Measuring Transmission Lines

Introduction

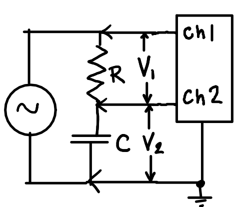
In this lab you will use a signal generator and an oscilloscope to measure the capacitance, inductance and length of a transmission line. These measurements will demonstrate transmission line theory and can also be used to measure or test transmission lines.

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 transmission line terminated in an open-circuit) 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.

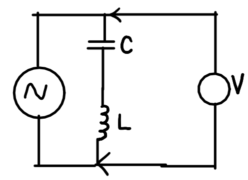


Note that the the transmission line is represented by the capacitor symbol in this schematic. There is no separate capacitor component for this measurement; one side of the twisted pair goes to ground and the other side to the bottom of the resistor. The twisted pair you are measuring is open-circuited at the other end and so in effect you are forming a capacitor from two pieces of wire that run parallel to each other for a meter or two. This is the capacitor in the schematic and the capacitance that you are measuring.

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 then compute the inductance of the transmission line.

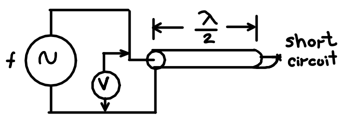
Note that to measure the capacitance and inductance this way the transmission line has to be short enough that it can be treated as a "lumped-element." "Short enough" means that the length of the transmission line is short relative to the wavelength. For a velocity factor of 0.66 the wavelength at 1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

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 and no power is consumed. This implies that all of the signal must be reflected back and that the reflected voltage must be inverted and equal in magnitude to the incident voltage. This inverted reflected signal will propagate back and appear at the input to the transmission line.

What happens if the two-way propagation delay along the transmission line causes a phase shift of 360 degrees? The reflected signal will arrive back at the input exactly one cycle later but inverted. Then the reflected signal will cause cancellation of incident signal at the source as well.



A two-way phase shift of 360 degrees (180 degrees one-way) is due to the signal travelling a distance of one wavelength (one-half wavelength one-way). From this 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, more accurately, it can be computed from the dielectric constant of the dielectric if known:

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

This technique is particularly useful when we only have access to one end of the transmission line. If we have access to both ends of the transmission line we can measure the phase shift directly. This technique is also useful when we cannot accurately measure delay but we have a way to accurately measure frequency and detect voltage nulls. If we have equipment that can measure the delay directly (reflected or one-way) we can also use a short pulse and measure the delay or a 'scope. You can try making these measurements if you have time.

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. Marks will be deducted for making large errors.

- get your assigned package of twisted-pair cable, a 10 kΩ resistor and a 220 nF capacitor from the instructor. Record the letter on the cable package (A, B, C, ...).
- measure the resistor value with your DMM and measure the capacitance with the LCR meter 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. Make sure none of the ends of the conductors are touching.
- hook up the capacitance-measuring circuit. Instead of a capacitor you will use 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 (if switchable) 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. Note that channel 2 will be measuring V_2 but you cannot measure V_1 directly.
- set the signal generator for a 50kHz sine-wave output of approximately 4 V_{pp} (the actual voltage is not important)
- measure V_1, the voltage across the resistor, by enabling the Math trace and selecting operation "A-B" with A as Channel 1 and B as Channel 2. Note that we must make this differential measurement because we cannot ground either end of the resistor.
- measure V_2, the voltage across the transmission line.

- compute the capacitance of your length of open-circuit cable using the two voltage measurements and the resistor value. Use the spreadsheet you prepared in the pre-lab. Double-check your measurements and results. Give your package letter and result to the instructor who will record it and advise if you should proceed. Make sure you have double-checked your measurements and calculations. Your lab completion mark will be reduced for each wrong "guess."

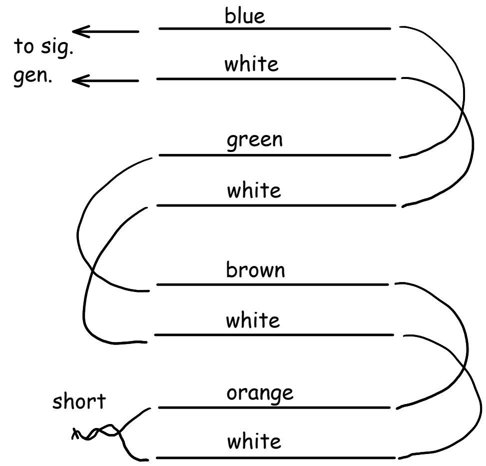
- replace the resistor with your 220 nF capacitor *and short-circuit* the end of the orange-white pair to create a series-resonant LC circuit as shown in the second schematic above. Note that there is no inductor – the transmission line is acting as an inductor in this case.

- adjust the signal generator frequency to find the "null" frequency where the voltage, V, 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.

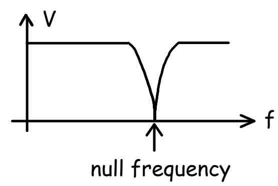
- record the null (resonant) frequency and compute the inductance. Give your answer to the instructor who will record it and advise if you should proceed. As above, marks will be deducted for wrong "guesses."

- 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)

- 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. If you have one of the longer lengths of cable you might see multiple nulls; *use the first (lowest frequency) null to compute the length*.



- record the frequency and compute the length of the line using the manufacturer's specifications for dielectric constant (use 2.2 if not given). Divide by four to find the length of the cable. Don't use the measured values of L and C to compute l since the compounded errors from three separate measurements are unlikely to give you an accurate result. Give your answer for the length of the cable to the instructor who will record it and advise if you are finished.

- if you have time, try one of the alternate length-measurement techniques by connecting a probe to an open-circuited termination and measuring the phase shift (for sine-wave input) or delay (for a pulse input).

Pre-Lab

Derive equations for the quantities you will measure: line capacitance, line inductance and line length as functions of the known or measured values: resistor

Quantity	Value	Units	Variable	Equation	Comments
resistor value	9.98	ohms	R		measured with LCR bridge
…					
line length	3.2	meters	l	v/(2f)	

and capacitor values, voltages, null frequencies and dielectric constant. Bring a copy of the equations to the lab.

Look up typical capacitance and inductance per meter, dielectric constant and velocity of propagation for Cat 5 cable so you have a rough idea of the results to expect.

Measurement data should be permanently recorded in a notebook but calculations are most conveniently done with a spreadsheet. Prepare a spreadsheet for the calculations above. Your spreadsheet should include the following six *columns* (not rows):

- 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)

See the sample above.

Submit a pre-lab report consisting of a printout of your spreadsheet in PDF format (landscape format if necessary) showing the column headings listed above and one row for each of the quantities you will measure or compute. The formula column should be filled in with the appropriate formulas (as text or formatted as math equations if you can). The cells in the value column that contain computed values should be filled in with the corresponding spreadsheet formula (even if they are not visible).

Lab Report

Your lab report should include:

- your name and BCIT ID, course, date and lab number
- the spreadsheet table showing the measurements, calculations and results 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 Lab 3 "dropbox" on the course web site.