Crosstalk experiment

EV6 - Hardware Implementation

van Iterson, Arne
Student Nr: 1798423

Selier, Tom
Student Nr: 1808444

April 12, 2024

Abstract

This document describes the process of, and measurements taken during the crosstalk experiment; Part of the EV6 Hardware Implementation course at the University of applied sciences Utrecht.

---

1 Introduction

Two conductors running parallel to each other can cause crosstalk, this is when the signal on one line induces a signal on the other line. This can cause signal integrity issues and can even cause the transmission hardware to malfunction.

This experiment will be performed on a pre-built contraption consisting of three wires above an metal plate connected to signal ground, two of which will be used. By putting a signal on one wire and measuring the resulting signal on the other, the difference between capacitive and inductive crosstalk can be observed, as well as the effect of different terminators on the signal and crosstalk.

1.1 Objective

The purpose of the experiment is to learn the difference between capacitive and inductive crosstalk and how different terminators affect the signal and crosstalk. Using the results of the experiment the mutual self-inductance and coupling capacitance of the setup should be determined.

2 Methodology

The lab manual does not provide a clear methodology for the experiment, requiring the students to setup a measurement plan themselves. We determined the following measurements would be required to determine the inductance and capacitance of the setup:

- Near and far side of the interfered conductor while the signal conductor is not terminated.
- Near and far side of the interfered conductor while the signal conductor is shorted to ground.
- Near and far side of the interfered conductor while the signal conductor is terminated characteristically.

The lab manual includes Figure 1 which describes the electrical properties of the setup.

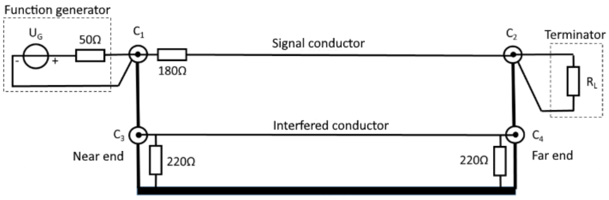

Figure 1: Measurement setup

Since the experiment setup includes a series 180 Ω resistor, the characteristic impedance would be the sum of the impedance of the resistor and the impedance of the function generator. This would make the characteristic impedance 230 Ω. The setup did include a terminator of 230 Ω, but it seemed to be somewhat sketchy, being hand made, and we were not sure if it was part of the setup at all. We decided to use both the 50 Ω and 230 Ω terminators to be sure and to see if there was any difference in the results.

The experiment called for the students to determine the ideal frequency at which to measure the crosstalk. We setup the function generator to sweep the signal between 1 kHz to 40 MHz, the maximum frequency of the function generator, and observed the crosstalk on the near and using the oscilloscope. We determined the frequency at which the crosstalk was the highest, which was around 20 MHz.

2.1 Equipment

The following equipment and settings will be used during the experiment:

- Rigol DG 2041A Function/Arbitrary Waveform Generator
  - Setup according to the method described in the lab manual and the determined frequency:
    - Sinusoidal waveform
    - Amplitude of 5 V_{pp}
    - Offset of 0 V
    - Frequency 20 MHz
    - Output impedance 50 Ω
- DPO 2012 Oscilloscope
  - Using default settings
- Oscilloscope probe with a 10:1 attenuation ratio
- Multiple 1 meter BNC cables with a characteristic impedance of 50 Ω
  - One for trigger output, one for the experiment itself
- Various BNC accessories
  - Short circuit terminator
  - 50 Ω terminator
  - 230 Ω terminator
  - T-connectors
  - Probe to BNC connector

2.2 Setup

All measurements will be taken using the setup in Figure 2, switching between the near and far side of the setup where applicable.

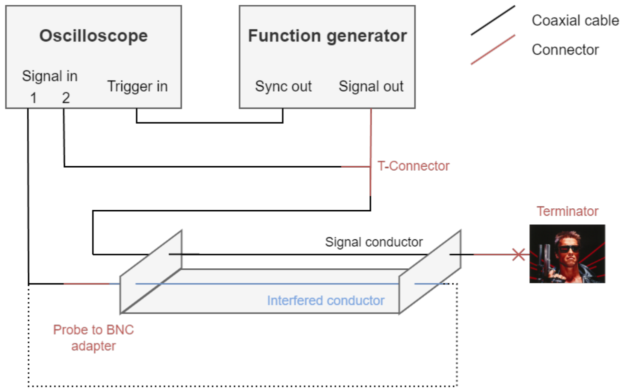

Figure 2: Measurement setup

3 Expected results

The results expected for the different types of crosstalk are described in the following sections.

Capacitive crosstalk

Capacitive crosstalk is caused by the electric field of the signal conductor inducing a voltage on the interfered conductor. This electric field is generated by the presence of a voltage on the signal conductor. Therefore, when the signal conductor is terminated by a short terminator, the voltage on the signal conductor is practically zero, making the capacitive crosstalk minimal. When the signal conductor is not terminated, the crosstalk should be at its maximum. Capacitive crosstalk does not have a phase shift.

Inductive crosstalk

Inductive crosstalk is caused by the magnetic field of the signal conductor inducing a voltage on the interfered conductor. The magnetic field is generated by the current flowing through the signal conductor. When the signal conductor is terminated through a short, the crosstalk should be at its maximum since the current is as high as it can be. When the signal conductor is not terminated, the crosstalk should be minimal. The magnetic field generates a current in the interfered conductor that is opposite to the signal conductor, creating a 180° phase shift

When the signal conductor is terminated with a characteristic terminator, or any non-shorting terminator for that matter, the resulting will be a combination of the capacitive and inductive crosstalk since the voltage is not shorted completely, creating a resistor divider, and there is some current flowing through the signal conductor; Causing both the electric and magnetic field to induce a voltage on the interfered conductor.

4 Results

This section will show the measurement results of the experiment. The results will be presented in the form of graphs which include peak-to-peak voltage, frequency and phase shift within the legend. Every termination method will include a measurement for both the far and near sides of the interfered conductor as per the determined methodology. In the next section, the results will be analysed and compared to the expected results.

4.1 Measurements

4.1.1 Open termination

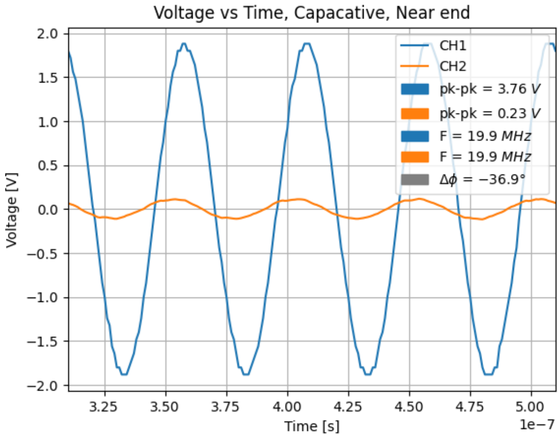

Figure 3: Open termination near end

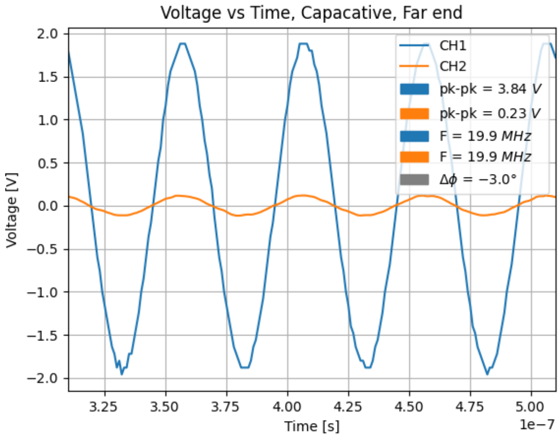

Figure 4: Open termination far end

4.1.2 Short termination

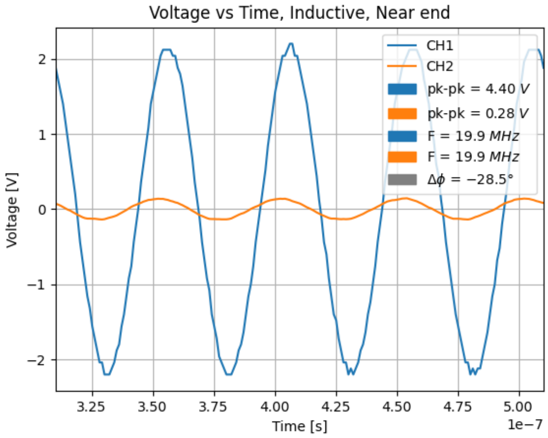

Figure 5: Short termination near end

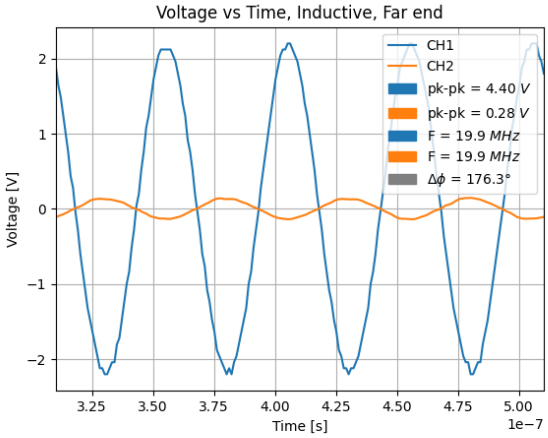

Figure 6: Short termination far end

4.1.3 Characteristic termination

50 Ohm terminator

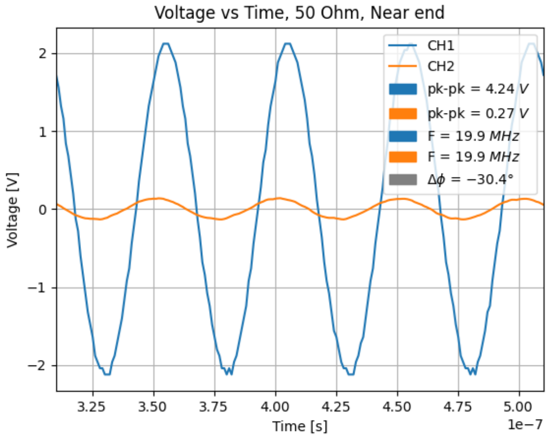

Figure 7: 50 Ohm termination near end

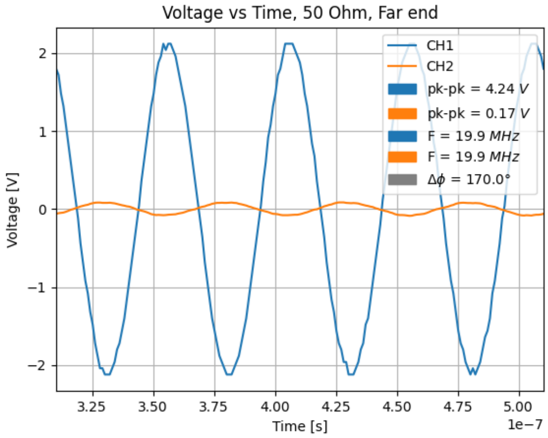

Figure 8: 50 Ohm termination far end

230 Ohm terminator

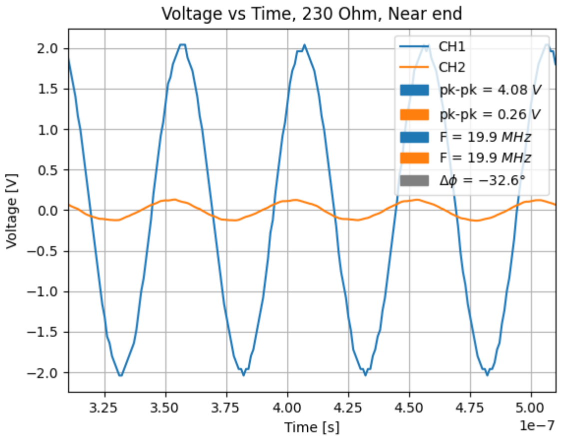

Figure 9: 230 Ohm termination near end

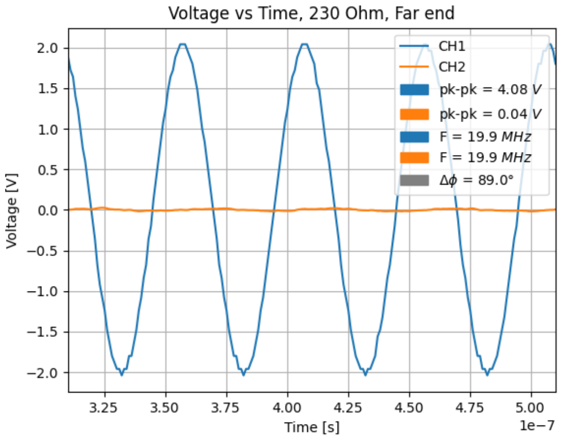

Figure 10: 230 Ohm termination far end

4.2 Analysis

In this section the results will be compared with the theory given in the reader.

4.2.1 Capacative

The formula for capacitive crosstalk is given by:

$$U = Z_0 \frac{j\omega C_{1,2} \cdot U_g}{2} \tag{1}$$

Solving equation 1 for $C_{1,2}$ gives

$$\begin{aligned} U &= Z_0 \frac{j\omega C_{1,2} \cdot U_g}{2} \\ 2U &= Z_0 \cdot j\omega C_{1,2} \cdot U_g \\ \frac{2U}{C_{1,2}} &= Z_0 \cdot j\omega \cdot U_g \\ C_{1,2} &= \frac{2U}{Z_0 \cdot j\omega \cdot U_g} \end{aligned} \tag{2}$$

Taking the results from figure 4,
$U_g = 2\ V$, $U = 0.14\ V$, $\omega = 20 \cdot 10^6\ Hz$ and $Z_0 = 220\ \Omega$

$$\begin{aligned} C_{1,2} &= \frac{2 \cdot 0.1\ V}{220\ \Omega \cdot j20 \cdot 10^6 Hz \cdot 2\ V} \\ &\approx j2.27 \cdot 10^{-11} F \\ &\approx j0.027\ nF \end{aligned} \tag{3}$$

Simulating the circuit to crosscheck if 0.027 nF is a realistic answer gives a promising result.

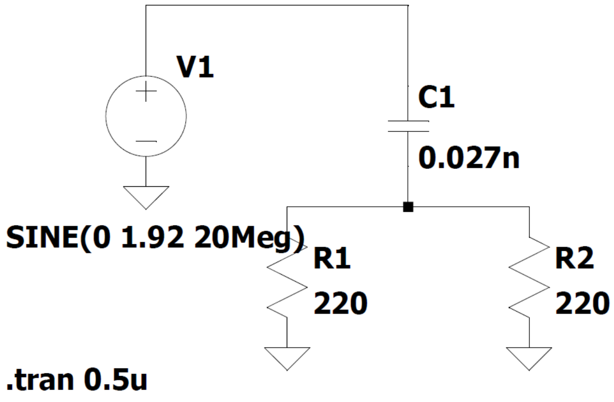

Figure 11: LTSpice schematic

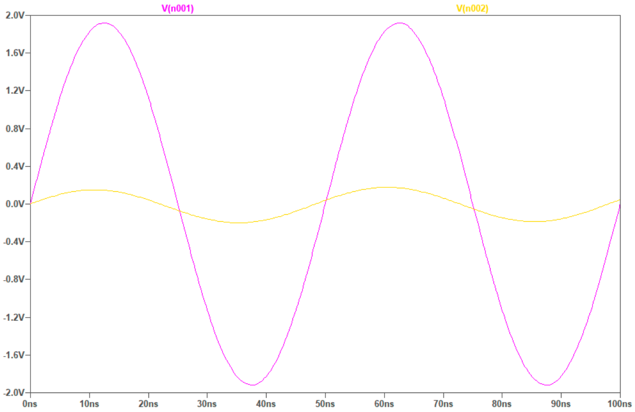

Figure 12: LTSpice Simulation, signal conductor (pink) and interfered conductor (orange)

The amplitude of the interfered conductor is roughly 0.2V, which is in the ballpark of the actual signal shown in figure 3 and figure 4.

4.2.2 Inductive

The formula of inductive crosstalk is given by

$$U = j\omega L_M \frac{U_g}{2 \cdot Z_0} \tag{4}$$

Solving equation 4 for L_M gives

$$\begin{aligned} U &= \frac{U_g \cdot j\omega L_M}{2 \cdot Z_0} \\ U_g \cdot j\omega L_M &= 2U \cdot Z_0 \\ L_M &= \frac{2U \cdot Z_0}{U_g \cdot j\omega} \end{aligned} \tag{5}$$

Taking the results from figure 6, $U_g = 2.2\ V$, $U = 0.14\ V$, $\omega = 20 \cdot 10^6\ Hz$ and $Z_0 = 220\ \Omega$

$$\begin{aligned} L_M &= \frac{2 \cdot 0.14\ V \cdot 220\ \Omega}{2.2\ V \cdot j20 \cdot 10^6} \\ &= j1.4 \cdot 10^{-6} H \\ &= j1.4\ \mu H \end{aligned} \tag{6}$$

A simulation for inductive crosstalk was not performed, since this simulation is more involved compared to the simulation for capacitive crosstalk and well beyond our area of expertise. However, the method of solving the equation was the same, thus the result is likely to be similar to the capacitive crosstalk.

4.2.3 Characteristic

From the measurements, it becomes clear that the correct characteristic termination is, in fact, 230 Ω. The 50 Ω terminator does dampen the crosstalk on the far end of the conductor (Figure 8), while the 230 Ω terminator effectively eliminates it (Figure 10).

Far end For the voltage at the far end, let the equation be

$$U_{fe} = j\omega L_l \frac{U_g}{4 \cdot Z_0}\left(\frac{C_{12}}{C_l} - \frac{L_M}{L_l}\right) \tag{7}$$

According to the reader and the measurements, when $Z_0 = R_L$ the circuit is terminated characteristically. Thus, $\frac{C_{12}}{C_l} = \frac{L_M}{L_l}$ has to be true. This makes the equation for the far end

$$\begin{aligned} U_{fe} &= j\omega L_l \frac{U_g}{4 \cdot Z_0}(0) \\ U_{fe} &= 0\ V \end{aligned} \tag{8}$$

Near end According to the reader the voltage at the near end is

$$U_{ne} = j\omega L_l \frac{U_g}{4 \cdot Z_0}\left(\frac{C_{12}}{C_l} + \frac{L_M}{L_l}\right) \tag{9}$$

When the circuit is terminated characteristically and $\frac{C_{12}}{C_l} = \frac{L_M}{L_l}$ this equation is non-zero. Since these fractions are the same, the equation can be written using a constant, K.

$$U_{ne} = j\omega L_l \frac{U_g}{4 \cdot Z_0}(2K) \tag{10}$$

Substituting K with $\frac{L_M}{L_l}$ gives

$$U_{ne} = j\omega L_l \frac{U_g}{4 \cdot Z_0} \cdot \frac{2L_M}{L_l} \tag{11}$$

Simplifying the equation gives

$$\begin{aligned} U_{ne} &= j\omega L_l \frac{2 \cdot U_g \cdot L_M}{4 \cdot Z_0 \cdot L_l} \\ &= \frac{2 \cdot U_g \cdot L_M \cdot j\omega L_l}{4 \cdot Z_0 \cdot L_l} \\ &= \frac{2 \cdot U_g \cdot L_M \cdot j\omega}{4 \cdot Z_0} \end{aligned} \tag{12}$$

Losing the dependence of the unknown variables L_l and C_l makes it possible to crosscheck this equation against one of the results. Figure 9 gives the values: $U_g = 2.04\ V$, $\omega = 20 \cdot 10^6\ Hz$ and $Z_0 = 220\ \Omega$

$$\begin{aligned} U_{ne} &= \frac{2 \cdot 2.04\ V \cdot 1.4 \cdot 10^{-6}\ H \cdot j20 \cdot 10^6\ Hz}{4 \cdot 220\ \Omega} \\ &= 0.129\overline{81}\ V \\ &\approx 0.13\ V \end{aligned} \tag{13}$$

0.13 V is equal to the amplitude measured in Figure 9, concluding that 230Ω is the characteristic termination.

5 Conclusion

During this experiment, we were successfully measure and analyse the crosstalk between two conductors. Furthermore we were able to determine the mutual self-inductance and coupling capacitance of the setup and validate those results through simulation. Lastly, we were able to determine and validate the correct characteristic impedance of the setup.

In conclusion, crosstalk can be minimized by using the correct termination, but not eliminated completely.