Introduction
This lab involves construction of circuits which demonstrate electromagnetic properties of cables used in sensor and instrumentation systems.

Materials you will need from TA (to be returned at end of lab period):
30 meter (100 feet) length of 50Ω coaxial cable
Prelab

All of your prelab work is to be done in your laboratory notebook and will be checked by a lab TA prior to the start of lab.

P1. The circuit in Figure 1 represents the circuit model of an interference path from source \( v_{in} \) to the 10 M\( \Omega \) load resistance at \( v_{out} \).

\[ H(f) = \frac{v_{out}}{v_{in}} \]

a) Determine the transfer function \( H(f) = \frac{v_{out}}{v_{in}} \) from \( v_{in} \) to \( v_{out} \).

b) Determine the output magnitude \( |v_{out}| \) when \( v_{in} \) is a 170V pk sine wave at 60Hz

c) Determine the output magnitude \( |v_{out}| \) when \( v_{in} \) is a 1V pk sine wave at 1 MHz

P2. The circuit in Figure 2 represents the circuit model of an interference path from source \( v_{in} \) to the 10 M\( \Omega \) load resistance at \( v_{out} \).

Repeat parts (a), (b), and (c) for the circuit of Figure 2. Hint: the answer is very, very simple in all three cases!
Lab

L1. Shielding

Figure 3a shows the physical configuration of a coaxial cable. Prepare your cable for the lab (if not done already) by using wire strippers, a utility knife, or other tool to

1. carefully remove ~3-5cm of the outer insulator from each end of the roll of coaxial cable. Try not to damage the outer conductor braid, foil, or drain wire.

2. then, remove ~1cm of the dielectric insulator, exposing the inner conductor

Each end of your prepared cable should look something like Figure

(For ease of handling, do not unroll your cable – leave it coiled.)

![Coaxial cable diagram](image1)

Figure 3a. Coaxial cable.

![Prepared cable end](image2)

Figure 3b. Prepared ends of cable.
Connect the center conductor of the cable to the oscilloscope input and look at the voltage on the cable center conductor. Leave the shield unconnected (“floating”) as shown in Figure 4a.

![Coaxial cable with floating shield.](image)

**Figure 4a.** Coaxial cable with floating shield.

You should see an ugly 60Hz waveform due to capacitive coupling from the building power lines to the center conductor of the shield. The amplitude of the 60Hz could be anywhere from 100 mV to 1V or more. This is sometimes called “hum” since if this waveform is coupled to an audio signal, it is in the audible range of frequencies and sounds like a low frequency hum.

If possible, try moving a power cord from one of your bench instruments to be nearer the coaxial cable and see if the magnitude of the sine wave changes.

This is a real problem in many instrumentation systems since we are often trying to find a small signal of order mV, which will be swamped by the 100mV 60Hz hum.

A scope measurement hint: use the “TRIG MENU” to select the AC Line as the trigger source. The display will be synchronous with the 60Hz interference and make it easier to see a stable trace on the scope.
Eliminating the 60Hz interference

The situation can be modeled by the circuit diagram of Figure 1. The series combination of C1 and C2 couple the 60Hz hum to the high impedance node at the scope input. Usually we need to maintain a high impedance at a voltage measurement node so we can’t change the 10MΩ resistor.

The solution is to tie the shield to ground as shown in Figure 4b. This shorts out the C1-C2 node (as shown in Figure 2) so any current in C2 flows to ground rather than through the 10MΩ resistor. With the shield shorted to ground you should see little or no 60Hz at $v_{out}$.

Figure 4b. Coaxial cable with grounded shield.
L2. Transmission Line

Connect the function generator to drive one end of the cable as shown in Figure 5.

![Figure 5. Terminated transmission line.](image_url)

Beginning with $R_T = 50\, \Omega$, look at the driven end and the terminated end of the cable on the scope. Set the scope time scale to $\sim 50$ nsec per division and look at the waveforms at each end of the cable on the same time scale. Explain.

Remove $R_T$ so that the cable is terminated in an open circuit $R_T = \infty$. Look at the waveforms at each end of the cable on the same time scale. Explain.

Short the far end of the cable so that the cable is terminated in a short circuit $R_T = 0$. Look at the waveforms at each end of the cable on the same time scale. Explain.
We can model the coaxial cable as a series of LC sections representing the energy stored in the region between the inner and outer conductors in the magnetic field (due to current flowing in the cable) and electric field (voltage across the inner-to-outer-conductor capacitance).

What is the impedance $Z$ looking into an infinite length of cable? If it really is infinite, then we can break the line one section down and it should still look like $Z$. Thus we get a condition for impedance

$$Z = j\omega L + Z||\frac{1}{j\omega C}$$

(1)
For this cable, the capacitance per unit length $C_0 \approx 100\text{pF/meter}$ and inductance per unit length is $L_0 \approx 250\text{nH/meter}$. If we replace the $L$ and $C$ in (1) with $L = L_0 \Delta x$ and $C = C_0 \Delta x$ where $\Delta x$ is the length of each LC segment, we get

$$Z = j\omega (L_0 \Delta x) + Z \left[ \frac{1}{j\omega (C_0 \Delta x)} \right]$$

expanding out the parallel impedance expression gives

$$Z = j\omega (L_0 \Delta x) + \frac{Z}{1 + j\omega (C_0 \Delta x)}$$

multiplying through and rearranging gives

$$Z + j\omega Z^2 (C_0 \Delta x) = j\omega (L_0 \Delta x) - \omega^2 (L_0 C_0 \Delta x^2) + Z$$

solving for $Z$ gives

$$Z = \sqrt{\frac{L_0}{C_0}} + j\omega (L_0 \Delta x)$$

In the limit as $\Delta x$ approaches zero, we have for $Z$

$$Z = \sqrt{\frac{L_0}{C_0}}$$

which works out to $50\Omega$ for this cable.
Lab “Writeup”

Since this is the last lab, no writeup will be handed in. Just record results in your lab notebook and get them checked out by a lab TA.

L1. Shielding

Record your waveform amplitudes at $v_{out}$ with and without the shield grounded.

L2. Transmission Line

Record your waveforms with $R_T = 0, 50, \infty$. 