Introduction: Electrical interconnects in digital systems act as transmission lines when the time-of-flight becomes comparable with the slew time.

General characteristics. When an electromagnetic wave is impressed on a two-conductor transmission line (coaxial, two parallel wires, two parallel plates), the E-M signal travels along the line at the velocity at which it would propagate as a place wave in the same medium as that separating the conductors. The E fields terminate on charges on the conducting surfaces, and the motion of this charge distribution can be interpreted as a surface current. Instead of solving the E-M field equations, an equivalent set of partial differential equations can be written in terms of the voltage between the lines (integrated E field from one conductor to the other) and the total current flowing at a given point along the axis of the line.

Characteristic impedance. The initial surge of input line current for a given impressed voltage is determined only by the cross-sectional geometry and constants of the medium (\( \varepsilon \) and \( \mu \)). Due to the finite velocity of propagation, it is not affected by the terminating impedance. The relationship between the \( v^+ \) and \( i^+ \) forward traveling wave along the line defines its “characteristic impedance”, \( Z_o \).

\[
i^+ = \frac{v^+}{Z_o}
\]

For a coaxial line, \( Z_o \) is given by the following equation:
If the losses in the line are small, the waveform distortion of the traveling wave will be small. Amplitude attenuation is approximately exponential:

$$v^+(z) = v^+(0)e^{-\alpha z}$$

where $$\alpha = \frac{R}{2Z_o}$$ and R is the resistance per unit length of the line. This may be neglected for pulse transmission along very short low-loss lines.

**Reflections and impedance matching.** If the terminating impedance, $$R_2$$ is equal to $$Z_o$$, then the $$v^+$$ and $$i_+$$ wave are matched to the load and no reflection occurs.

If $$R_2$$ is not equal to $$Z_o$$, then a reflection occurs. The reflected $$v^-$$ wave is related to $$i^-$$ by the negative of $$Z_o$$ since the wave is traveling in the opposite direction (this is just a sign convention due to the previous choice of a positive direction for current in the conductor). The actual load current and voltage are, therefore:

$$v_2 = v^+(l) + v^-(l)$$
$$i_2 = i^+(l) + i^-(l)$$

Since

$$\frac{v_2}{i_2} = R_2$$

and

$$i^+ = \frac{v^+}{Z_o}$$
$$i^- = -\frac{v^-}{Z_o}$$

the magnitude of the voltage reflection coefficient, $$\Gamma$$, can be determined as follows, where $$\Gamma = (v^- / v^+)$$:

$$R_2 = \left[ \frac{v^+ + v^-}{i^+ + i^-} \right] = \frac{v^+}{i^+} \left[ 1 + \frac{(v^- / v^+)}{1 + (i^- / i^+)} \right]$$

$$= Z_o \frac{1 + \Gamma}{1 - \Gamma}$$

Solving this equation for $$\Gamma$$:

$$\Gamma = \frac{R_2}{Z_o} \frac{1}{1 + \frac{R_2}{Z_o}}$$

so that $$\Gamma = 0$$ if $$R_2 = Z_o$$, $$\Gamma = 1$$ for $$R_2 = \infty$$, $$\Gamma = -1$$ for $$R_2 = 0$$ and $$\Gamma = 0.33$$ if $$R_2 = 2Z_o$$.

This reflected wave will travel back to the sending end of the line, and there it may be re-reflected if $$R_1$$ is not equal to $$Z_o$$.

The reflection coefficient for the current wave is the negative of the voltage reflection coefficient:
\[
\Gamma_i = \frac{i^-}{i^+} = -\Gamma
\]

**Goals:** In this lab, you will study transmission line behavior. Specifically, you will:
1. Understand the effects of transmission line termination (near-end and far-end) on transmission-line response (reflection properties).
2. Understand the effects of capacitive termination.
3. Understand impedance matching issues for TTL and CMOS drivers.

**P** Set the signal generator to a square wave at about 2 V peak and 200kHz frequency. With the oscilloscope, determine the no load (open circuit) output amplitude \(V_{source}\) from the signal generator.

**Q1** Connect the signal generator to a 50 \(\Omega\) load and measure the new \(V_{source}\). What is the output impedance of the signal generator?

**P** Now connect the signal generator to an open line (the coaxial cable). Connect the oscilloscope (using two channels) at both the near-end \((v_A)\) and far-end \((v_B)\) as shown in Fig. 2.

**Figure 2.** Unterminated far end.

**Q2** Record the oscilloscope traces on the computer to include in your lab report. From the observed near-end and far-end waveforms, what is the approximate characteristic impedance of the transmission line? From the waveform at the near-end and from the cable length, compute the propagation velocity in the line?

**Q3** Now terminate the far-end of the line with a 50 \(\Omega\) resistor as shown in Fig. 3. Record the oscilloscope traces now on the computer to include in your lab report. Contrast the waveforms with those measured in Q2.
Now connect a series resistance of 220 Ω between the generator and the line as shown in Fig. 4. Leave the line open at the far end.

Figure 4. Unmatched source termination, unterminated far-end

Record the waveforms at the near-end and far-end. What is the reflection coefficient at the near-end? How does this compare with what you would expect?

Repeat the measurements and discussion of Q4 with a 22 Ω series resistance and open-circuited far end.

Connect a 1 nF capacitor at the far end of the line with the near-end connected directly to the source as shown in Fig. 5. Record the waveforms at the near-end and far-end. Explain the waveforms that you observe.

Figure 5. Capacitive far-end load

The experimental set-up that you have been using here with a step or pulse generator and an oscilloscope is referred to as time-domain reflectometry/time-domain transmissivity (TDR/TDT). This is often available as a free-standing instrument (or a plug-in to a high-end oscilloscope frame). It is used to characterize transmission lines from “one side,” allowing one to characterize the length and characteristic impedance as well as determine and characterize the presence of any impedance discontinuities in the lines.

Attach a 50 ft cable to the end of the existing 50 ft cable as shown in the Fig. 6. Record the waveforms at \( v_A \) and \( v_B \). Verify the length of the secondary cable
We are now going to consider transmission line effects associated with employing SSI logic gates as line drivers.

Let’s first use the TTL 74F04 parts as the transmission line drivers. Bipolar logic families typically have $I_{OL} > I_{OH}$, giving asymmetric rise and fall behaviors.

Using the TTL inverters to drive the line as shown in Fig. 7, record the waveforms at $v_A$ and $v_B$. Estimate the effective driver impedances for the pull-up and pull-down.

Repeat the measurement of Q8 using the 74HC04 parts. Comment on the differences with the results of Q8.