Lab 2 - Measuring Transmission Lines

Introduction

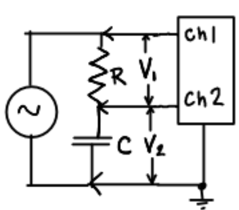
This lab will show how to use a signal generator and an oscilloscope to measure the capacitance, inductance and length of a transmission line. These measurements will demonstrate transmission line theory and can also be used to characterize or test transmission lines.

Capacitance

A transmission line terminated in an open circuit forms a capacitor. The reactance of a capacitance C at frequency f is given by:

$$X_C = \frac{1}{j2\pi fC}$$

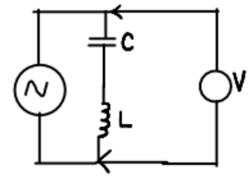
One way to measure capacitance is to measure the capacitor's reactance at a known frequency and compute the corresponding capacitance. In the circuit shown below the resistor and the capacitor representing the open-circuit-terminated transmission line form a voltage divider. Given a known resistance R and the voltages V_1 and V_2 we can compute the capacitor's reactance and capacitance.



Inductance

A transmission line terminated in a short circuit forms an inductor.

If we replace the resistor in the circuit above with a known capacitance we form a series-resonant circuit:



The inductance can be measured indirectly by measuring the resonant frequency of this LC circuit.

At the resonant frequency the inductive and capacitive reactances cancel and the circuit will have minimum impedance. The resonant frequency can be found by adjusting frequency of the signal until the voltage is a minimum.

The resonant frequency of an LC circuit can be found by setting $X_L = j\omega L = -X_C$ and is:

$$f = \frac{1}{2\pi\sqrt{LC}}$$

From the known capacitance value and the resonant frequency we can compute the inductance of the transmission line.

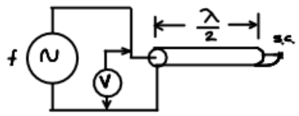
Note that to measure the capacitance and inductance this way the transmission line has to be short enough that it can be treated as a "lumped-element." "Short enough" means that the length of the transmission line is short relative to the wavelength. For a velocity factor of 0.66 the wavelength at 1 MHz is 200m. The lines you will be asked to measure are shorter than 5m.

Length

We can measure the length of a transmission line by measuring the propagation delay and multiplying by the velocity of propagation.

If a transmission line is terminated in a short-circuit the voltage at the termination must be zero. This implies that the incident and reflected voltages are equal in magnitude and opposite in sign. This reflected signal will propagate back and appear at the input to the transmission line.

When the input frequency is such that the propagation delay along the transmission line causes the reflected signal to be 180 degrees out of phase with the input signal the two signals will cancel out.



At this frequency the propagation delay in one direction is equal to one half of the signal period. From the null frequency and the cable's velocity of propagation we can compute the length of the transmission line:

$$l = \frac{\lambda}{2} = \frac{v}{2f}$$

The velocity of propagation can be computed from the capacitance and inductance per unit length that we measured previously or it can be computed from the dielectric constant of the dielectric if known:

$$v = \frac{1}{\sqrt{LC}} = \frac{c}{\sqrt{\varepsilon_r}}$$

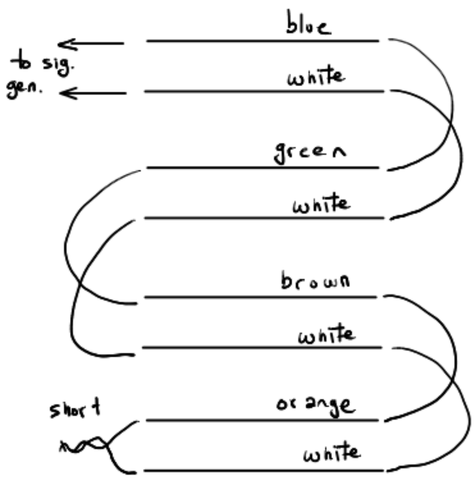
Procedure

You will be supplied with an unknown (to you) length of Cat 5 UTP cable. Part of your mark will be based on how accurately you measure its length and other parameters.

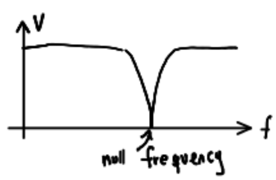
- get your assigned package of twisted-pair cable, a 10 kΩ resistor and a 220 nF capacitor from the instructor.
- measure the resistor value with the DMM and measure the capacitance with an LCR meter if one is available in the lab; record your measurements
- if necessary, strip about 10 cm of the jacket from each end of the cable to expose the pairs.
- if necessary, strip about 1 cm of insulation from the end of each wire
- hook up the capacitance-measuring circuit to the orange-white open-circuit-terminated pair. You can use the oscilloscope "grabber" probe tips to connect to the components and hold them together.
- set both probes to 10X mode to reduce their capacitive loading
- connect the channel 1 probe to the signal generator output and the channel 2 probe to the connection between the resistor and the transmission line.
- set the signal generator for a 50kHz sine-wave output of approximately 4 Vpp (the actual voltage is not important)
- measure the voltage across the resistor differentially[1]
- measure the voltage across the transmission line
- Note: for the capacitance measurement the probe capacitance is significant. Leave both probes connected when making the measurements and record the capacitance of the probe used to measure the capacitor (marked on the probe, typically 10–15 pF).
- compute the capacitance. Subtract the probe capacitance. Give your result to the instructor who will record it and advise if you should proceed.
- replace the resistor with a 220 nF capacitor and short-circuit the end of the orange-white pair to create a series-resonant LC circuit
- adjust the signal generator frequency to find the "null" frequency where the voltage across the LC circuit is minimum. You may have to increase the 'scope gain and adjust the triggering as the signal level drops. You can also compute the average of two frequencies on either side of the null where the signal has equal amplitude.
- record the frequency and compute the inductance. Give your answer to the instructor who will record it and advise if you should proceed.
- connect all four pairs in series as shown below to increase the length of the transmission line (this reduces the null frequency to within the frequency range of the signal generator)

[1] To make a differential measurement set both channels to the same gain, set Mode to "Add" (both Ch1 and Ch2 pushed in), and set the Channel 2 Polar(ity) to Inv(ert).

- connect the signal generator directly across the input (blue-white pair below) and verify the short-circuit termination (orange-white pair)



- increase the frequency until the signal level is minimum There could be multiple nulls; use the first one to compute the length.



- record the frequency and compute the length of the line. Give your answer to the instructor who will record it and advise if you are finished.

Pre-Lab

Obtain equations for the quantities you will measure: line capacitance, line inductance and line length as functions of the known or measured values: resistor and capacitor values, voltages, null frequencies and dielectric constant. Bring your equations to the lab for the instructor to check.

Measured data should be permanently recorded in a notebook but calculations are most conveniently done with a spreadsheet. Prepare a spreadsheet for the calculations above. Include the following columns:

- description of the quantity (e.g. `Wavelength`)
- value (`20`)
- units (`m`)
- variable name (`L`)
- equation in terms of other variables if computed (`v/(2f)`)
- comments (optional)

Lab Report

Your report should include:

- the identification information as in the previous lab report
- a table showing the measurements and calculations described in the procedure section
- compute the characteristic impedance and the capacitance per unit length using your measurements. Compare these to the specifications for Cat5 cable.

Submit your lab report in PDF format to the "dropbox" on the course web site.