BASIS OF ELECTROMAGNETIC COMPATIBILITY OF INTEGRATED CIRCUIT

Chapter XII - MODELLING IC SUSCEPTIBILITY - BASIC CONCEPTS

Corrections of exercises

I. EXERCISE NO 1 - DPI injection into circuit pads

The input impedance of two pads—Pad 1 and Pad 2—in an integrated circuit has been characterised with a vector network analyser. The measurements are shown in the figure below and can be found in files book\ch12\Zin_pad1.s1p and Zin_pad2.s1p. The IC is supplied with 3.3 V. Pad1 is a digital input with high and low level input voltage limits equal to 2.6 V and 0.7 V respectively. Pad2 is the input of a 10-bit analog-to-digital converter (ADC). The conducted susceptibility of the circuit is tested according to IEC62132-4. Both pads are supposed to be local pins and heir susceptibility levels have to comply with severity level 3 according to Table 9-1. We neglect the influence of ESD protections.

1. Build the equivalent electrical model of both pads.

2. Build the model of the DPI injection test bench. Precise the components used for the test, the frequency range and the maximum amplitude of the disturbance.

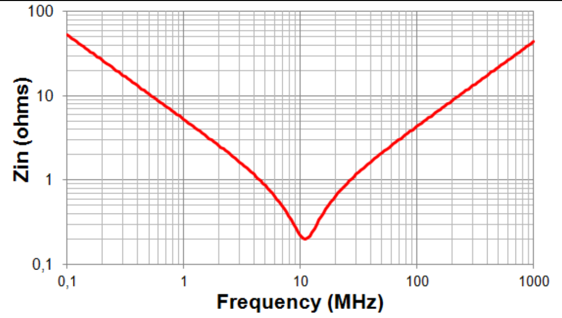
3.Propose a susceptibility criterion on the RF voltage induced on Pad1. Simulate the conducted susceptibility to RF disturbance of this pad.

4. The ADC conversion is supposed to be corrupted if the coupled disturbance introduces an arror larger than one least significant bit (LSB).

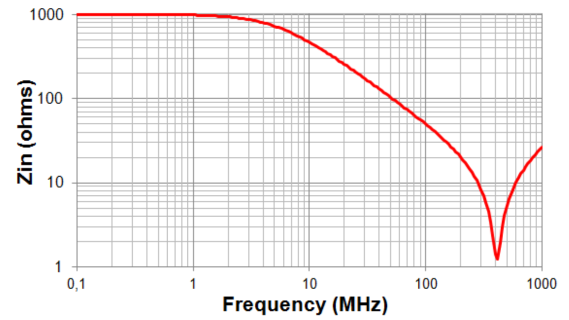
a. Propose a susceptibility criterion on the RF voltage induced on Pad2.

b. Simulate the conducted susceptibility to RF disturbance of Pad2.

c. Without any simulation, deduce what would be the susceptibility level of Pad2 if we consider that the ADC conversion is corrupted when the error reaches 2 LSB? 3 LSB?



Impedance of Pad 1 (Zin_pad1.s1p)



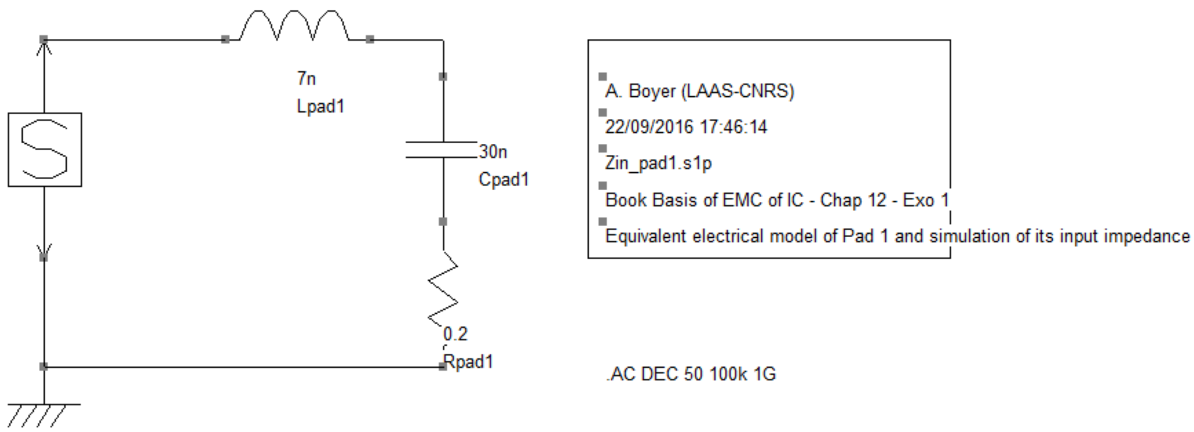
Impedance of Pad 2 (Zin_pad2.s1p)

Corrections:

1. From the impedance measurements of both pads, the following electrical models are proposed:

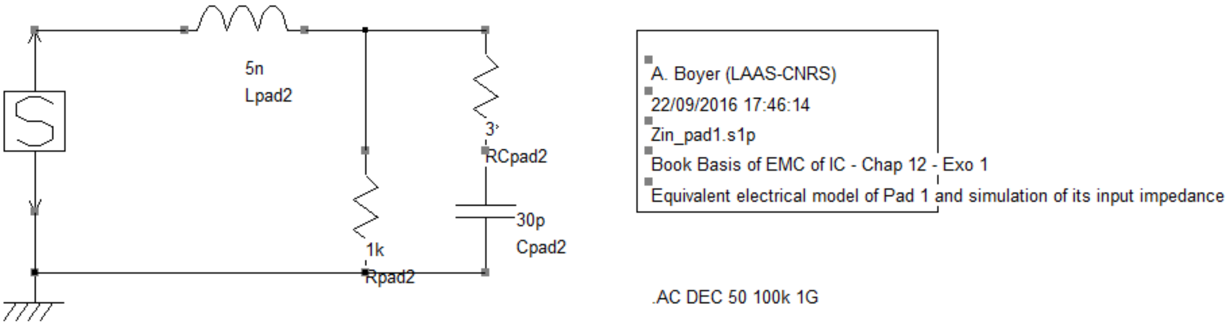
Pad 1:

The pad is characterized by a large capacitance equal to 30 nF, typical of the equivalent capacitance seen between power and ground pins of digital circuits (microprocessor, FPGA). The serial inductance introduces a resonance at nearly 10 MHz. In practice, this inductance would be linked to circuit package.



Pad 2:

In low frequency, the pad is equivalent to a parallel R-C network, where R = 1 kΩ anc C = 30 pF. This is typical of the input impedance of an analog input of an analog-to-digital converter. The serial inductance introduces a resonance at nearly 400 MHz. In practice, this inductance would be linked to circuit package. A resistance is added in series with capacitance to limit the quality factor of the L-C resonance.



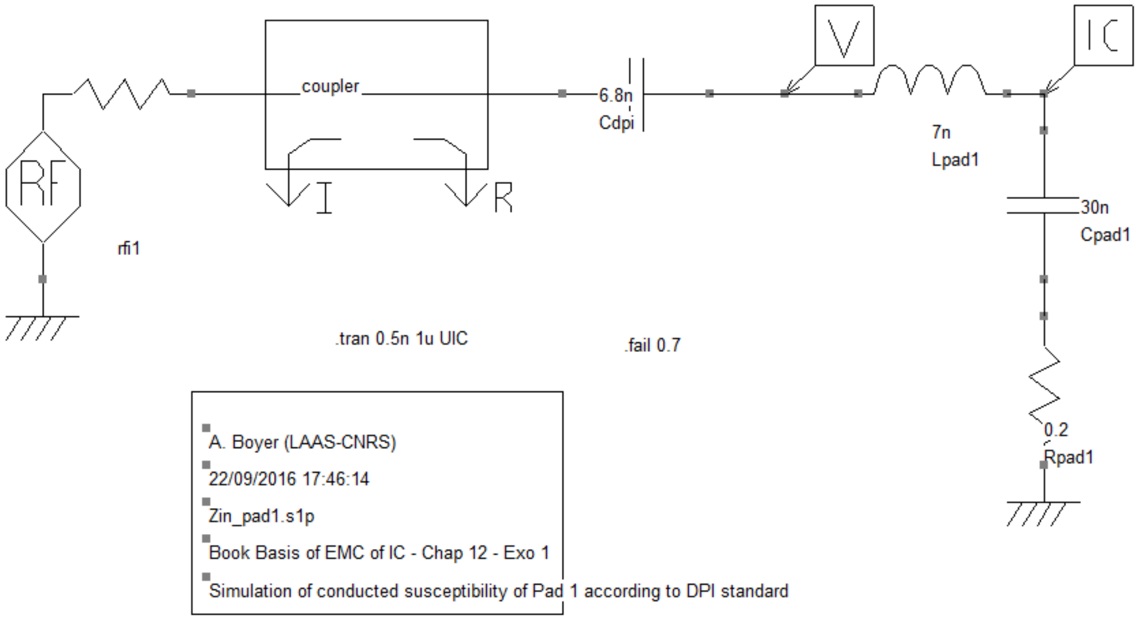
2. The DPI test suggests to use a ceramic capacitor comprised between 1 and 10 nF. 6.8 nF is a typical value. A resistor or an inductance are added to apply a nominal signal to the tested pin and isolate the source from RF disturbance. DPI capacitor and this RF isolation component form a bias tee. A RF isolation component, such as an inductor, should be inserted in the model to add a low frequency signal to both pads. Here, we neglect this part.

As suggested by the standard IEC62132-4, the DPI test covers the range 150 kHz - 1 GHz. The maximum power to apply depends on the nature of the tested pin (see table 9-1). With severlty level 3, themaximum forward power is limited to 10-17 dBm.

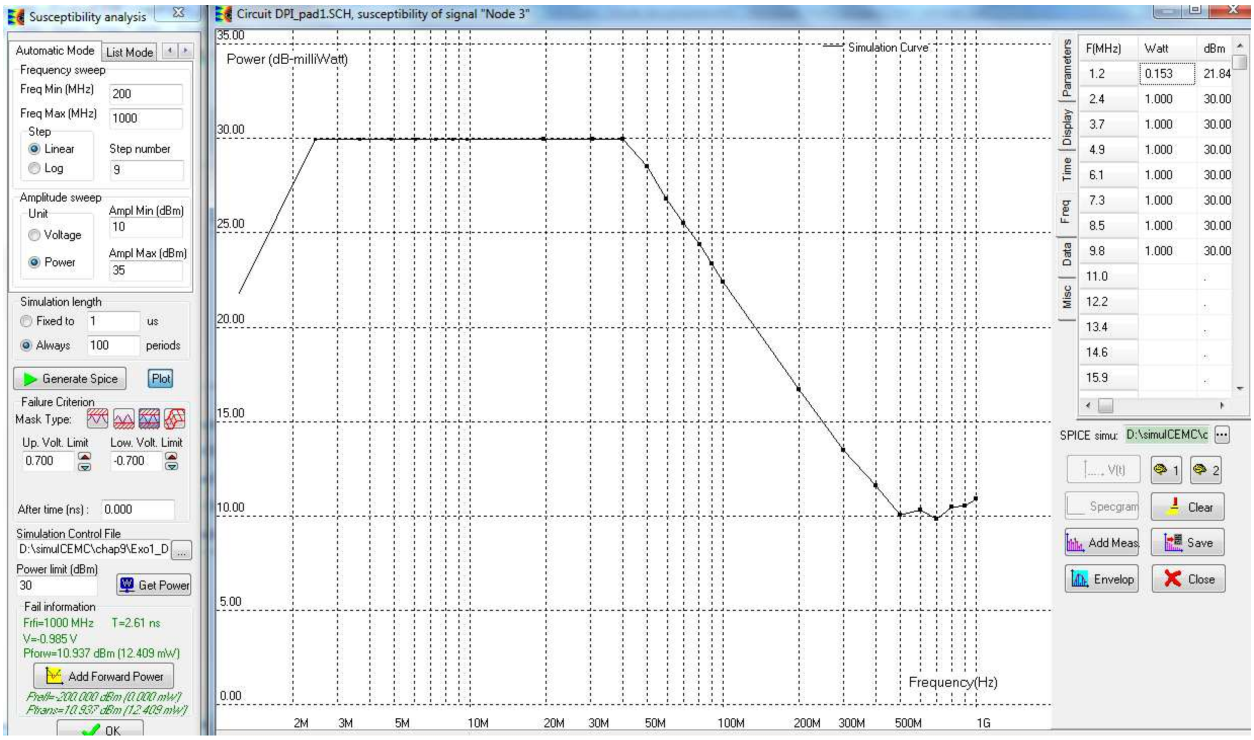
3. RF disturbance coupled on Pad1 should not corrupt the logical level of the digital signal received by the pad. The RF disturbance superimposed on an ideal '0' or '1' level (0 V or 3.3 V) should not exceed the high and low level input voltage limit. Thus, the RF voltagecoupled on Pad1 should not exceed 0.7 V.

DPI injection on Pad 1:

The following figure presents the electrical model of the DPI injection on pad 1. It is available in the file DPI_pad1.sch. The model include a RFI source (necessary for DPI simulation), a bidirectional coupler (required to extract the forward power), the 6.8 nF DPI capacitor, a voltage probe across the electrical model of Pad 1. The initial condition  forces the voltage across the capacitor Cpad1 to zero at t = 0.



The following graph presents the simulated susceptibility threshold of Pad1 (the result is given in the file DPI_susceptibility_pad1.tab). The immunity of Pad1 to conducted injection is maximum around 10 MHz since the impedance of the pad is minimal at this frequency. In practice, external decoupling capacitors would have been added on power supply, reducing the impedance of the power supply and thus its susceptibility.



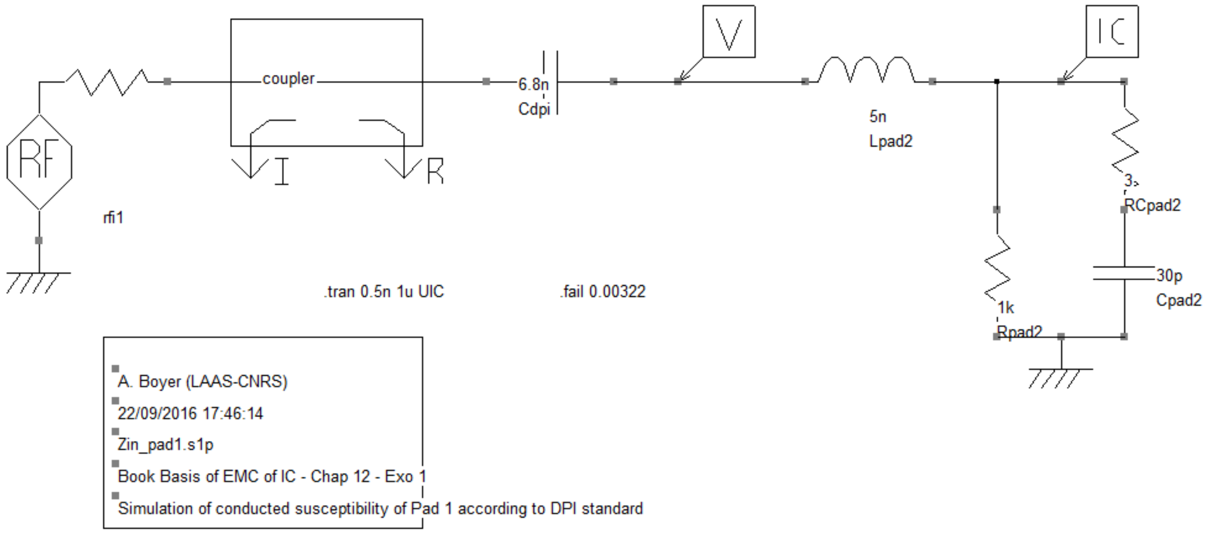
4. a. With a 10-bit ADC, the voltage associated to one LSB is equal to the ADC resolution:

$$\Delta V = \frac{V_{DD}}{2^{10}} = \frac{3.3}{2^{10}} = 3.22\ mV$$

The amplitude of RF disturbance coupled on Pad2 should not exceed 3.22 mV.

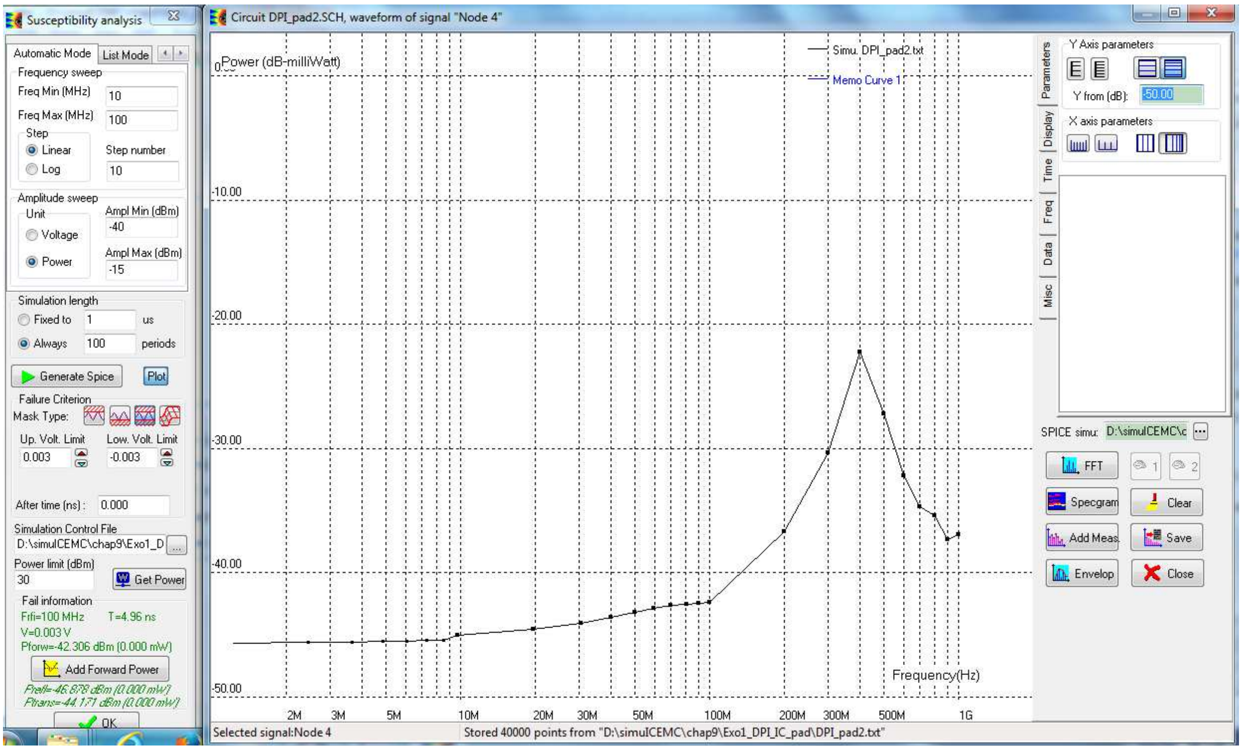
b. DPI injection on Pad 2:

The following figure presents the electrical model of the DPI injection on pad 2. It is available in the file DPI_pad2.sch. The model include a RFI source (necessary for DPI simulation), a bidirectional coupler (required to extract the forward power), the 6.8 nF DPI capacitor, a voltage probe across the electrical model of Pad 2. The initial condition  forces the voltage across the capacitor Cpad2 to zero at t = 0.



The following graph presents the simulated susceptibility threshold of Pad2 (the result is given in the file DPI_susceptibility_pad2.tab). The susceptibility of Pad2 to conducted injection is maximum in low frequency because of the its high impedance. Any noise coupled on pad2 would certainly induce excessive voltage fluctuation for an analog input. If this pad is connected to a long external interconnect, an external filter should be added to improve the noise rejection in low frequency.

The immunity improves above 100 MHz because the impedance of Pad2 becomes less than 50 Ω. When the impedance tends to increase above the L-C resonance, the susceptibility also increases.



c. The second LSB becomes erroneous when the disturbance amplitude is equal to 2ΔV = 6.64 mV. To induce this RF voltage, the forward power of the RF disturbance have to be multiply by 4, i.e. +6 dB.

The third LSB becomes erroneous when the disturbance amplitude is equal to 4ΔV = 12.89 mV. To induce this RF voltage, the forward power of the RF disturbance have to be multiply by 8, i.e. +9 dB.

II. EXERCISE NO 2 - Susceptibility of a CAN transceiver

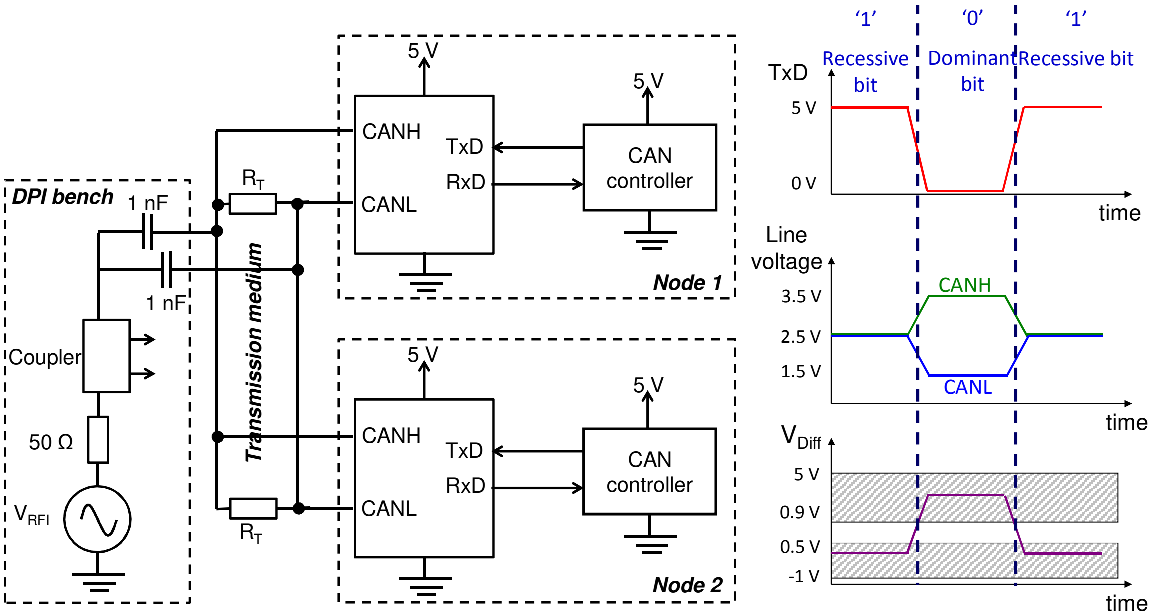
This exercise is based on the paper of M. Fontana and T. H. Hubbing, "Characterization of CAN Network Susceptibility to EFT Transient Noise", IEEE Trans. on EMC, vol. 57, no. 2, April 2015.

The Controller Area Network (CAN) bus is a serial bus widely used for automobile applications, dedicated to communication between various items of the vehicle's electronic equipment. The bus was developed by Bosch in order to propose a real-time communication protocol dedicated to distributed systems and satisfying numerous requirements (robustness to electromagnetic interference and errors, reliability and more). It was standardised in 1991 and is now known as IEC 11898.

The following figure illustrates the hardware architecture of the CAN bus between two nodes. It is formed by three different devices:

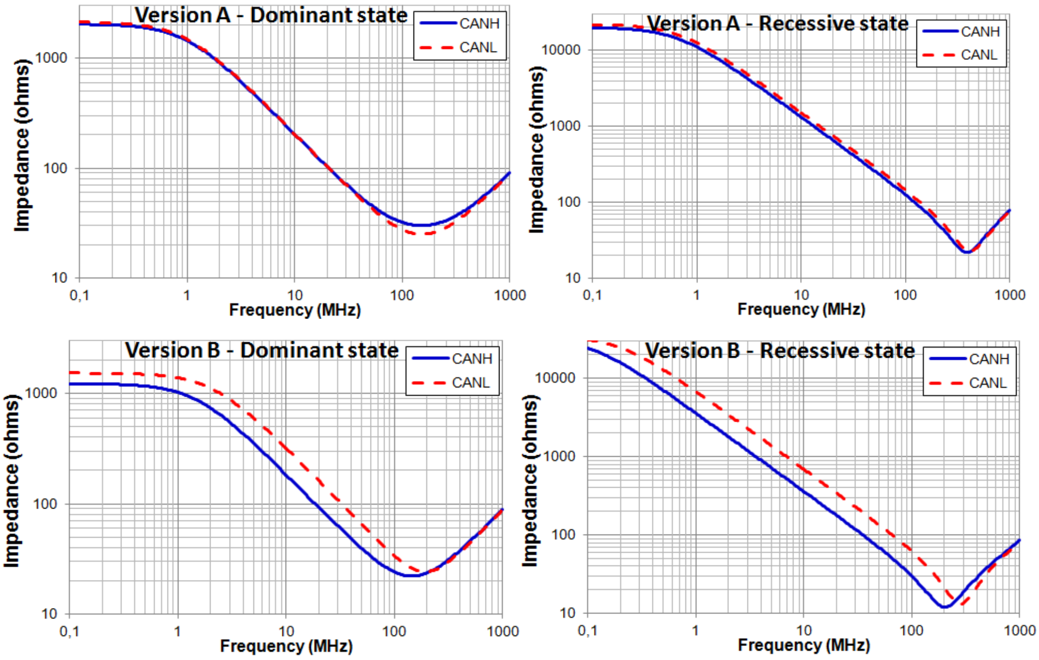
- the CAN controller which manages access to the medium, message construction and error detection to name but a few of its functions. The controller is usually a peripheral embedded in a microcontroller. Two physical pins, TxD and RxD, are dedicated to transmitting or receiving digital messages;
- the CAN transceiver, which acts as the physical interface between the CAN controller and the transmission medium;
- the transmission medium, which is usually a 120 Ω twisted-wire pair (TWP). Both wires propagate signals called CANH and CANL, and form a differential pair. The logic state transmitted along the bus depends on differential voltage $V_{Diff} = V_{CANH}-V_{CANL}$.

In order to prevent unwanted collisions due to several nodes trying to transmit simultaneously, bus access is based on Carrier Sense Multiple Access/Bitwise Arbitration (CSMA/BA). A priority level is assigned to every message during an arbitration process. Priority is based on the difference in weighting of binary states: level '0' is the dominant state (i.e. it forces the electrical state of the bus), while level '1' is the recessive state, which does not have priority. This is the bus state when it is in default or idle mode. During the arbitration process, a node cannot transmit if it senses a dominant state on the bus. Its CAN transceiver output is in recessive mode and remains in receiving mode. In the recessive state, V_{Diff} is less than 0.5 V. In the dominant state, V_{Diff} must be greater than 0.9 V. Usually, V_{Diff} is equal to 2 V in a dominant state and 0 V in a recessive state.



As CAN transceivers are directly connected to a long cable harness, they must meet stringent RF susceptibility requirements. The figure above shows a common conducted injection set-up for a CAN bus based on the DPI standard. During conducted susceptibility tests, CAN communication has to remain unaffected by harmonic disturbances between 150 kHz and 1 GHz with a forward power limit set at 30 dBm.

The objective of this exercise is to model the conducted RF injection ino a CAN bus driven by two different versions of CAN transceivers and to predict their susceptibility levels. The two versions are called version A and version B. Their input impedances have been characterised for both logical states. The measurement results are shown in the figure below. Moreover, CANH and CANL pins are internally protected by diodes triggered at +/- 30 V. They are not supposed to trigger during the conducted susceptibility test.



1. Is the conducted injection carried out in common mode or differential mode? Why is it a representative injection mode for a practical situation?

2. What is the role of resistor R_T? Propose an adequate value.

3. Is it possible for the outputs of two nodes connected to the same bus to be in the same logic state?

4. What happens if the voltage coupled to the CANH or CANL pin during the susceptibility test reaches 30 V? And what if the differential voltage induced by the RF disturbance reaches 0.4 V?

5. From the impedance measurements taken on the CAN transceiver (versions A and B), build equivalent electrical models of pins CANH and CANL in recessive and dominant state.

6. The conducted susceptibility tests are carried out on two transceivers of the same versions connected by a short TWP. We consider the case where a recessive state is transmitted.

Build the electrical models of the conducted injection into the CAN bus terminated by two transceivers (version A or B). The TWP and internal protection diodes are ignored.

7. The models are initially used to predict whether the internal protection diodes will trigger during the conducted injection test.

a. Modify the previous electrical model to detect this type of failure.

b. Simulate the susceptibility level of this type of failure for both transceiver types. Are the protection diodes likely to trigger during the conducted susceptibility test?

8. The models are then used to predict transmission errors due to bit flipping (misinterpretation of the binary state by the receiving node).

a. Modify the previous electrical model to detect this type of failure.

b. Simulate the susceptibility level of this type of failure for both transceiver types. Is the risk of communication error due electromagnetic disturbance negligible for transceiver version A? What about transceiver version B?

9. Explain the difference in susceptibility between both versions of the CAN transceiver. What recommendation could you give a designer wishing to make a robust CAN transceiver that withstands electromagnetic disturbance?

Corrections:

1. The disturbance source excites terminals CANH and CANL symetrically so it is a common-mode injection. In practice, CAN bus is a long bus that can be illuminated by radiated disturbances, whose coupling induces common-mode currents.

2. R_T is required for impedance matching at each bus terminal. Its value must be equal to the bus characteristic impedance, i.e. 120 Ω.

3. Yes, but only in recessive state. Due to the arbitration process, they cannot be in dominant state simultaneously . If this situation happens, the communication is interrupted immediately.

Several scenarios are possible:

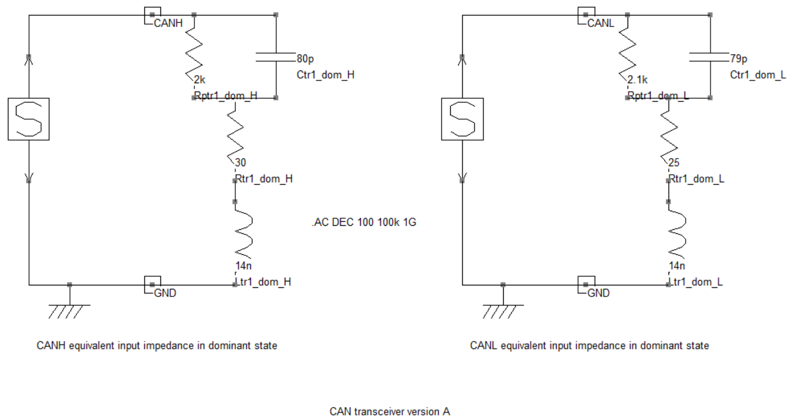
- in idle mode, both node outputs are in recessive state so the bus logical state is forced to be logical state '1'.
- during transmission, only one node is allowed to transmit, the other is in receiving mode because of the arbitration process. The output of the receiving node is in recessive state. If the transmitting node transmits a logical '1', its output is in recessive state, so both nodes forces the bus to be in recessive state. If the transmitting node transmits a logical '1', its output is in dominant state and forces the bus to be in dominant state.

4. During the susceptibility test, if the RF voltage coupled on CANH or CANL pins reaches 30 V, the protection diode triggers to limit the voltage applied to the internal electronic blocks of the CAN transceiver and prevent from degradation.

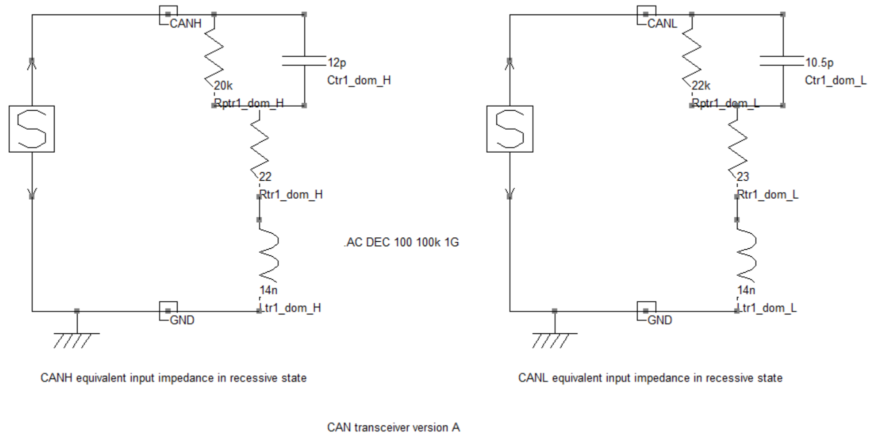
If the RF disturbance coupled to the CAN bus lead to a differential voltage equal to 0.4 V, a binary error may arise. Let consider the worst-case situation: the differential voltage is equal to 0.5 V in recessive state without the RF disturbance. If the RF disturbance superimposed to the recessive state is equal to 0.4 V, the differential voltage will exceed the 0.9 V threshold so that a receiver can misinterpret the transmitted state as a dominant state.

5. The following figure presents the equivalent models of pins CANH and CANL for both transceiver versions, either in dominant or recessive state.

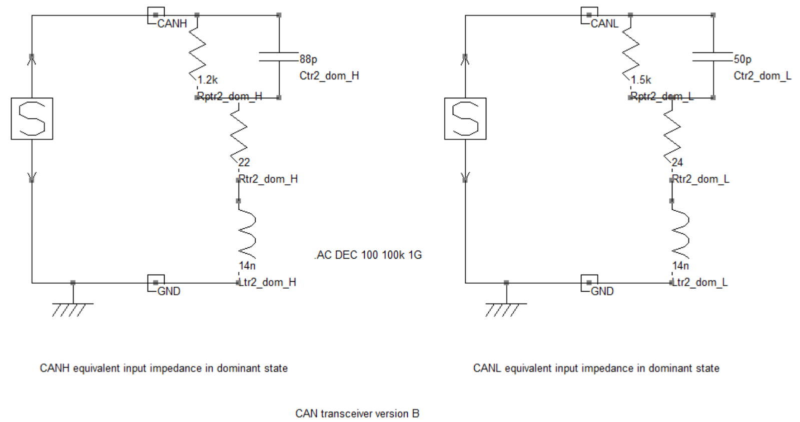
<u>Transceiver version A - Dominant state (Zin_transceiverA_dominant.sch):</u>



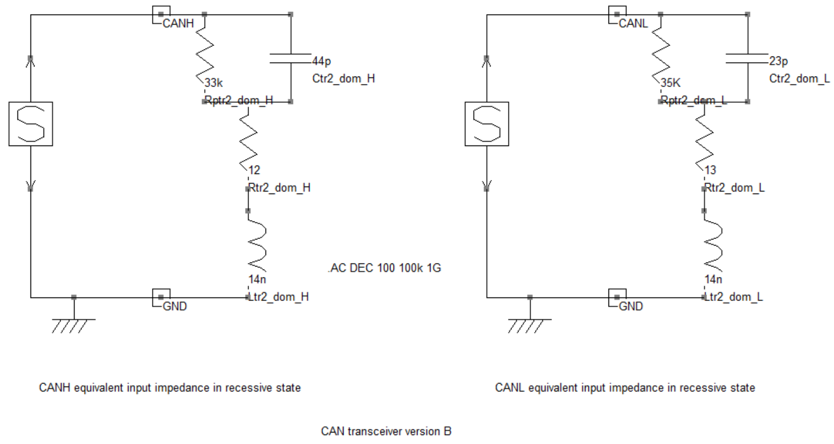
<u>Transceiver version A - recessive state (Zin_transceiverA_recessive.sch):</u>



<u>Transceiver version B - dominant state (Zin_transceiverB_dominant.sch):</u>



Transceiver version B - recessive state (Zin_transceiverB_recessive.sch):

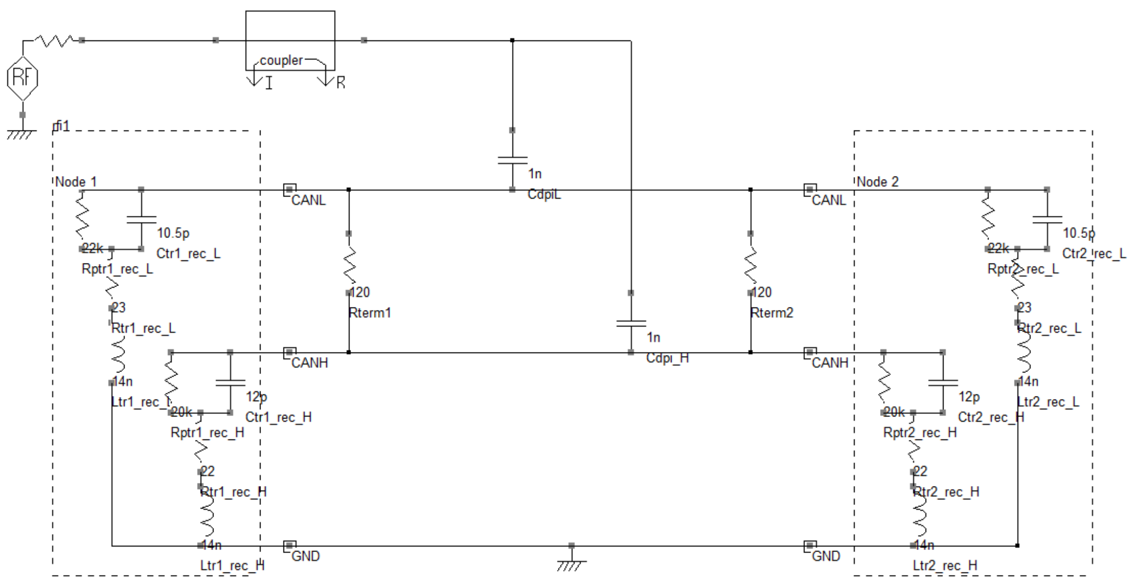


It is interesting to notice:

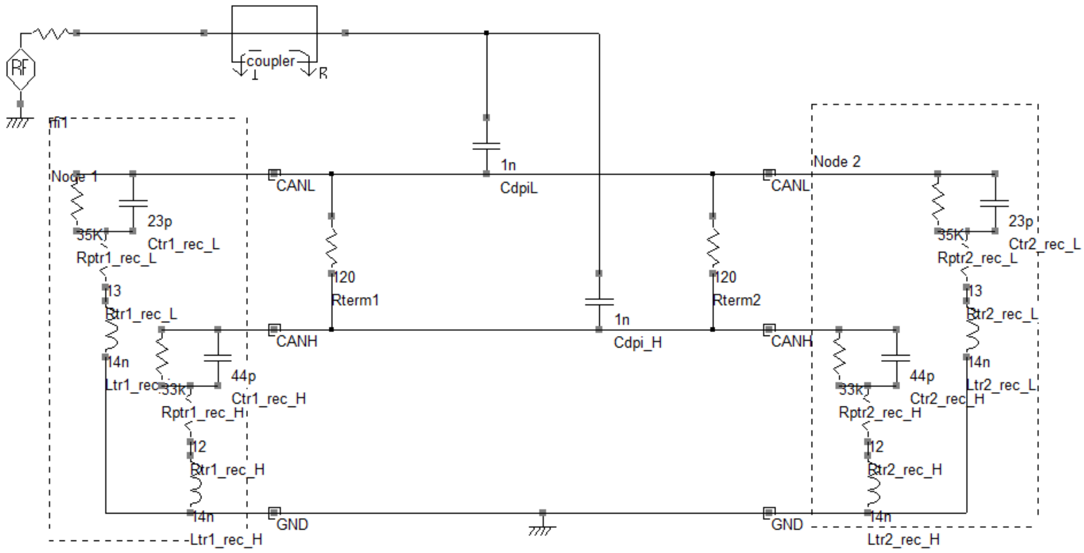
- the differences between dominant and recessive states are related to changes in the equivalent capacitance and resistance of the pin. The inductance remains unchanged because it is related to the package interconnects.
- pins CANH and CANL are nearly identical in transceiver version A, while significant differences are visible in transceiver version B.

6. The following figure presents the models of conducted injection on CAN bus terminated by both versions of the CAN transceivers. The harmonic disturbance source is modeled by a RFI source followed by a directional coupler to monitor the forward power. The TWP model is not added because the line is supposed electrically small.

With CAN transceiver version A (DPI_TranscA_recessive.sch):

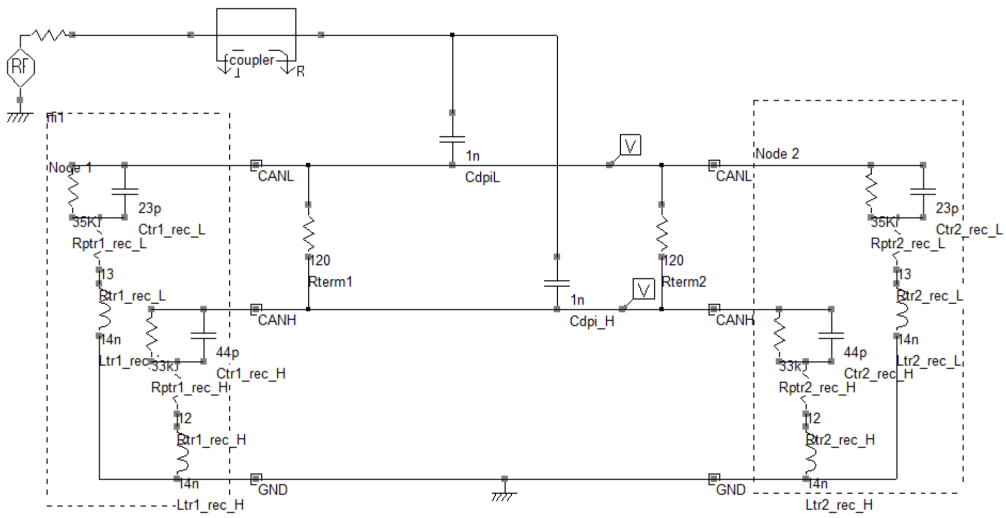


With CAN transceiver version B (DPI_TranscB_recessive.sch):



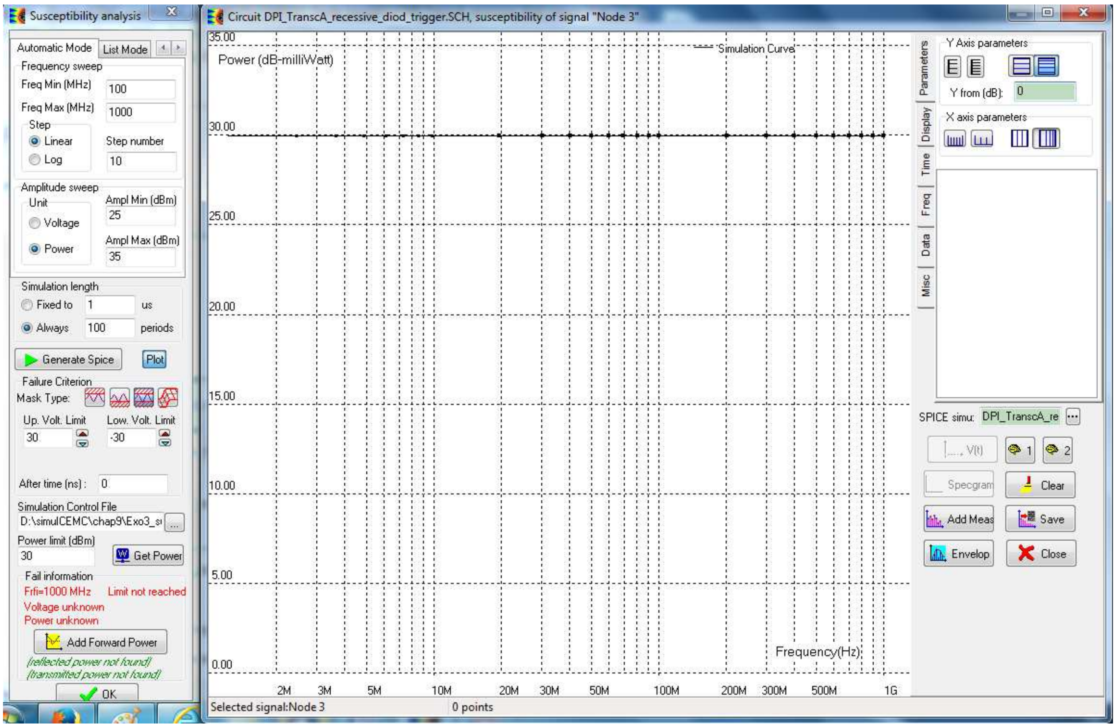
7. a. The internal protection diodes trigger if the voltage applied on CANH or CANL goes beyond or below +/- 30 V. To detect this failure in simulations, the voltages on CANH and CANL have to be monitored. Two voltage probes are added on the CANH and CANL wires. As the TWP is considered electrically small, the same voltage appears on both side of the bus.

b. The simulation files for both CAN transeiver versions are given by DPI_TranscA_recessive_diod_trigger.sch and DPI_TranscB_recessive_diod_trigger.sch.



In both cases, even with the maximum forward power (30 dBm), the amplitude of the induced voltages on CANH or CANL does not reach 30 V. The susceptibility threshold simulated with the tool "Susceptibility analysis" and its configuration is shown below. For all the test frequencies between 150 kHz and 1 GHz, no failures are observed for forward power less or equal to 30 dBm.

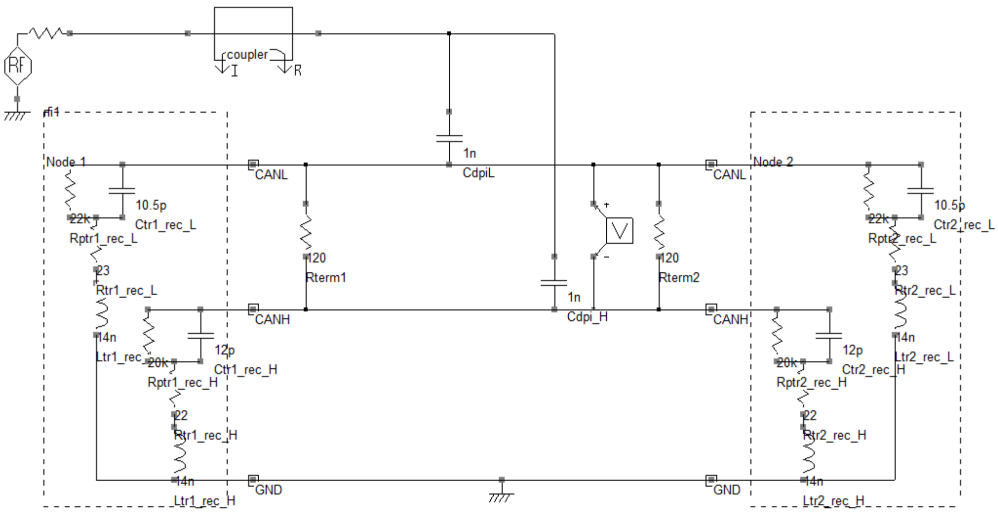
We can conclude that the protection diodes may not trigger during the susceptibility test.



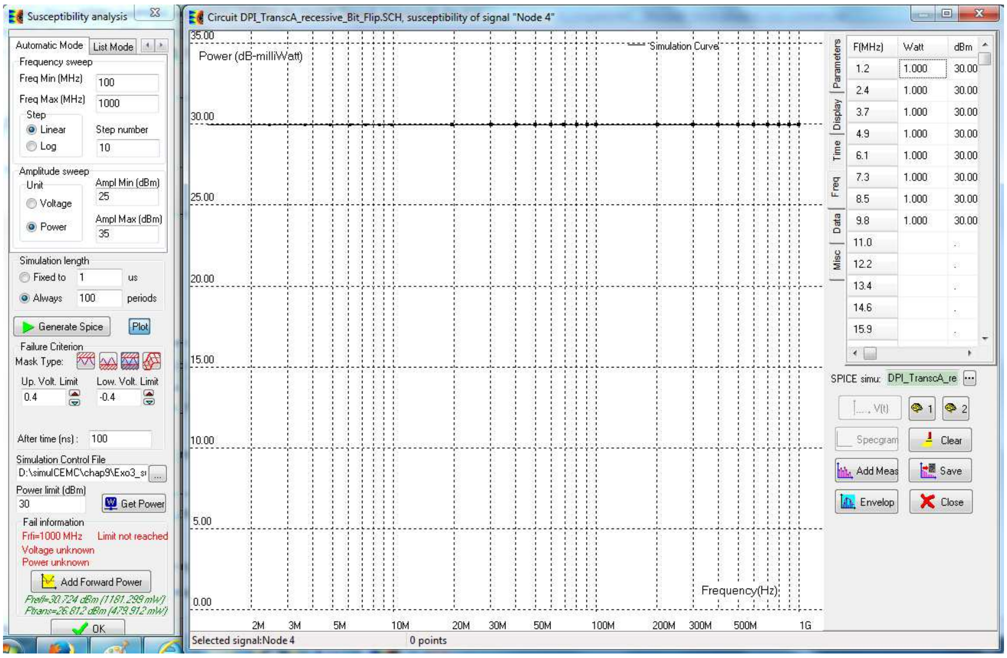
8. a. The binary state transmitted on the CAN bus depends on the differential voltage V_{Diff}. According to question 4, if the differential voltage induced by the conducted disturbance exceeds 0.4 V, a misinterpretation of the recessive state may arise. To detect this failure in simulations, the differential voltage between CANH and CANL has to be monitored. A differential voltage probe  is placed between CANH and CANL lines.

b. <u>Simulation of the conducted susceptibility of transceiver version A:</u>

The following figure presents the electrical model to simulate the susceptibility of transceiver version A (DPI_TranscA_recessive_Bit_Flip.sch).

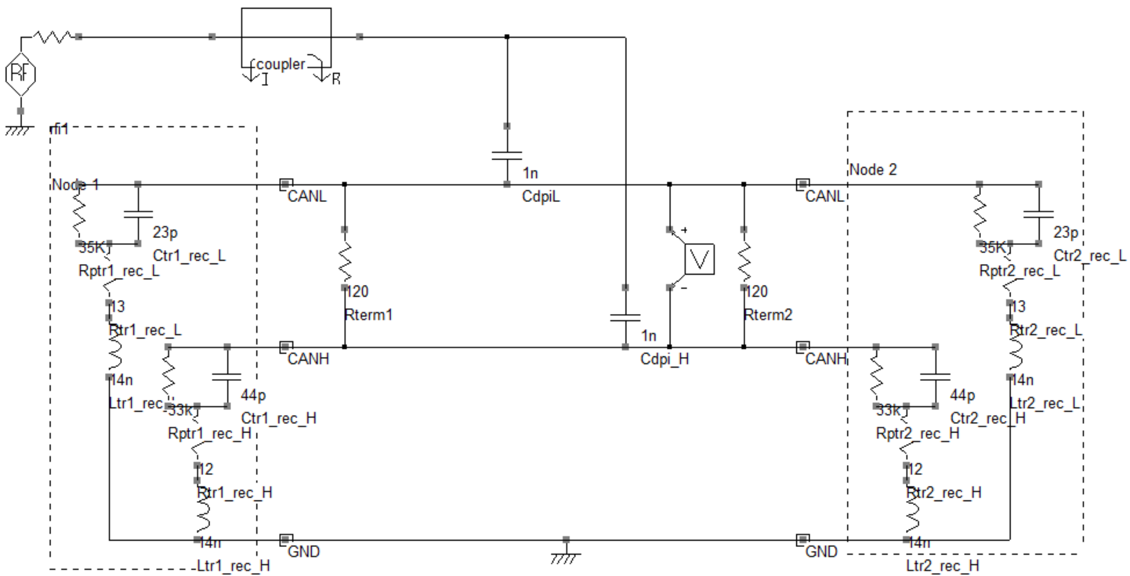


Whatever the frequency between 150 kHz and 1 GHz, the induced differential voltage does not exceed 0.4 V for a forward power less or equal to 30 dBm. The simulated susceptibility threshold and the configuration of the "Susceptibility analysis" tool are presented below. The transceiver version A is immune against electromagnetic disturbances.

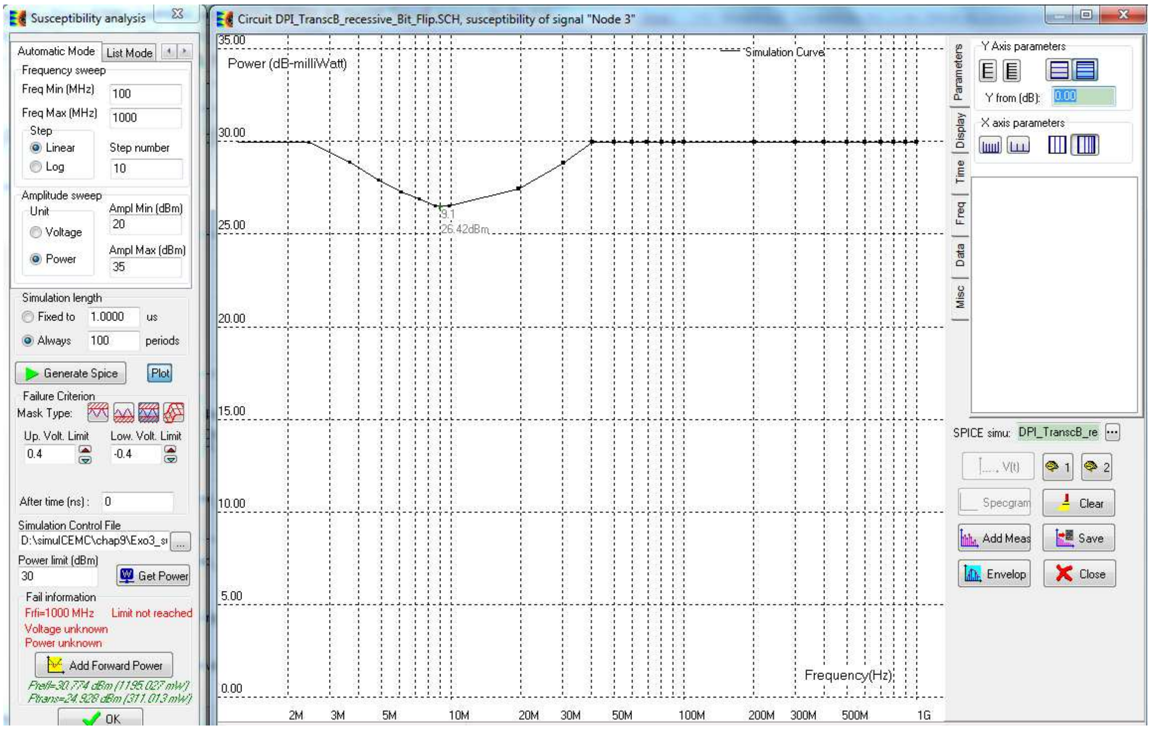


Simulation of the conducted susceptibility of transceiver version B:

The following figure presents the electrical model to simulate the susceptibility of transceiver version B (DPI_TranscB_recessive_Bit_Flip.sch).



The simulated susceptibility threshold and the configuration of the "Susceptibility analysis" tool are presented below. Failures appear for power less than 30 dBm between 3 and 40 MHz. The transceiver version B is not immune enough against electromagnetic disturbances over this frequency range.



9. The main difference between both CAN transceiver versions is the symmetry between CANH and CANL pins. In version A, CANH and CANL pins have nearly the same impedance, in contrary to CANH and CANL pins of version B. This better symmetry results in a better immunity. The reason is that any dissymetry between both terminals of a differential pair leads to common-mode to differential-mode conversion.

The conducted injection is done in common-mode and should not induce differential-mode voltage if the differential bus and terminations are perfectly balanced or symmetrical. Common-mode voltage does not disturb the communication along the bus, since CAN bus is differential (except if the common-mode voltage exceeds +/- 30 V and leads to protection diodes triggering).

If there is any unbalance, a part of the common-mode voltage is converted in differential-mode voltage that can disturb the transmitted signal.

A precious recommendation for the designer of CAN transceiver version B is to ensure the symmetry between pins CANH and CANL. This recommendation is valid for any differential driver or receiver.