EEs MUST LEARN WHEN INTERCONNECTIONS AMONG CIRCUITS BEHAVE AS TRANSMISSION LINES, WHICH CAN UNEXPECTEDLY ALTER SIGNALS. SYSTEMS WHOSE DESIGNS IGNORE THESE EFFECTS PERFORM POORLY OR FAIL ALTOGETHER.

As edge speeds increase, wires become transmission lines

Electronic engineers, both digital and analog, must now understand how to live with transmission lines. Behind the need for improved understanding are today’s ICs, which produce signals that rise and fall so rapidly that they cause interconnections to behave as transmission lines. This behavior can alter waveforms and timing and even damage components.

Rise and fall times are now as short as 100 psec. When presented with such fast signals, many interconnections behave as transmission lines, even though they don’t do so when subjected to signals that change more slowly. Transmission-line effects can arise even if a system’s clock frequency remains moderate. By understanding transmission lines’ analog characteristics, designers can prevent interconnections from limiting the speed and reliability of their systems.

This article explains what transmission lines are and how they function. It includes the basics on how proper terminations allow you to live with transmission lines.

You should care about the speed of system interconnections because electronic signals propagate at a significant fraction of the speed of light. It takes about 2 nsec for a signal to traverse 12 in. (30 cm) of interconnection on a typical pc board. A few years ago, when gate delays were 5 to 10 nsec, the propagation time of a signal through an IC might have been tens to hundreds of nanoseconds. So, a fraction of a nanosecond or even 2 nsec was not a significant portion of the total signal-propagation time.

In the last decade, however, logic-gate delays have decreased to only a fraction of a nanosecond (50 psec in some 0.25-μm, 3.3V ASICs). Rise and fall times are less than 500 psec. Moreover, although many more functions now fit within the typical IC, the typical pc board now performs so many additional functions that the board size hasn’t changed appreciably. Therefore, the time that signals spend getting from place to place on pc boards has become a significant factor in system speed.

How can interconnections limit the speed and integrity of high-speed systems?

Improperly terminated transmission lines can cause the following problems:

Ringing delays cause lower system speeds
A high-speed signal transition on an interconnection that behaves as an improperly terminated transmission line can generate reflections. Reflections cause temporary ringing (voltage oscillations above and below the eventual steady-state level). One way to avoid the consequences of ringing is to wait for the reflections to subside before allowing the system to process new data. To achieve the extra delay, you can add one or more clock cycles to each operation, or you can reduce the system’s clock frequency.

Overshoot exceeds maximum-IC-voltage ratings
A reflection can cause a voltage to rise above or, because of negative overshoot, fall below the minimum rating an IC’s maximum rating. When the excessive voltage persists for more than a trivial amount of time, the IC is overstressed and may latch up. Latch-up can cause temporary or permanent
Transmission lines

Crosstalk increases bit-error rate

Reflections on an improperly terminated transmission line cause larger voltages and currents, which radiate larger electric and magnetic fields and transfer more crosstalk energy into neighboring wires. Undershoot increases bit-error rate.

Why is signal integrity poor if an interconnection is unterminated?

Under certain conditions, an interconnection ceases to act as a simple pair of wires and behaves as a transmission line, which has different characteristics. The term “wires” includes all types of conductors: traces on PCB boards, twisted pairs, ribbon cables, and coaxial cables.

What differentiates a pair of wires from a transmission line?

The length of the interconnection and the highest frequency signal component are the determining factors.

A short interconnection or one that operates at a low frequency behaves as a group of lumped circuit elements, such as one capacitor and several resistors (Figure 1a). A typical PCB board’s interconnect resistance is usually insignificant, so, when you calculate the interconnection delay, you need to consider only the capacitance. If the interconnection is long or the signal frequency is high, the interconnection behaves as a transmission line, which has decidedly different characteristics (Figure 1b). For example, at 1 Hz, a circuit that drives a 100-kΩ load through a long cable sees the cable merely as a 1Ω resistor in series with the 100-kΩ load. However, at 300 MHz, the driver sees only the cable’s characteristic impedance, which consists of a continuous uniform resistance, inductance, and capacitance. The driver does not see the 100-kΩ load during the 300-MHz signal’s transitions.

This article attempts to answer the following questions:
- What are short and long interconnects?
- What are low- and high-frequency signals?
- What is a transmission line?

Table 1—Relative Permittivity and Permeability of Some Common Materials

<table>
<thead>
<tr>
<th>Material</th>
<th>Dielectric constant $\varepsilon_r$</th>
<th>Permeability $\mu_r$</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air</td>
<td>$\varepsilon_r = 1$</td>
<td>$\mu_r = 1$</td>
<td>a great transmission material</td>
</tr>
<tr>
<td>Cable (RG-58)</td>
<td>$\varepsilon_r = 2.3$</td>
<td>$\mu_r = 1$</td>
<td></td>
</tr>
<tr>
<td>PCB (FR-4)</td>
<td>$\varepsilon_r = 4$</td>
<td>$\mu_r = 1$</td>
<td></td>
</tr>
<tr>
<td>Glass</td>
<td>$\varepsilon_r = 6$</td>
<td>$\mu_r = 1$</td>
<td></td>
</tr>
<tr>
<td>Ceramic</td>
<td>$\varepsilon_r = 10$</td>
<td>$\mu_r = 1$</td>
<td></td>
</tr>
<tr>
<td>Barium titanate</td>
<td>$\varepsilon_r = 1200$</td>
<td>$\mu_r = 1$</td>
<td>a great capacitor material; $C = \varepsilon \mu A/d$, where $A$ = area, and $d$ = thickness</td>
</tr>
<tr>
<td>Steel</td>
<td>$\varepsilon_r = \text{Not applicable}$</td>
<td>$\mu_r = 2000$</td>
<td></td>
</tr>
<tr>
<td>Permalloy</td>
<td>$\varepsilon_r = \text{Not applicable}$</td>
<td>$\mu_r = 80,000$</td>
<td>(a great magnetic material)</td>
</tr>
</tbody>
</table>

Notes: $\varepsilon_r = \epsilon_r/\epsilon_r'$; $\mu_r = \mu_r/\mu_r'$; and velocity $= 1/\sqrt{\varepsilon_r \mu_r' \varepsilon_r' \mu_r'}$.
• How does a transmission line differ from a simple interconnection?
• How can a transmission line hurt the signal’s integrity?
• How can proper terminations fix signal-integrity problems?

Short interconnections
A short interconnection is one whose length is a small fraction of the signal’s sinusoidal wavelength. A conservative rule of thumb for a small fraction is one-tenth. For example, you can treat a 32-in.-long (81-cm) interconnect as a lumped capacitor at signal frequencies as high as 24 MHz. You arrive at that frequency because 320 in. (8.2 m) is the wavelength for which 32 in. is one-tenth. A signal with a wavelength of 8.2 m has a frequency of 24 MHz. You can derive this frequency from:

\[
distance = velocity \times time
\]

Where velocity = frequency, then:

\[
velocity = \frac{velocity \times (1/frequency)}{time}
\]

For example, with a driver that has \( R_0 = 50 \Omega \), a pc-board-trace capacitance of \( C = 50 \text{ pF} \); and a fast 5 V input pulse, the signal would be at 3.15 V in one time constant \( t = RC \). Also, at \( t = 2.5 \text{ nsec}, V = 3.15 \text{ V} \) (63% of 5 V); at \( t = 5.0 \text{ nsec}, V = 4.30 \text{ V} \) (86% of 5 V); and at \( t = 7.5 \text{ nsec}, V = 4.75 \text{ V} \) (95% of 5 V).

The interconnection’s propagation delay would be the time from the application of the new signal until the signal reaches the receiver’s switching threshold.


Table 2—Electromagnetic-Wave Speeds

<table>
<thead>
<tr>
<th>Material</th>
<th>( \varepsilon_r ) at 10 kHz</th>
<th>Square root of ( \varepsilon_r )</th>
<th>Speed (in./nsec)</th>
<th>Speed (cm/nsec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air</td>
<td>1</td>
<td>1</td>
<td>12</td>
<td>30.5</td>
</tr>
<tr>
<td>Teflon</td>
<td>2</td>
<td>1.41</td>
<td>8.5</td>
<td>21.6</td>
</tr>
<tr>
<td>Silica glass</td>
<td>3.8</td>
<td>1.95</td>
<td>6.2</td>
<td>15.7</td>
</tr>
<tr>
<td>Epoxy glass</td>
<td>5</td>
<td>2.2</td>
<td>5.4</td>
<td>13.7</td>
</tr>
<tr>
<td>Ceramic</td>
<td>10</td>
<td>3.2</td>
<td>3.75</td>
<td>9.5</td>
</tr>
</tbody>
</table>

\[
\text{Speed} = \frac{C_0}{\sqrt{\varepsilon_r}} = \frac{\text{Speed of Light}}{\sqrt{\text{Relative Dielectric Constant}}}
\]

This value is for electromagnetic waves in free space. A subsequent discussion covers the effects of a dielectric material adjacent to the conductor. The effect of the dielectric is the reason for the \( \sqrt{\varepsilon_r} \) factor that appears in the earlier discussion of short interconnections.

A short-length interconnect looks like a pair of wires and a simple capacitor.

The RC time-constant formula for the charging of a capacitor through a resistor determines the signal delay through a short or low-frequency interconnection (Figure 3). The resistance of a conductor on a pc board is usually too small to consider, but you should include the driver’s output resistance in calculating the time constant.

A short or low-frequency interconnect looks like a pair of conductors and a lumped capacitance. The resistance of a conductor on a pc board is usually too small to consider, but you should include the driver’s output resistance in calculating the time constant.

So, how do the high-speed signals travel on a pc board?

High-speed signals travel on a pc board as electromagnetic waves at about half the speed of light (15 cm/nsec, or 6 in./nsec) on the surface of the conductors and in the pc-board dielectric. Light, which is also an electromagnetic wave, travels in free space at 30 cm/nsec (\( C_0 = 300 \times 10^6 \text{ m/sec}, \) or 186 miles/nsec). What is a long interconnection?

As you have probably guessed, where-as a short interconnection is less than 0.1 of a signal’s wavelength, a long interconnection is longer than 0.1 of the signal’s wavelength. The basic guideline is that you must accord transmission-line status to any interconnection whose length is a significant portion of the signal’s wavelength. You should recognize, however, that with pulse waveforms, the rise time is easier to use than the wavelength is for determining whether an interconnection is long or short.
Interconnection resonance

When the interconnect length approaches one-fourth of the signal’s wavelength, the interconnect starts to resonate and no longer behaves as a lumped capacitor. For example, the 32-in.-long cable in Figure 5 is one-fourth of a 60-MHz signal’s wavelength.

\[ d = v t = v f, \text{and} f = v / d = (3 \times 10^8 \text{m/sec} / \sqrt{2.3}) / (4 \times 32 \text{ in.} \times 1 \text{m/39 in.}) = 60 \text{ MHz}. \]

So, this resonance phenomenon is a reason for not having an interconnection length close to one-fourth the wavelength.

Component size versus wavelength

Figure 6 shows 100-MHz, 1-GHz, and 10-GHz current-signal frequencies. At 100 MHz, the current in the 2-cm-long resistor is the same throughout the resistor. At 1 GHz, the current in the resistor differs slightly at each end. You can’t even define the current in the lumped-component resistor at 10 GHz, however: At one end, the current is positive; at the other end, it is negative. Conventional components’ distributed nature is one reason to use small thin-film resistors at such high frequencies.

What is a high-frequency interconnection?

A high-frequency interconnection is one in which the signal’s rise time \( t_R \) is less than twice the propagation time \( t_{PD} \), or time of flight, for the signal’s electromagnetic wave to reach the end of the interconnect.

Although the wavelength criterion illustrates a basic principle, this rise-time rule is easier to use and should form the basis for deciding whether an interconnection behaves as a transmission line. The reason is simple: All digital signals contain frequency components that are higher than the fundamental. To have sharp corners, square waves contain at least the third and fifth harmonics. Although you could use the frequency of these harmonics, most digital-system designers think in rise and fall times, which are easier to measure with an oscilloscope. If you can’t measure the rise and fall times, you can estimate them. Typically, each time is 10 to 20% of the period.

Designers should not fall into the trap of thinking that their ICs’ rise times are those on that data sheets. Most data sheets don’t even specify rise and fall times, but the data sheets that do generally provide only the maximum (slowest) values. The parts that you receive are likely to be at least slightly faster and may be several times faster. So, you should use a rise-time figure that you base on a manufacturer’s guarantee or on your own tests.

For the earlier example of a 32-in.-long cable, you must treat the cable as a transmission line for signals at frequencies greater than 24 MHz. The following formula illustrates this point:

\[ t_{PD} = \frac{\text{DISTANCE}}{\text{VELOCITY}} = \frac{D}{C_D / \sqrt{\varepsilon_R}} = \frac{32 \text{ IN.} \times \sqrt{2.3}}{300 \times 10^6 \text{ m/SEC} \times 39 \text{ IN.}/\text{m} = 48.5} \]

where \( t_{PD} \) equals 4.15 nsec, which is the time it takes for the electromagnetic wave to make a one-way trip. The \( 2t_{PD} \) figure equals 8.3 nsec, which is the time it takes for a two-way trip. So, if the rise
time is less than 8.3 nsec, this cable is a transmission line. If you assume the rise time to be 20% of the signal’s period (0.2T = 8.3 nsec), then T = 41.5 nsec, and frequency = 24 MHz. So, for signals with frequencies higher than 24 MHz, this cable is a transmission line, in which ε is the relative dielectric constant (2.3 for RG-58 cable) and C₀ is the speed of light (300 × 10⁶ m/sec).

To save calculation time, you can use a graph that shows the boundary between wire pairs, which don’t need terminations, and transmission lines, which do (Figure 7). The data is based on interconnection lengths on a pc board and the signal’s rise time.

WAVEFORMS ON INTERCONNECTIONS

Figure 8 shows signal propagation along simple wires and along transmission lines. The figure shows signal amplitude versus distance along the line at specific times. With short interconnections or low-frequency signals, the applied signal voltage appears instantaneously at every point on the interconnection (Figure 8a). Propagation is instantaneous if, as it usually is on pc boards and short cables, the cable’s RC time constant is smaller than the signal’s period.

Actually, the signal’s electromagnetic wave travels at a finite speed along the interconnect from the source to the load (and back if there is a reflection). However, this movement is unnoticeable. The wave travels so often from the source to the load and back after every amplitude change that the transients are too small to observe.

Figure 6

You can’t even treat resistors as lumped components at high frequencies because the current density varies widely within their bulk. At 100 MHz, a 2-cm-long resistor has the same current throughout the resistor. At 1 GHz, the resistor has slightly different current at each end. You can’t even define the current in the lumped-component resistor at 10 GHz, however: At one end, the current is positive; at the other end, it is negative.

However, with long interconnections or high-frequency signals, the electromagnetic-wave propagation time is comparable with the rise time (Figure 8b). Hence, the transient incident and reflected-wave amplitudes are comparable in size to the applied signal. So, by t₁ in Figure 8, the applied signal voltage has traveled only a short distance from the source end. Only after the passage of time, t₂, does the voltage appear at a point closer to the load.

A signal propagates down a transmission line as an electromagnetic wave at a velocity close to the speed of light. In free space (in an antenna, for example), where there is no dielectric (insulating) material next to the conductor, the signal’s electromagnetic wave travels at exactly the speed of light. On a pc board, the electromagnetic wave’s speed is lower because of the dielectric material adjacent to the interconnect conductors.

The electromagnetic wave’s speed on the pc-board interconnections equals the speed of light divided by the square root of the relative dielectric constant of the material adjacent to the conductors. For example, on a board made of FR-4 material, the relative dielectric constant (εᵣ) = 4, and √(1/εᵣ) = 1.41. So, the signal speed on the board is half the speed of light (1.5 × 10⁸ m/sec or 60 in./nsec).

WAVE PROPAGATION

The concept of waves is one of the great unifying concepts of physics. The physical environment has many types of waves: light waves, sound waves, waves on water, heat waves, radio and TV waves, seismic waves, and even traffic waves. Moving waves carry energy. Most waves travel through media, such as earth, air, water, and steel, without actually carrying the substance with them, though they need the substance to propagate.

Water waves exemplify wave propagation that requires an intermediate material. When you drop a pebble into still water, the water particles near the pebble immediately move from their equilibrium positions. The motion of these particles disturbs adjacent particles,
causing them to move, and the process continues, creating a wave. The water wave consists of ripples that move along the surface away from the initial disturbance. Individual water particles move mainly up and down with a slight side motion. However, the cumulative effect of all the particles produces a wave that moves radially outward from the initial disturbance point.

Electromagnetic waves, which have a property uniquely different from those of other waves, are of interest in transmission lines. Electromagnetic waves can propagate in a vacuum without any matter present. So neither the copper on the pc board nor the electrons in it needs to move to get a transient signal to its destination. Similarly, the ability of electromagnetic waves to propagate in a vacuum allows communication with satellites in the vacuum of outer space.

A compact set of principles known as Maxwell’s equations describes electromagnetic-wave phenomena. These equations are based upon experimental observations and provide the most accurate model of the basic relationships of electric fields, charges, currents, and magnetic fields. The equations cover the entire electromagnetic spectrum of radio waves, infrared rays, visible-light rays, X-rays, and gamma rays.

**ELECTROMAGNETIC-WAVE PROPAGATION**

Electromagnetic waves consist of time-varying electric and magnetic fields. When the electric charge on a pair of conductors changes, the electric field that the charges create changes. This time-varying electric field generates a magnetic field. The time-varying magnetic field, in turn, creates an electric field. (Two charged electrodes or a changing magnetic field can create an electric field.) These time-varying fields continue to generate one another in an ever-expanding region, and the resulting waves propagate away from the location of the initial charge change.

**Figure 9** shows both the electric and magnetic waves traveling on a transmission line. These waves are the result of a sinusoidal signal at the source. These waves are in a transverse-electromagnetic (TEM) mode because the fields are perpendicular (transverse) to the direction of travel. The electric (E) and magnetic (H) fields are also perpendicular to each other.

**Wave propagation in free space**

The permittivity and permeability of the medium in which it travels determine an electromagnetic wave's velocity of propagation.

Permittivity, $\varepsilon$, is the ability of a dielectric to store electrical potential energy under the influence of an electric field. The permittivity of free space is $\varepsilon_0 = (1/36\pi) \times 10^{-12}$ F/m.

Permittivity is an important parameter of a capacitor. The presence of farads in the measurement unit should help you to remember the definition and to distinguish permittivity from permeability.

Permeability, $\mu$, is the property of a magnetic substance that determines the degree to which the substance modifies the magnetic flux in the region of a magnetic field that the substance occupies. The permeability of free space is $\mu_0 = 4\pi \times 10^{-7}$ H/m. Velocity, $v$, in free space is $v_0 = 1/\sqrt{\varepsilon_0 \mu_0} = 300 \times 10^6$ m/sec.

**Table 1** shows the dielectric constants of various substances.
and relative permeabilities of various materials.

Skin effect

To an electric field outside a good conductor, such as copper, the conductor appears to exhibit infinite conductivity. However, inside a perfect conductor, there can be no electric or magnetic field. Inside a good conductor, a varying electric field can penetrate only a thin region, or skin. As the signal frequency increases, the thickness of the skin decreases.

The formula for calculating the skin depth in meters is \( \sqrt{\frac{\rho}{\mu f}} \), where \( \rho \) is the conductor resistivity in ohm-meters, \( \mu = 4\pi \times 10^{-7} \text{H/m} \), and \( f \) is the frequency in hertz. (The skin depth in copper, for example, might be only 10 \( \mu \text{m} \).)

**Speed of wave on a transmission line**

Table 2 shows electromagnetic-wave speeds on transmission lines using various dielectrics.

**LUMPED-COMPONENT CIRCUIT MODELS**

The above electromagnetic-wave models are the most accurate that physicists have devised to explain their experimental observations. However, these models and their accompanying equations are inconvenient for electronics engineers who are accustomed to circuit models that contain lumped components, such as resistors, capacitors, and inductors. The designers of the lumped-component circuit models intended them to handle only dc and very-low-frequency currents, but engineers have adapted these models to represent transmission lines.

Many small, lumped R, L, and C components represent the transmission line’s continuous uniform resistance, inductance, and capacitance. Conventional currents and voltages represent the electromagnetic waves. **Figure 10** shows two versions of this lumped-component model. The second-order transmission-line model is more accurate, because it incorporates all three component types. However, engineers more often use the first-order model because most transmission-line cables and pc-board conductors have \( L \) and \( C \) values that dwarf the \( R \) values. Therefore, it is often safe to ignore series resistance and shunt conductance.

**Characteristic impedance of circuit model**

The most important parameter of the transmission line’s lumped-component circuit model is the characteristic impedance, \( Z_0 \). \( Z_0 \) is the effective transmission-line impedance that the source signal driver sees during the signal’s high-speed transition. After the transition ends, the impedance of the cable or pc-board conductors returns to that of simple wires, which each have a near-zero resistance. The most surprising aspect of a transmission line’s \( Z_0 \), however, is that even though the circuit model consists of inductors and capacitors, \( Z_0 \) is effectively a pure resistor with no reactive component. Moreover, unlike the conductors’ series resistance, \( Z_0 \) is not near-zero in value.

During the signal transition, the driver sees only \( Z_0 \) and does not see the load impedance, \( Z_L \), which is at the end of the transmission line.

You can derive \( Z_0 \) from the transmission-line circuit model. **Figure 11** shows two versions of this lumped-component model. The second-order transmission-line model is more accurate, because it incorporates all three component types. However, the first-order model sees more use because most transmission-line cables and pc-board conductors have \( L \) and \( C \) values that dwarf the \( R \) values.

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**Equation 3** is the solution to the equation \(d^2V/dx^2 = z dI/dx = zyV\), where \(V\) is the voltage at any point on the transmission line as \(x\) approaches zero and \(V_L = V_1 + V_2\).

When you substitute equations 3 and 4 into equations 1 and 2 and combine them, the equations become:

**INCIDENT** \(V_1 = \sqrt{z/y} I_1\),

**REFLECTED** \(V_2 = -\sqrt{z/y} I_2\), AND

\[ Z_0 = \sqrt{z/y} = \sqrt{\frac{1}{j\omega L} / j\omega C} = \sqrt{L/C}, \]

which is the characteristic impedance.

Note that the characteristic impedance is a pure resistance that is completely independent of frequency, even though the transmission-line circuit consists of reactive inductive and capacitive elements.

A derived formula expresses velocity as a function of the transmission line’s \(L\) and \(C\) per unit length. Velocity \(= 1/\sqrt{LC}\).

Usually, however, it is easier to derive the velocity from the speed of light divided by the square root of the relative dielectric constant, \(\varepsilon\). You can more easily obtain the value of \(\varepsilon\) than you can determine the transmission line’s \(L\) and \(C\) per unit length.

**Characteristic impedance from physical dimensions**

Because the inductance and capacitance of a transmission line depend solely on the physical characteristics of the implementation, you can also derive a transmission line’s characteristic impedance from the line’s physical dimensions.

**Figure 12** shows three configuration examples. Typical dimensions for microstrip transmission lines are: \(T\) (conductor thickness) = 0.0015 in. for 1-oz copper, \(H\) (substrate thickness) = 0.062 in. for G-10 glass epoxy, and \(W\) (conductor width) = 0.015 in.

**Multiple loads on a transmission line**

Most academic textbooks on transmission lines assume that every transmission line has only one load, but many pc boards place multiple loads on one transmission line. So, practicing engineers have developed an empirical formula to modify the characteristic impedance and signal velocity to account for the additional capacitance that multiple loads add. The formula is as follows:

**Figure 13**

Because the inductance and capacitance of a transmission line depend solely on the physical characteristics of the implementation, you can derive a transmission line’s characteristic impedance from the line’s physical dimensions.

The lumped-component circuit model uses uniformly distributed inductance and capacitance, which appear as many infinitesimal lumped elements. Voltage and current define the signal.
Transmission lines

\[ Z_{\text{effective}} = \frac{Z_0}{\sqrt{1 + (C_L/C_0)}}, \text{ AND} \]

\[ t_{\text{PD effective}} = \frac{t_{\text{PD}}}{\sqrt{1 + (C_L/C_0)}}. \]

\( C_0 \) is unloaded capacitance per unit length of the transmission line, and \( C_L \) is the added load capacitance per unit length. The added capacitance decreases the effective \( Z_0 \) and increases the propagation delay. Although these formulas aren’t in the theoretical textbooks, they are in many application notes, including one classic—the Motorola (www.motorola.com) MECL (Motorola emitter-coupled logic) Handbook. This handbook is also a source of \( C_0 \) values for microstrip transmission lines.

**Reflections on transmission lines with open-circuit loads**

What follows is a heuristic description of a signal wave traveling on a transmission line from the source to an open-cir-

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**Figure 14**

You can use a lattice diagram to calculate reflections.
cuited load end where the signal reflects back to the source. The lumped-component circuit model in Figure 13 uses uniformly distributed inductance and capacitance, which appear as many infinitesimal lumped elements. Voltage and current define the signal.

When the signal arrives at the load end of the transmission line, its orderly progress is interrupted. At time $t_1$, the wave is approaching the load end. The voltage and current of the signal’s energy wave are progressing together: $L_y$ is carrying current, but $L_z$ is not, and $C_y$ is charged to $E$, but $C_z$ is not. There is voltage across $C_y$, so current immediately begins to flow through $L_z$. Because $L_z$ carries as much current as $L_y$, the charge on $C_y$ increases no further than $E$. Current entering $L_z$ flows into $C_z$, charging it to $E$. At time $t_2$, the energy wave reaches the end. All capacitors are now charged to $E$, and all inductors are now carrying current $I$.

At this point, the progress of the wave cannot continue. $L_z$ is carrying current to $C_z$, but there is no inductor beyond $C_z$ to act as an outlet for current as $C_z$ becomes charged. You can see the result at time $t_3$ when $C_z$ becomes overcharged. $L_z$ cannot stop carrying current until it exhausts its magnetic energy. $L_z$ continues to drive current into $C_z$ until $C_z$’s voltage is $2E$. At this point, the current in $L_z$ is zero. At time $t_4$, when $L_z$ stops carrying current, all current that $L_z$ carries is driven into $C_z$, doubling the voltage of $C_y$ and forcing the current in $L_z$ to stop.

At the same time, the voltages at the two ends of $L_z$ become equal, so the overcharge on $C_z$ cannot escape. The voltage
across $C_y$ and $C_z$ is $2E_y$, and the current in $L_y$ and $L_z$ is zero. This process continues progressively along the line, assuming that the energy of each $L$ equals the energy of each $C$. The result is a voltage wave of magnitude $E$ traveling back to the source and adding to the original wave. The reflected-current wave appears as a negative $I$ wave traveling back to the source and canceling the original wave, so that the net current is zero. No current flows back to the source, but a wave front does propagate. The current that flowed away from the source continues to do so until it meets the reflected wave.

Remember that this explanation is merely an attempt to model experimental data (reality) with lumped components originally intended for low-frequency circuits. You can more accurately model these phenomena with electro-

### SUMMARY OF KEY POINTS ON TRANSMISSION LINES

- Interconnections via pc boards or cables can behave differently depending upon the ratio of the interconnection length to the signal’s wavelength. Signal-integrity problems occur if the interconnection is a transmission line and the system’s design doesn’t account for the transmission-line characteristics.
- A high-speed signal on a pc board or in a cable travels at the speed of electromagnetic waves (speed of light) modified by the dielectric constant (permittivity) of the material between the conductors.
- You should treat an interconnection as a transmission line when the signal’s rise time is less than twice the electromagnetic wave’s propagation time over the length of the interconnect. In other words, treat interconnections as transmission lines if their length is a significant portion of the signal’s wavelength. Remember, however, that the criteria of $\frac{t_{rise}}{2} < \text{time of flight and interconnect length}\times 0.1$ wavelength are not absolute but are rules of thumb. The effects of the impedance mismatches and reflections are analog in nature.
- During a signal’s high-frequency transitions, the characteristic impedance, $Z_0$, of a transmission line is purely resistive and depends upon the uniformly distributed values of capacitance and inductance; that is, $Z_0$ depends on the geometry of the conductors and dielectric. At low frequencies, the interconnection functions as simple wires between a driver and its load.
- To avoid signal-integrity problems in most situations, the transmission-line load impedance, the source impedance, or both should equal $Z_0$ or should add a termination resistor to make it equal $Z_0$. 


magnetic-wave differential equations or wave equations and boundary conditions.

Reflections on transmission lines with short-circuit loads

Reflections for a short-circuit load are similar to the above with the voltage and current waveforms interchanged.

Reflections on transmission lines with a matched load impedance

When the load impedance equals the transmission line’s characteristic impedance, no reflection occurs. The load looks like the uniform characteristic impedance of the transmission line, so the load absorbs all of the wave energy. In general, this configuration is ideal. Also, in general, when the load impedance doesn’t match the transmission line’s characteristic impedance \( Z_0 \), you should add a \( Z_0 \) termination resistor in parallel with the load. The load impedance is usually high, so its value is inconsequential. Because the source impedance is usually low, you can put a termination resistor in series with the source so the total resistance equals \( Z_0 \).

Use caution in applying these guidelines, because exceptions do occur.

Reflections on transmission lines with a discontinuity or intermediate load

A discontinuity (change in the uniform characteristic impedance) or intermediate load on a transmission line causes a reflection just as does an impedance mismatch at the load end. Any intermediate reflection travels back to the source and adds to the other waves traveling on the transmission line.

Reflections on transmission lines with any load impedance

If the load impedance, \( Z_L \), doesn’t match the transmission line’s \( Z_0 \), and if \( Z_L \)
is neither zero nor infinity, the signal energy that the load doesn’t absorb reflects back toward the source. When the reflection reaches the source, if the source impedance, $Z_s$, doesn’t match $Z_0$, there is a reflection from the source back toward the load. The reflections continue until the load, the source, and losses along the transmission line fully absorb the wave’s energy.

The following formula for $\rho$ determines the size of the reflection at a transmission line’s mismatched end (source or load):

$$\begin{align*} V_L &= V_{\text{INCIDENT}} + V_{\text{REFLECTED}}, \\
I_L &= I_{\text{INCIDENT}} + I_{\text{REFLECTED}}, \end{align*}$$

$$Z_L = \frac{V_L}{I_L} = \frac{V_I + V_R}{I_I + I_R}$$

$$\frac{V_L + V_R}{V_L - V_R} = \frac{Z_0}{Z_0} \quad \text{AND}$$

$$\text{REFLECTION FACTOR } \rho = \frac{V_R}{V_I} = \frac{Z_L - Z_0}{Z_L + Z_0}.$$

![Lattice diagram](image)

**Figure 14**

A different configuration of source impedance, transmission line, and load produces reflections that appear as ringing on the transmission line. The overshoot can damage the receiver circuit, or, if the receiver reads the signal before the ringing subsides, corrupt the data.

This formula is for the load mismatch. You can use the formula for a source end if you substitute $Z_s$ for $Z_L$. For the open-circuit calculation, divide the formula by $Z_L$ to avoid infinity over infinity.

**Lattice diagram**

You can use a lattice diagram to calculate reflections (Figure 14). First, note that the initial source voltage, $V_{0s}$ at $V_s$ is 0.5V, because the voltage, $V$, of 1V divides between $Z_L$ and $Z_0$. The lattice diagram shows that at $t=0$, the $V_0=0.5V$ voltage wave propagates to the load end where the reflection factor is 0.6. So the total
voltage, $V_L$, at the load at $t = 1$ is 0.8V. The reflected voltage of 0.3V then travels back to the source on the 0.5V incident wave. When the 0.3V wave reaches the source, no reflection occurs because $Z_S = Z_0$, making the reflection factor zero.

Bergeron plot

You might calculate the reflections using the more sophisticated Bergeron-plot technique (Figure 15). This technique is especially useful for nonlinear terminations; that is, where the driver or receiver has different impedances depending on whether the signal level is high or low.

Stair-stepping reflections

Figure 16 is an example of a transmission line whose source and load impedances produce reflections that cause the voltage to rise in stair-step fashion. This phenomenon occurs when $Z_S$ and $Z_L$ are only slightly higher than $Z_0$. The first signal wave is a fraction of the full driver signal because the driver signal divides between $Z_S$ and $Z_0$. The signal at the receiver needs approximately four round trips of reflections (40 nsec) before it reaches its full value.

Ringing reflections

Figure 17 provides an example of a different configuration of source impedance, transmission line, and load that produces reflections, which appear as ringing on the transmission line. The overshoot can damage the receiver circuit or, if the receiver reads the signal before the ringing subsides, corrupt the data. The waveform in the figure has square edges instead of curves only because it is from a simulation. In this simulation, $Z_L >> Z_0$. The ringing decays as the load and cable losses gradually absorb the signal's energy. You can now see that the criteria of $t_{rise} < 2$ times time of flight and interconnect length $> 0.1$ wavelength are not absolute demarcations but are rules of thumb because the effects of impedance mismatches and reflections are analog in nature.

Author’s Biography

James Sutherland is a senior applications engineer with California Micro Devices (Milpitas, CA), where he has worked for the past year. His responsibilities include defining new products and assisting customers. In a previous job, he developed ICs for DSPs, FPGAs, and disk drives. He holds a BSEE and an MBA from Stanford University (Palo Alto, CA) and is a member of the IEEE. His activities outside work include worldwide travel, photography, and parenting.