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The enormous increase of vehicle functions realized through electronic components significantly impacts the communication within the vehicle network. More functions are requesting higher bandwidth; safety applications require a deterministic communication scheme to ensure reliable system performance even under harsh real world conditions. The new FlexRay vehicle communication standard addresses these requirements, with production networks already on the road. The high transmission rate introduces new challenges for network developers dealing with the implementation of the electrical physical layer as the dynamic behavior of the system cannot be predicted using manual calculations. The FlexRay physical layer working group has therefore established a simulation task force dealing with issues related to FlexRay's physical layer implementation. This task force has developed a virtual prototype based methodology to give network developers early verification of FlexRay physical layer implementations. Topology variants that depend on equipment in the vehicle can be investigated quickly with regard to their robustness under nominal and even worst

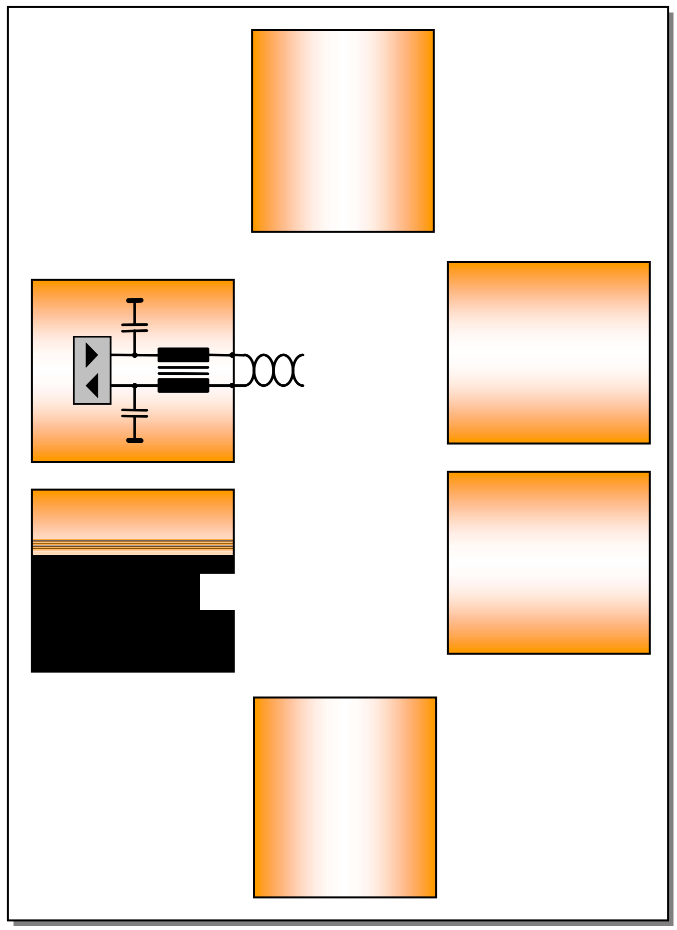
In order to build up a virtual prototype for the FlexRay topology implementation, a simulator and a simulation model of the topology is needed. The simulator of choice is the Saber® simulator from Synopsys® Inc. which has the ability to simulate analog/mixed-signal systems and supports a robust design methodology. In addition, Saber supports the popular MAST (open industry standard) and VHDL-AMS (IEEE standard) modeling languages as well as models created in PSpice, HSpice and Berkley Spice. Flexible language support is required as OEMs typically receive models from multiple suppliers who use various language formats.

Derived from the evaluation criteria above, a simulation model is needed that allows analyzing the network implementation before the real vehicle prototype is available. The components that need to be considered for the simulation are:

- FlexRay Bus driver (transceiver)
- Transmission line
- Split termination for the ECU
- ESD protection (in terms of signal integrity aspects)
- EMC or HF circuitries that significantly contribute to the overall signal integrity

For the FlexRay bus driver a model for the TJA1080 from NXP semiconductor [8] has been chosen. This is a behavioral model of the IC component and was specially created to address the needs of system simulation. It is a compromise of simulation speed and accuracy. In addition, the model lets developers analyze the worst case behavior of the transceiver component. This will be described in more detail later in this document.

The behavior of the transmission line is covered through a frequency dependent transmission line model known as the w-element [5] which is the most accurate transmission line model for signal integrity analysis. The requirements of the model were standardized by the FlexRay consortium, and the FlexRay simulation task force defined corresponding test benches to validate the accuracy of the simulation model. Figure 6 shows a comparison of simulation results and measurements that were done for one of these test benches. All models can now be put together in a test bench. The design under test contains six ECU nodes similar to the FlexRay backbone network in figure 2. The overall topology of this



implementation is shown in figure 7. The network is a passive star topology. In addition, the nodes A and F are low impedance terminated as suggested by the FlexRay EPL specification. It should be noted that this is not necessarily the optimal type of termination. It may be that another termination method could be more efficient. This is up to the experience of the network developer and depends on the specific network implementation. Simulation can also help to investigate this issue very early in the development and concept phase.

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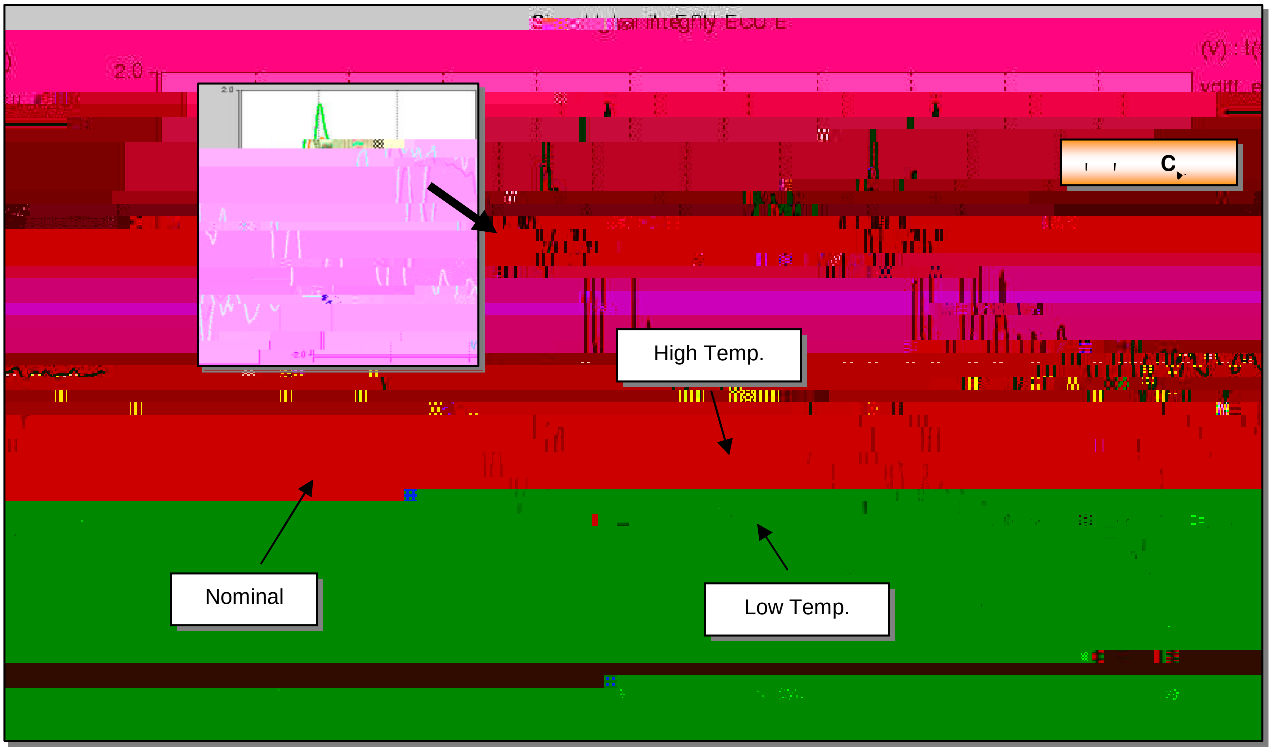
A nominal design analysis is the first simulation to be performed. This means topology parameters are set to their nominal values without any variation. For a complete analysis of the overall topology in figure 7, a Round Robin communication is performed. Each ECU acts once as transmitter and sends a test pattern to the network; signal shapes are then evaluated for all ECUs. For the representation of simulation results, the test plane definition as specified in the FlexRay EPL specification and as depicted in figure 8 is applied. Simulation results for a nominal topology configuration are shown in figure 9 where ECU C is acting as transmitter and sends a single bit to all other ECUs. Figure 9 shows the differential mode signal for ECU E at test plane 4. This test enables the analysis of several important items. Figure 10 shows the transmit signal at ECU C (upper signal) and the digital receive signal of ECU E. In FlexRay, each communication element starts asymmetric delay. The last step contains the definition of customized results documentation. Microsoft Excel is a common platform typically used for documentation purposes to exchange information between OEMs and suppliers. Saber's environment is based on the interpreted TCL/TK language and allows through the Windows COM interface a communication with Microsoft applications like Excel. This connection is used to create an automated report showing the simulated values of the asymmetric delays. This approach allows any extension for any arbitrary customized verification procedure. The automation might be extended to contain e.g. the information about the simulated propagation delay, the truncation of the TSS or any other required evaluation criteria. Figure 13 shows a possible output format for the evaluation of the asymmetric delays for a Round Robin communication. This matrix representation contains transmitters and receivers and covers all possible



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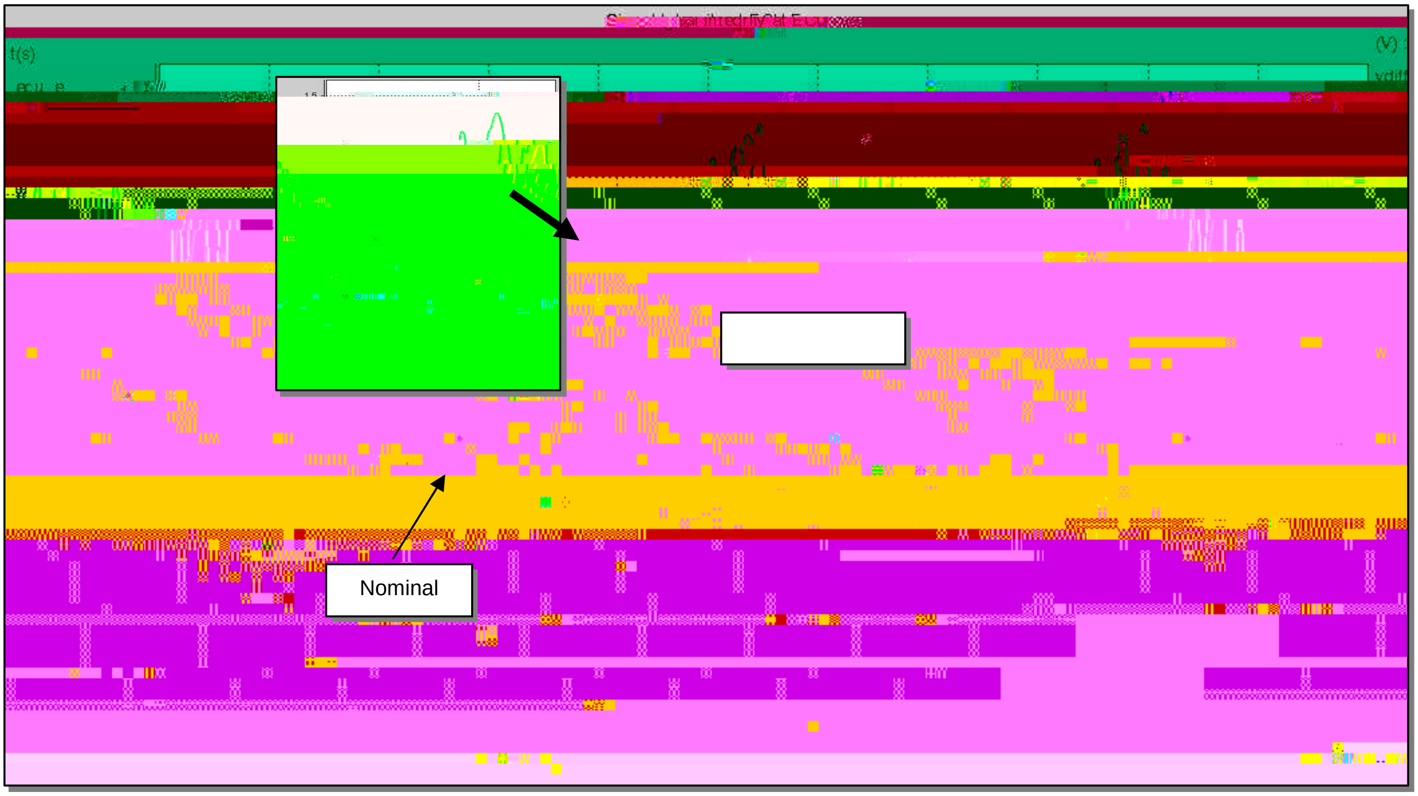
- Low temperature (all component parameters are set to their worst case values for low junction temperatures)
- High temperature (all component parameters are set to their worst case values for high junction temperatures)
- Receiver mismatching (considers mismatching of receiver thresholds)

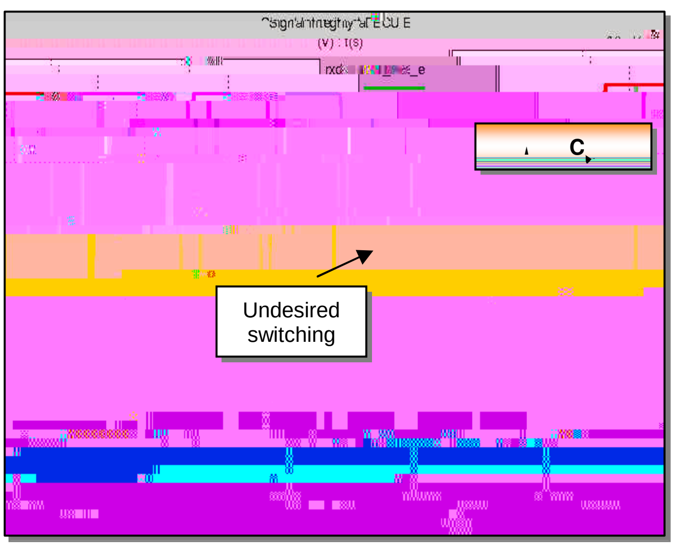
All of these items are very important and must be taken into consideration since they have a significant impact on a variety of items:

- Differential output voltage
- Threshold for differential voltage detection
- Signal propagation delay through transceiver
- Rise and fall time of state transitions
- Idle and activity detection time.

Following the investigation of the nominal case we must now take into account the possible variations of this component. The experiment for this is once again a Round Robin communication. The difference when compared with the nominal analysis is that the complete Round Robin communication cycle is repeated several times for different operational states of all transceiver instances in the topology. This kind of analysis in Saber is a variation loop. Since we need to take into consideration the behavior at nominal, low and high temperatures, and have to consider the mismatching of the receiver thresholds, a nested variation loop will be performed. Figure 14 shows the simulation results for a variation at ECU E when ECU C is acting as transmitter. Depending on the operational state of the transmitting node, the level of the differential voltage changes significantly. The magnitude of the circuit ringing is also heavily dependent on the operational state. This analysis must be done for all nodes of the topology as the behavior of all nodes can differ significantly and cannot be derived from the analysis of one single node. Taking a look at the simulation results when ECU F is acting as transmitter and ECU E receives the single bit, as depicted in figure 15 and 16, tolerance issues can cause undesired switching of the digital receive pin Rxd at ECU E. This may lead to a sampling error since it occurs at around 75% of the bit time and must be treated carefully. It is up to the network designer to analyze whether a change in the implementation of the topology is needed to make the topology more robust and reliable against variations. Perhaps the termination concept can be revised again to help improve the behavior at Node E. In addition, the asymmetric delays for each ECU must be evaluated. The evaluation for the variation analysis is now different when compared with the nominal case. For the nominal case only one measurement was obtained. For the variation analysis the result of the simulation is an array of asymmetric delays for each ECU. In order to prove the quality of the topology implementation, only the maximum delay value at each ECU is relevant and needs to be taken into consideration. A manual evaluation of this would be pretty time consuming. As



with the nominal case analysis, the post processing has been automated and a matrix is generated containing the maximum values of asymmetric delays based on variations for all simulation scenarios of the Round Robin communication. Figure 17 shows the Excel report that is automatically generated after the simulation. The field for



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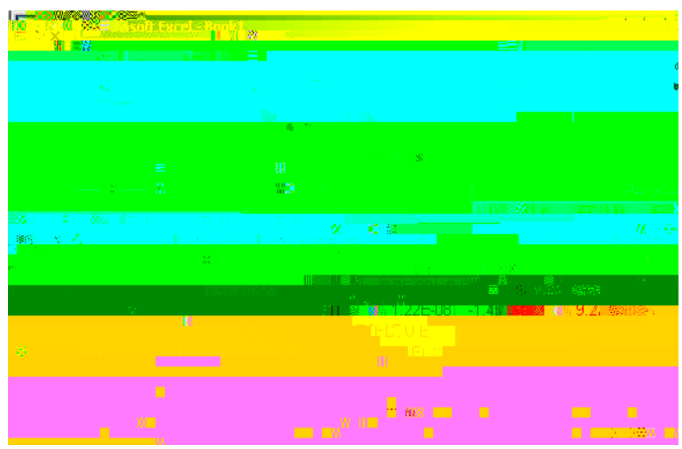
ECU F acting as transmitter and ECU E acting as receiver is marked in red. Due to the undesired switching at ECU E's Rxd pin, no measurement is available. From the simulated matrix above it is now very obvious that it is a fundamental requirement to take variations of the transceiver into consideration. The maximum value for the asymmetric delay is now 22.5 ns. The maximum asymmetric delay for the nominal case is -7.6 ns (see figure 12) which is only a third of the worst case. Taking into account an additional reserve against



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RF injection issues, and additional parasitic effects that have not been modeled, the system is very close to its limits but still within the range specified by the FlexRay EPL specification (±30.75 ns).

The benefit of this automated evaluation approach is now even more obvious than before since the network developer must only compare the values of the automatically generated Excel report with the limits specified in the FlexRay EPL specification or additional OEM specific requirements. This is one of the additional benefits of automating the evaluation process using system simulation.

The previous example has shown that an in depth understanding and comprehensive analysis of FlexRay topologies is needed in order to ensure a reliable implementation. The development and evaluation process for FlexRay topologies can almost be completely automated through system simulation. It requires the automatic evaluation of all important aspects of the FlexRay EPL specification as defined through limit values like the asymmetric delay example described here. An example output for a completely automated evaluation process for FlexRay electrical physical layer topologies is depicted in figure 18. Similar to the automation of the asymmetric delay analysis, additional sheets are added to the Excel report taking into account:

- Propagation delay
- Truncation of TSS
- Detection of undesired switching
- Shifting of Channel Idle Recognition Point (CHIRP, Transition from active to idle).

This output bundles together all required information to evaluate the reliability of the topology in terms of signal integrity.

glance the reliability of the implementation against component variations. The paper shows an example method depicting how the network developer can evaluate all items of the FlexRay EPL specification and OEM specific requirements through simulation and view the results at a glance in a single topology workbook.

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[1] FlexRay Consortium, www.flexray.com

[2] FlexRay Specification 2.1