen as different pulse width values are recorded for the same noise frequency and power. The lowest noise power value provoking a failure is then recorded for each frequency as the minimum level required to fail the immunity test.

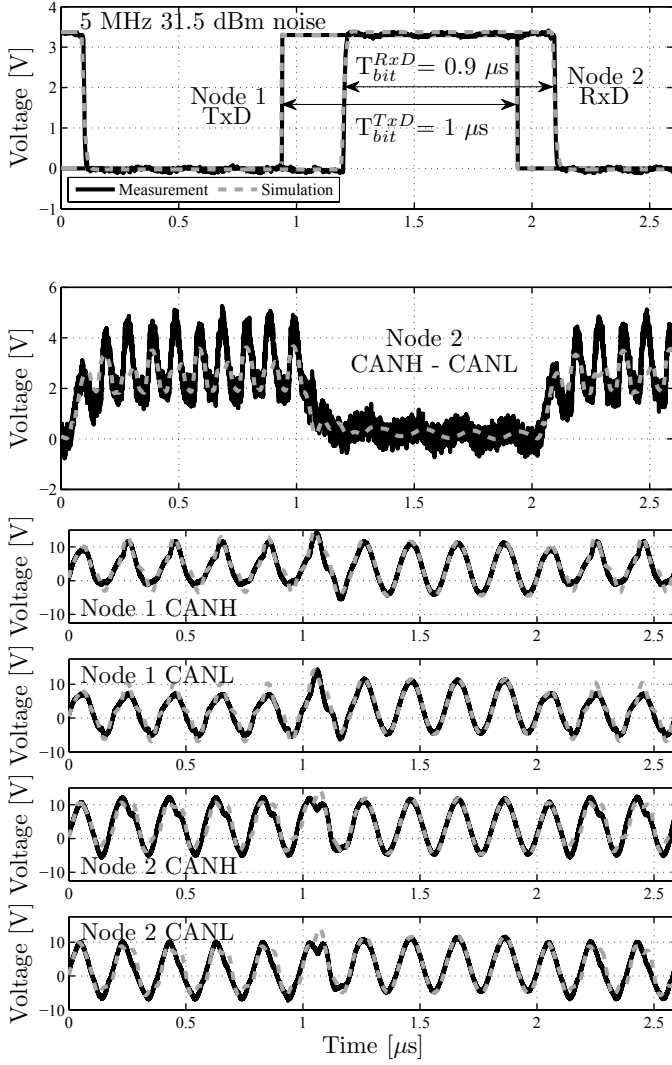The results are then collected into the immunity graph

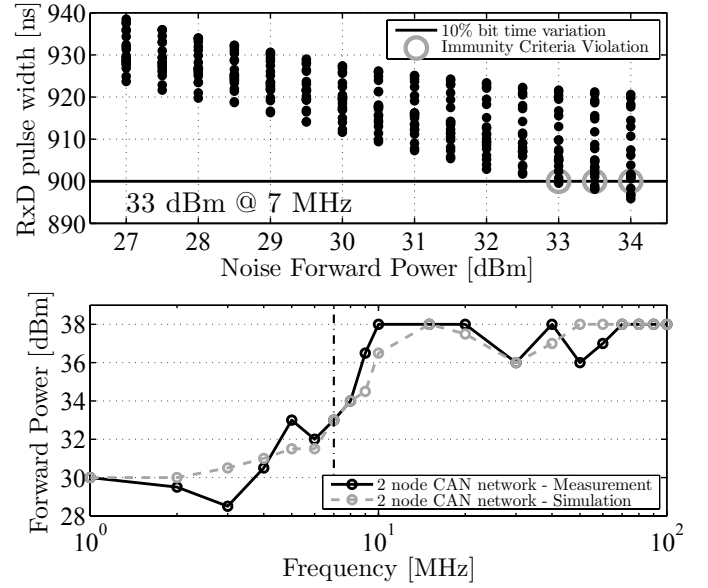Figure 7. 31.5-dBm 5-MHz RF noise DPI test simulation on 2-node CAN network

Figure 8. Node 2 Rxd signal pulse width jitter obtained in DPI simulation on TLE6250G33V transceiver at 7 MHz for different noise power level and phase (top graph); DPI immunity graph measurement and prediction on 2 nodes CAN network (bottom graph).

models and it allows to predict the behavior of CAN networks when affected by RF disturbances.

A characterization of a realistic CAN bus and the corresponding immunity measurements have been carried out and the feasibility of testing noise immunity in a simulation environment has been proven. The immunity model was validated by reproducing the standard DPI test with RF noise injection and a good agreement between measured waveforms and simulation is obtained. It was shown that the model can be used to predict the resulting immunity graph, leading to a deeper understanding of the network behaviour at system level. The prediction helps to evaluate the available noise margins and to determine critical levels at a design stage.

shown in Fig. 8 (bottom graph) and it shows good agreement between the data obtained by measurements and the simulation of the immunity test on the equipment. At 1 MHz both the real CAN network and the model returns 30 dBm as a maximal acceptable value of the RF noise power. For the frequency range from 2 MHz up to 15 MHz, this value increases for both setups, with the exception of 2 and 3 MHz frequencies where the maximum errors is 2 dB. For frequencies higher than 15 MHz, the network is able to withstand RF noise whose power is between 36 and 38 dBm, a very high power level. To obtain the results of this test, the simulation time is about 14 hours on a common laptop.

V. CONCLUSION

In this paper the noise immunity testing at system level on a mixed-signal communication network is addressed. The AMS modeling strategy is based on the combination of ICs and wire

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