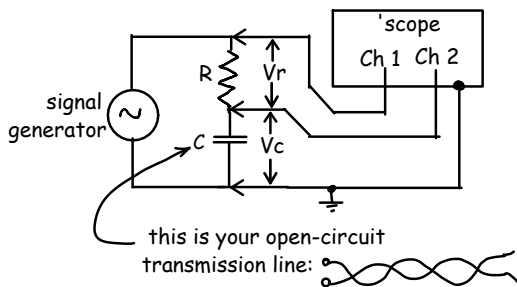# Measuring Transmission Lines

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:

$$X_C = \frac{1}{j2\pi f C}$$

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 transmission line form a voltage divider. Since $V_R/V_C = R/X_C$, from the resistance R and the voltages V_R and V_C we can compute the transmission line's reactance (X_C). Then from this reactance we can compute the transmission line's capacitance.


There is no actual capacitor used for this measurement. In the schematic above the capacitor is actually the transmission line. 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 will measure.

Inductance

Similarly, a transmission line terminated in a short circuit forms an inductor. Although we could measure the inductance by measuring its reactance as we did for the capacitance, we will use another method.

If we connect a capacitor of known capacitance in series with a transmission line terminated in a short circuit we form a series-resonant LC circuit:
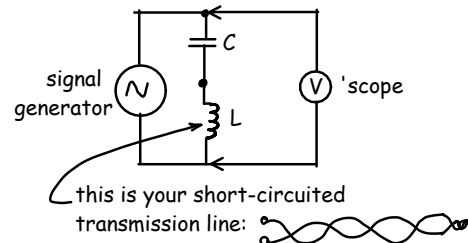
The inductance can be measured indirectly by measuring the resonant frequency of this LC circuit.

At the resonant frequency the inductive and capacitive reactances cancel and the circuit will have minimum impedance. This will short-circuit the output of the signal generator resulting in a low voltage across its output.

The resonant frequency therefore can be found by adjusting frequency of the signal until the voltage across the series LC circuit is a minimum.

The resonant frequency of an LC circuit can be found by setting $X_L = -X_C$ and solving $j2\pi f L = -\frac{1}{j2\pi f C}$ for f. The resonant frequency 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 (a typical test frequency) 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. In some cases we can transmit a pulse through the transmission line and measure the delay directly. But there are indirect methods that are sometimes more convenient.

When a transmission line is terminated in a short-circuit the voltage at the termination must be zero and therefore no power is being consumed. This implies that all of the signal must be reflected back towards the source. A zero voltage also implies that the reflected signal must be equal in magnitude but of opposite sign to the incident signal. 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. The reflected signal will cause maximum cancellation of incident signal at the source (a "null").
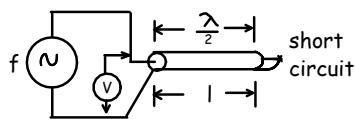
A two-way phase shift of 360 degrees (180 degrees one-way) is due to the signal travelling a total distance corresponding to one wavelength (one-half wavelength each way). From the null frequency and the cable's velocity of propagation we can compute the length of the transmission line:

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

The velocity of propagation can be computed from the dielectric constant of the dielectric constant[1]:

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

This method of measuring the resonant frequency is 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 could measure the phase

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[1] We could also compute it from the measured inductance and capacitance using the formula $v = \frac{1}{\sqrt{LC}}$ but the compounding of measurement errors would not give you an accurate value

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 you 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

Read and understand the Introduction. If you don't understand what you are doing you will not be able to follow the procedure below.

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 unreasonably large measurement errors[2].

- 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.

- 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 measure V_C but you cannot measure V_R directly because connecting the ground of channel 1 would set V_C to zero.

[2] Typically caused by not paying attention to details and calculation errors.

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

- set the signal generator for a 50kHz sine-wave output of approximately 4 V_{pp} (the actual voltage is not important)

- measure V_R, 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_C, the voltage across the transmission line/capacitor.

- 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 check it and advise if you should proceed. Units are important. Make sure you have double-checked your measurements and calculations. Your lab completion mark will be reduced for each wrong "guess."

- hook up a series LC circuit using the 220 nF capacitor and the *short-circuited* orange-white transmission line pair as shown in the second schematic above. Note that there is no inductor – the transmission line is the inductor.

- 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.

- 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. Note that poor connections will yield poor results.

- connect the signal generator directly across the input (blue-white pair below) and verify the short-circuit termination (orange-white pair)
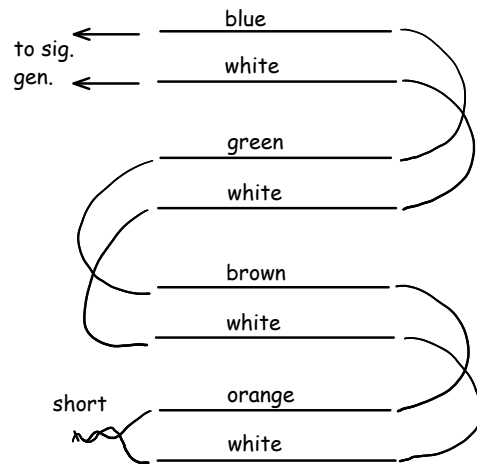
- increase the frequency until the signal level is minimum. If you have one of the longer lengths of cable you might see multiple nulls; *use the first (lowest frequency) null to compute the length*. Note that at low frequencies the shorted transmission line also acts as a short circuit.
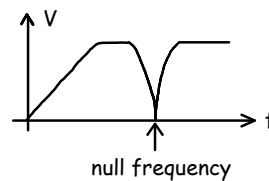
- record the frequency and compute the total length of the four pairs using the manufacturer's specifications for dielectric constant (use 2.2 if not given). Divide by four to find the length of the cable. Don't use the measured values of L

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 three quantities you are measuring (C, L and l) in terms of the values you are measuring (known capacitance, known resistance, voltages and frequencies). 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. It's a good idea to cross-check your values using different sources.

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. `Capacitance per meter`)

- value (e.g. `20`). In some cases this will be measured and the value can be entered in the cell. For computed values the cell should contain a formula that computes the result based on the other cells. Don't use a calculator to compute these values.

- units (`pF`)

- variable name (`C`)

- equation in terms of other variables if this is a computed value (e.g. `v/(2f)`)

- comments (optional)

See the sample above.

Submit a pre-lab report in PDF format containing:

- the usual cover page information

- equations for the three quantities you are measuring (C, L and l).

- the specifications for C and L (per meter) for Cat 5.

- the smallest and largest values of C and L you expect to measure if the transmission line length is between 1 and 5 meters long. Include the units.

- your spreadsheet (in landscape format if necessary) showing the column headings listed above, with one row for each of the values you will measure and one row for each of the quantities you will compute. For the computed values 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).

Engineering spreadsheets should format cells that display physical quantities (resistances, currents etc.) in engineering rather than scientific notation. For example a 10 kΩ resistance should be displayed as 10.0E3 rather than 1.00E4). You can apply a custom field format string of `##0.0E+0` to obtain engineering notation (Format Cells -> Custom -> `##0.0E+0`).

Lab Report

Your lab report should include:

- the usual cover page information

- the letter of the package you measured (e.g. 'C')

- the table from your spreadsheet showing the measurements, calculations and results described in the procedure section

- a comparison of the measured capacitance and inductance per meter to the published values for Cat5 cable.

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