

# SYSTEM LEVEL MODELING, SIMULATION AND VERIFICATION OF A CAN PHYSICAL LAYER STAR NETWORK USING BEHAVIOR MODELING LANGUAGE

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## KEYWORDS

CAN physical layer verification, CAN network system modeling and simulation, CAN star topology, Mentor Graphics System Visions, VHDL-AMS.

## ABSTRACT

The star topology is sometimes used in automotive applications to overcome wiring constraints within a car. It has to be mentioned that star topology is neither covered by ISO11898 nor by SAE J2284 therefore it is recommended to prove the feasibility of a specific topology in each case by simulations or measurements on a system setup (NXP-Semiconductors 2006). This paper considers the verification of an 8-node CAN physical layer star network by using behavior modeling and simulation in comparison to measurement. The main purpose is to verify the CAN transceiver behavioral model together with other CAN physical layer simulation components against measurements at system level. The measurement environment of the CAN network modeling methodology is discussed, showing how to get the measurement and simulation results matched. This demonstrates that it is a reliable simulation solution, which is highly desirable and very important for the verification requirement in CAN physical layer design. Last but not least, the paper also shows that different network topologies at different transmission rates can also be simulated to gain better understanding about the behavior of CAN network in the early phase of design process.

## INTRODUCTION

Designers face challenges in implementing hardware of CAN network's architecture, topology, termination and interconnect. The main task in analyzing physical layer is to identify and evaluate signal integrity issues for the network (Synopsys 2007). The transmitted and received waveforms need to be checked against system specification. Problems which relate to the physical layer will impact the entire communication system, slow down the network performance or cause errors in the control system behavior. Moreover, in-vehicles networks nowadays also have a very high complexity

due to the increasing number of ECU and functionalities. From an analysis of almost 100 different topologies of auto makers all over the world, more than 50% of these designs failed when all the parameters involved had been in their worst-case conditions (Lawrenz and Bollati 2007). Therefore, there is a very great demand in verifying such critical designs.

Almost all car manufacturers and semiconductor suppliers have started simulations based on different modeling activities as a part of their development and verification process (Thorsten and Carsten 2005), (Pelz et al. 2004), (William et al. 2007), (Ravatin et al. 2002). They tried to simulate the in-vehicle network with different types of models (e.g. VHDL-AMS models, MAST models). However it is still not clear how much one can rely on simulation because putting the simulation models together and simulating those do not necessarily mean that simulation will reflect the physical system.

Improving CAN network reliability and quality requires a comprehensive and reliable simulation environment to manage complex communication network issues. A reliable simulation solution means that simulation should resemble real situation by at least 80%. In order to achieve a reliable simulation solution, simulation models need to be verified for its accuracy against the physical models. Several verification techniques are discussed in (Pelz 2003), however, these techniques concentrate on verification of the simulation models at conceptual level. One of the disadvantages in these techniques is that although the verification process is carried out at each the individual models, putting them together do not mean the simulation system will reflect the same as in reality. This paper aims to simulate all of CAN physical layer components in the context of system level, which means that not only the transceivers, chokes, transmission lines are simulated but the measurement environment of the CAN network is also taken into account. This is also a key for the matching between measurement and simulation.

## Components of CAN physical layer

The CAN physical layer presented in this work involves the following main parts:

- CAN Transceivers
- Choke coils are placed between the transceiver and the bus line to harmonize non-symmetric differential mode signals
- CAN bus line/ Twisted-pair transmission line
- Termination circuits are typically attached to the end to transmission line to reduce reflection on the CAN Bus

## Nominal voltage level on the CAN bus

Figure 1 shows the nominal voltage level on a CAN bus when it operates ideally. A bus node shall detect a recessive bus condition (bit '1' is transmitted) when the voltage difference between CAN\_H and CAN\_L is not higher than 0.5V. The bus dominant condition (bit '0' is transmitted) shall be detected if the voltage difference between CAN\_H and CAN\_L is more than 0.9 V. When the bus operates at recessive mode, both CAN\_H and CAN\_L have 2.5V amplitude, while it is 3.5V for CAN\_H and 1.5V for CAN\_L when the bus operates at dominant mode.

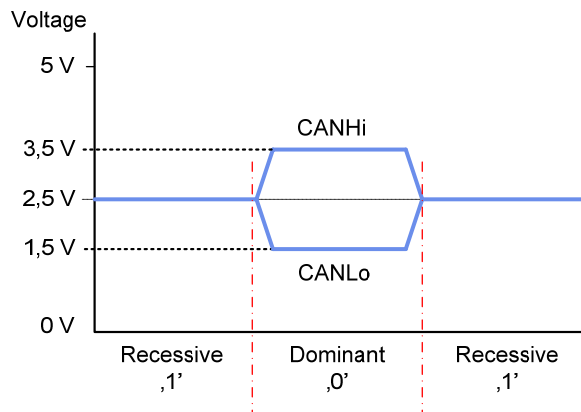


Figure 1: Nominal voltage level on CAN bus

## THE SYSTEM MEASUREMENT SETUP

For demonstration, a full CAN network is developed for measurement. The measurement CAN network consists of 8 nodes connected in star topology with different stub lengths as shown in Figure 2. A split termination circuit ( $2 \times 62\Omega$  and  $1 \times 47\text{nF}$ ) is implemented at the star connection point. At every node, the new choke coil founded in (Nguyen et al. 2008) with higher coupling factor between the two wires in the coil, is used to effectively reduce ringing on the CAN network.

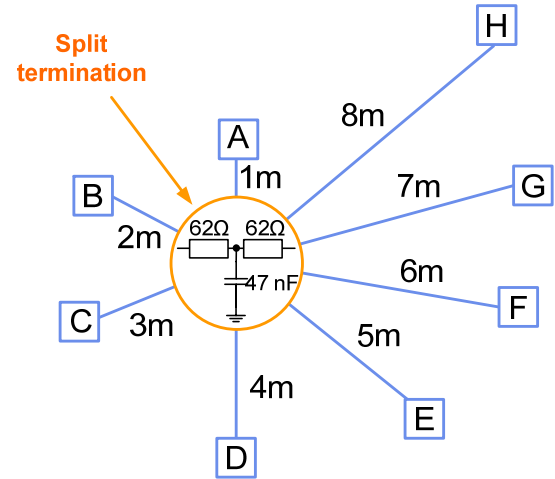


Figure 2: The 8-node star CAN network with different stub lengths configuration

The whole CAN measurement setup with measurement equipments is shown in Figure 3.

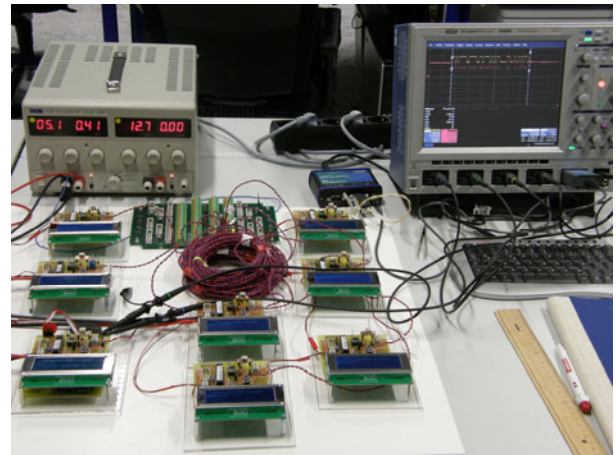


Figure 3: The 8-node CAN measurement system

A CAN triggering module from LeCroy, which will be explained in more details, is used together with the oscilloscope for the measurement of CAN\_Hi and CAN\_Lo signals.

## MODELLING OF THE CAN PHYSICAL LAYER COMPONENTS

### System Vision simulation environment

All of the components of the 8-node CAN physical layer network were modeled with VHDL-AMS and 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 or

parameters sensitivity analysis. Description of simulation models is discussed in the following sections.

### Transceiver simulation model

Signal integrity of the CAN network is fundamentally impacted by transceiver (Thorsten and Carsten 2005). Therefore the transceiver model must be very accurate. A model of the CAN transceiver, developed by Infineon Technologies AG, is used. It was specially modeled for system simulation using VHDL-AMS because of simulation speed and accuracy reasons.

Figure 4 shows a block diagram of the Infineon CAN transceiver. The transceiver simulation model covers all required functions such as temperature monitoring, and bus failure detection. It has a complex structure with similar behavior as the physical model.

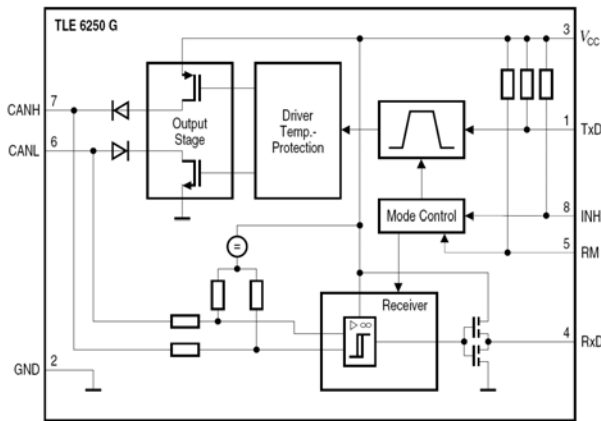


Figure 4: Block diagram of a CAN transceiver from Infineon Technologies AG

### Common mode choke simulation model

Common mode choke coils placed between transceiver and the bus line help to filter out common mode signals noise produced by RF noise and non-perfect transceiver driver symmetry (NXP-Semiconductors 2006). In (Nguyen et al. 2008), the coupling factor between two wires in the choke is proved to have a very big impact on the signal integrity on CAN bus. Choke coil also becomes an important component at the CAN physical layer. The choke coil model was also developed with VHDL-AMS based on the spice model provided by EPCOS. Therefore it has a very accurate behavior.

### Transmission line simulation model

One of the critical parts in the simulation test bench is the transmission line simulation model (Lorena Diaz 2005). The transmission line model is modeled with VHDL-AMS. The model parameters (e.g. characteristic impedance, propagation delay, length etc.) are characterized and determined via measurements. The

star cable tree is then modeled by single transmission line model with different length connected together. This can be easily achieved by using SystemVision Schematics/Designes entry.

## MODELLING OF THE CAN SYSTEM MEASUREMENT ENVIRONMENT

In order to achieve a good match between measurement and simulation, not only the core components of the CAN physical layer are carefully modeled but also the measurement environment (e.g.: measurement probes, CAN triggering module termination resistor and CAN frame generator) of the 8-node CAN system is taken into consideration.

### The measurement probes model

Probe basically provides a physical and electrical connection between measurement point/signal sources to an oscilloscope. A passive voltage probe has a typical equivalent circuit as shown in Figure 5

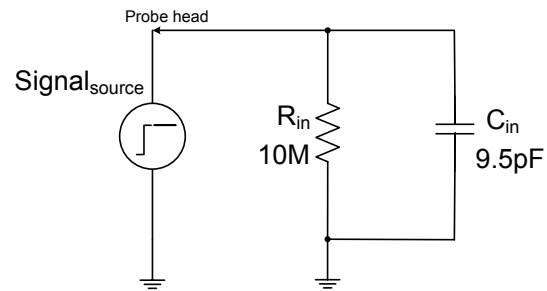


Figure 5: Equivalent circuit of a typical passive voltage probe

Measurement probe of oscilloscope is modeled by a capacitor connecting in parallel with a high-ohmic resistor. During the verification process, a comparison between active probe and passive probe is carried out, showing that better measurement results and better matching can be achieved when using active probe. Active probe has basically very low input capacitance and resistance with some compensated network compared to passive probe. In this paper, the two measurement probe models are different only in their capacitance and resistance values.

```
entity capacitor is
  generic(c:real:=1.0e-9);
  port(terminal p, m : electrical);
end entity;
```

architecture behav of capacitor is

```
quantity v_pm across i_pm through p to m;
```

```

begin
    i_pm==c*v_pm'dot;
end;
-----

```

Listing 1: An example of capacitor model by using VHDL-AMS modeling language

### CAN triggering module termination resistor

For the measurement of the CAN network, a CAN triggering module from LeCroy is used besides the oscilloscope. The CAN triggering module is a CAN node that is set to filter and provide triggering signal when certain conditions are met. It interfaces with the CAN bus by a twisted pair with its own 120Ohm termination resistor. For the verification of the 8-node CAN network in this paper, this termination resistor is considered as a part of the simulation system. Otherwise, it will show different in amplitude of the compared signals. This phenomenon has been observed and simulated at the beginning of our modeling process. The resistor is modeled exactly at the point which it is connected in the network.

### CAN frame generator

The CAN transceiver input is CAN frame (CAN message) which is generated from CAN microcontroller. In Figure 6, it shows a CAN message recorded from the 8-node CAN network. It is important to keep in mind that, the CAN microcontroller is not simulated in this work. The transmission speed of a CAN network in reality is decided by the CAN microcontroller. One can measure the transmission speed by measuring the duration of a single bit on a CAN frame. For example, if a CAN bit has duration of 2 microseconds; the transmission speed is 500kbps.

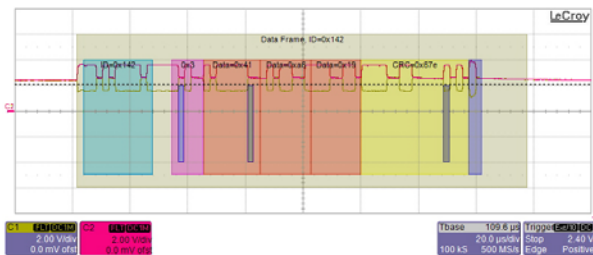


Figure 6: Example of a CAN frame recorded from the 8-node CAN network

In order to model the CAN microcontroller output to an abstract level, it is necessary to be able to reproduce exactly at least the smallest bit in a CAN frame which is really generated by the CAN microcontroller. This is the whole idea of modeling the CAN frame generator whose generics are the bit duration (to determine the transmission speed) and the ramping time from 0 to 1 level. The CAN frame generator model generics were

carefully configured as exact as the measurement value of a CAN frame bit from the real microcontroller. By this way, we can be certain that the microcontroller is not necessary to be simulated, hence it saves time and complexity for the simulation but still can produce a reasonable simulation results.

### THE 8-NODE CAN NETWORK SIMULATION TEST BENCHES

Each of the models is created with a graphical symbol. This helps the simulation test benches in this work to be setup easily with Schematics/Designs entry of System Vision. All the simulation models described in the previous sections are connected together exactly the way they are arranged in the measurement setup as shown in Figure 7. A transient simulation is then performed. With the test bench, it is possible to setup different network topologies with a variety of cable stub length or different transmission rates and simulate them.

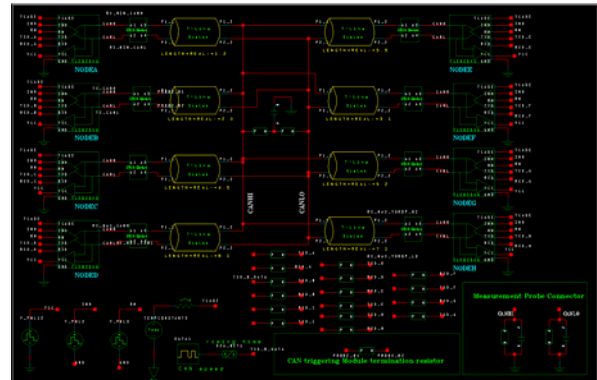


Figure 7: The 8-node CAN network simulation test benches with Schematics/Designs entry from System Visions of Mentor Graphics

Major differences between measurement and simulation setup are power supply, battery voltage sources and ground. In simulation test bench all of the electric sources and ground are set to be ideal.

### VERIFICATION OF THE EIGHT-NODE CAN PHYSICAL LAYER STAR NETWORK

#### Verification of CANHi and CANLo signals at star connection point

In this section, comparison between measurement and simulation signals at the star connection point (CANHi and CANLo) is discussed. The results of measurement and simulation are compared by plotting in the same figure. The first verification is carried out on the 8 node CAN star network operated at 500Kbps transmission rate. The comparison shown in Figure 8 shows that deviation between measurement and simulation is quite small.

However, when looking close to the behavior of the CANHi and CANLo signal changing from dominant to recessive mode, it shows a faster switching behavior by measurement than simulation. In order to fit the simulation curves, different values of the capacitors used in the measurement probe models were simulated. Decreasing the capacitance value results in a faster switching behavior of the CANHi and CANLo signals in simulation. A new measurement is then performed by an active probe and the same simulation test bench is simulated again with the new value of the capacitor (0.95pF) and resistor (1.0MOhm) from the active measurement probe.

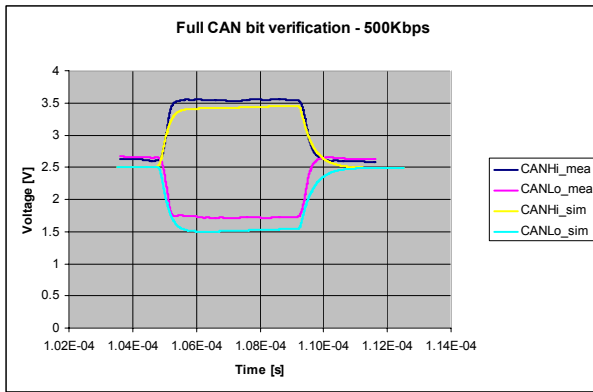


Figure 8: A full CAN bit comparison of CANHi and CANLo signal at star connection point of 8 nodes CAN network (500Kbps transmission rate) using passive measurement probe (10.0 MOhm + 9.5pF)

In

Figure 9, it shows a new comparison between measurement and simulation when using an active measurement probe model.

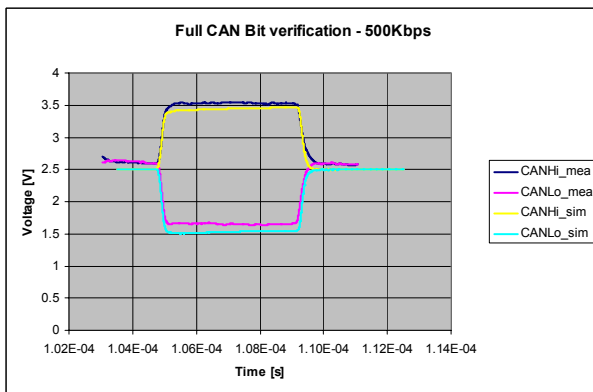


Figure 9: A full CAN bit comparison of CANHi and CANLo signal at star connection point of 8 nodes CAN network (500Kbps transmission rate) using active measurement probe (1.0 MOhm + 0.95pF)

The matching of switching behavior from dominant to recessive mode of CANHi and CANLo signal is

significantly improved with the model from active measurement probe.

The same setup of measurement and simulation is applied for verification at transmission rate of 1.0Mbps. Once again, it shows a very good matching between measurement and simulation results of CANHi and CANLo signals at star connection point in Figure 10.

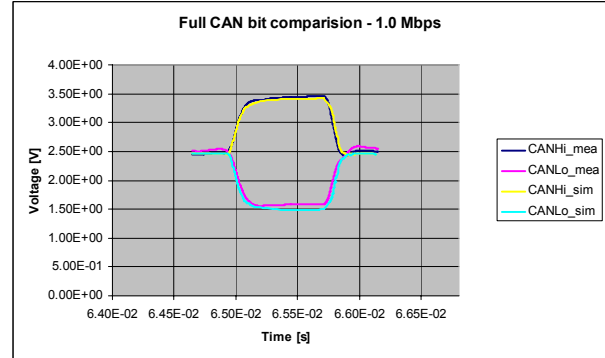


Figure 10: A full CAN bit comparison of CANHi and CANLo signal at star connection point of 8 nodes CAN network (1.0Mbps transmission rate) using active measurement probe (1.0 MOhm + 0.95pF)

### Simulation of Tx and Rx signals of the CAN micro controller interface

The CAN system used in this paper can visualize the whole CAN protocol up to application layer. As mentioned above, this CAN system is mainly developed for the measurement purpose. The control pin RM is connected to 5.0V while the pin INH is connected to ground for a low level signal. By this setup, the CAN nodes are tested at their normal operation mode as shown in Figure 11.

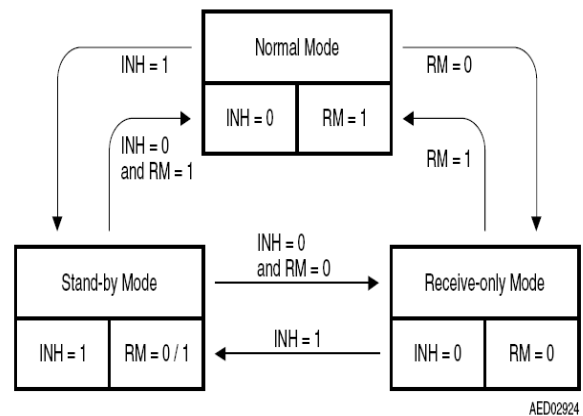


Figure 11: Mode state diagram of the Infineon CAN transceiver used in this work

As demonstration, a simulation scenario from Stand-by mode switching to Normal mode is performed. The control signal RM and INH are modeled by a piecewise linear voltage source (V\_PWL). The RM signal starts



at 0.0 second and remains its 0.0 volt for duration of 2.0 nanoseconds and then it is switched to 5.0V for the rest of the simulation time (300 microseconds). In a similar way, the INH signal starts at 0.0 second with 0.0V until the 2<sup>nd</sup> nanosecond, then it switches to 5.0V until 50.0 microseconds then it switches back to 0.0V for the rest of simulation time.

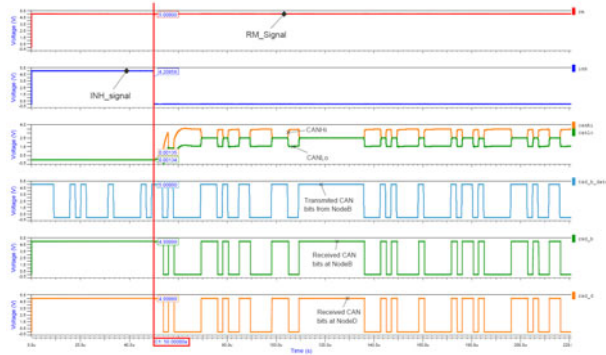


Figure 12: Simulation scenario of 8 node Star CAN network from Stand-by operating mode switching to Normal operating mode

With this setup as shown in Figure 12 (the 1<sup>st</sup> and 2<sup>nd</sup> windows correspond to RM and INH signals respectively), the simulation shows that the first 50 microseconds of the simulation time all the CAN transceiver are at the Stand-by mode because RM = high and INH = high. During this first 50 microsecond, bus voltage is 0.0V (please refer to Figure 12, the 3<sup>rd</sup> window which shows CANHi and CANLo voltage level) demonstrate that there is no communication between the 8 nodes regardless CAN bits from Tx pin interface of the CAN micro controller on NodeB are already transmitted (please refer to Figure 12, the 4<sup>th</sup> window which shows CAN bits transmitted from NodeB).

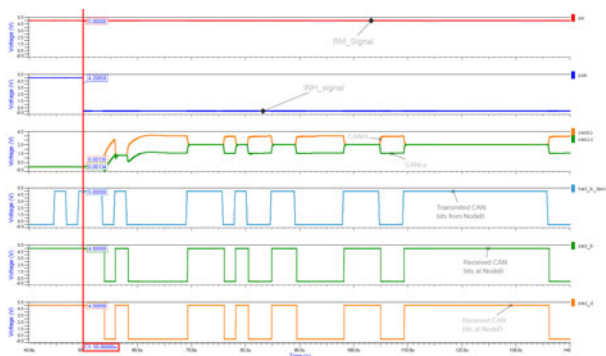


Figure 13: Simulation scenario of 8 node Star CAN network from Stand-by operating mode switching to Normal operating mode – Zoom 40 us to 140 us

The 5<sup>th</sup> and 6<sup>th</sup> represents for the CAN bits received from NodeB and NodeD respectively. It shows also that the first 50 microseconds, NodeB and NodeD could not receive any CAN bits due to the CAN transceivers are

set to Stand-by mode. For the last 250 microseconds of the simulation, all the CAN transceiver is set to operate at Normal mode because of the control signal state RM=high and INH=low (please refer to Figure 11).

By comparing CAN bits transmitted and received in the 3<sup>rd</sup>, 4<sup>th</sup>, 5<sup>th</sup> windows of Figure 13, it shows that all the bit transmitted from NodeB are received by NodeD and NodeB itself (CAN is a serial broadcast communication protocol). All the received CAN bits at NodeA to Node H are checked however they are not shown here due to writing space limitation. Electrical signal CANHi and CANLo of CAN bus at star connection point are also correctly demonstrated based as described in Figure 1, excepted some the first several CAN bits which are not 100% matching to the nominal voltage level on CAN bus. This is explained by the electrical transient switching behavior of the CAN transceiver.

## CONCLUSION

With the implementation the new choke coil BS82789C513 with a very high value of the coupling factor and a proper termination circuit, the star configuration topology described above shows a quite stable behavior of the electrical signal on the CAN physical layer. The good matching between measurement and simulation once again proves that the models used in the simulation system are accurate and very reliable. Models of measurement probe, the CAN triggering module termination resistor as well as the CAN frame generator model should not be ignored when performing the system modeling, simulation and verification against real measurement.

The described modeling methodology also shows that the CAN physical layer is able to be simulated up to the interface of the CAN microcontroller without having to model and simulate the CAN controller. This is a real advantage in reducing the complexity of the simulation system, thus reducing the computational effort and simulating time.

The next part of this work will focus on using these accurate simulation models to investigate the behaviors of a larger CAN network with different types of topology (linear bus, star or hybrid) at different transmission speed. Bus error detection and network delay analysis by using simulation will be also the next steps.

## ACKNOWLEDGEMENT

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