The Critical Length of a Transmission Line

Dr. Eric Bogatin
President, Bogatin Enterprises

Oct 1, 2004

Abstract
A transmission line is always a transmission line. However, if it is physically short enough, a signal may not be sensitive to some of the important properties we usually associate with a transmission line. In this article, we show that if the length of the interconnect, in inches, is longer than 2 x the rise time of the signal, in nsec, its transmission line properties are important, and the board should be designed with controlled impedance, and a termination strategy implemented. Read on to see the details.

A Transmission Line by Any Other Name
Signal integrity is often confusing because we use the same terms, multiple ways, and we don't always let on which way we intend. Take for example, the words, "transmission line".

There are really two ways in which we use these words, each very different. First there is the real, physical transmission line that we fabricate out of copper and dielectrics, such as FR4. All it takes to make a physical transmission line is two conductors with some length.

When we look at a circuit board and see a bunch of surface signal traces, such as in Figure 1, we should always try to see with our mind's eye, the return path for each signal line. The return path conductor is usually a buried plane, such as a ground plane. One of the signal traces and its associated return plane, make up a physical transmission line.
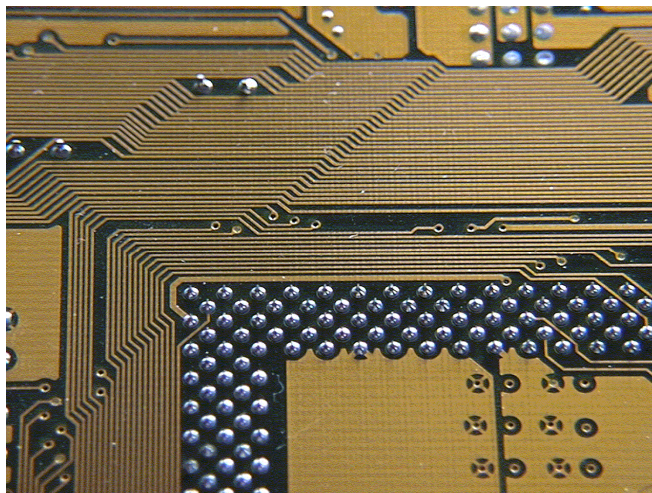
Figure 1. Example of surface traces as real, physical transmission lines on a circuit board.

For buried traces, such as stripline traces, the return path conductor might actually be two planes, one above, and one below. Even though these conductors may have a different DC voltage, their high frequency impedance is probably very low, typically less than 0.1 Ohms. This is virtually a short compared with the typically 50 Ohms between the signal and return path conductors. For this reason, from the return current's perspective, the two different planes are effectively shorted together, and can be considered as the same conductor.

Both microstrips and striplines are examples of physical transmission lines; structures used to transport a signal from one point to another with an acceptable level of distortion.

However, we also use the same words, transmission line, when we describe how this real physical interconnect behaves electrically. We use an equivalent circuit model called an ideal lossless transmission line model, to approximate the electrical properties of the real, physical transmission line. An example of the symbol used to refer to an ideal lossless transmission line circuit model is shown in Figure 2.
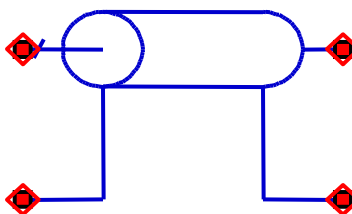

Figure 2. The symbol commonly used to represent an ideal lossless transmission line circuit element.

We often get lazy, and instead of calling this model the ideal, lossless transmission line model, we just call the model a transmission line.

When we refer to just a "transmission line", are we referring to a real physical interconnect structure on a circuit board, or are we referring to how it behaves, approximated as an ideal lossless circuit model? Sometimes it's hard to know.

The Ideal Lossless Transmission Line Model
One metric of electrical performance is impedance. The input impedance we would see looking into the front of a real, physical transmission line is basically what a device driver would see, driving a line. This is an important electrical property to be able to describe.

We can measure the impedance looking into one end of a transmission line, when the other end is open, using a network analyzer. Figure 3 is the actual, measured, input impedance, plotted on a log-log scale, of a 1 inch long microstrip transmission line built on FR4. It was designed to have a characteristic impedance of roughly 50 Ohms.
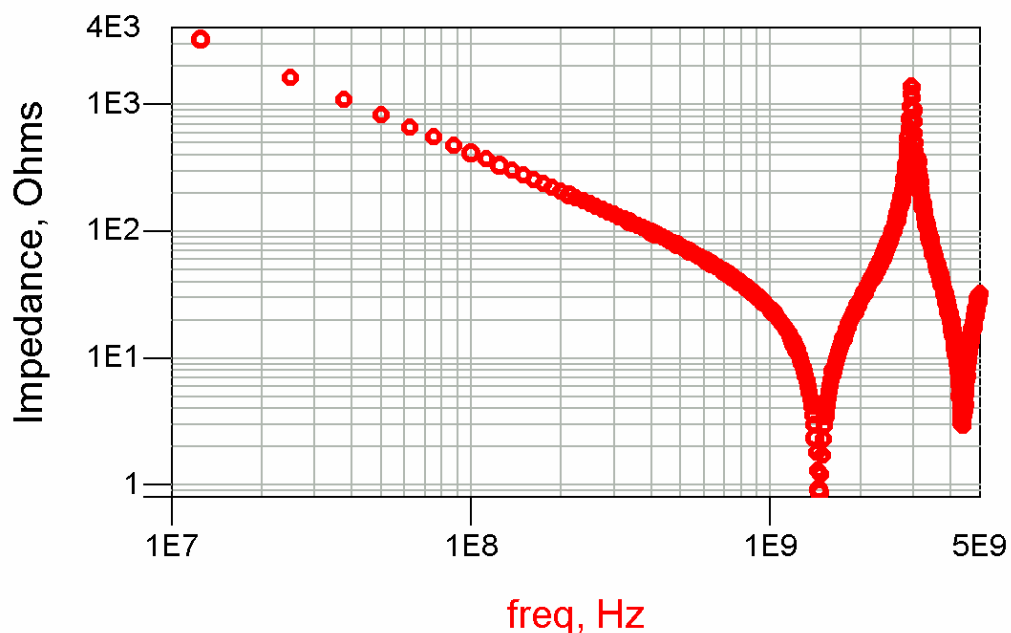

Figure 3 Measured impedance of a real, physical transmission line, 1 inch long, with a 50 Ohm characteristic impedance.

How do we describe the electrical behavior of this real, physical transmission line interconnect? We could just carry around all this measured data and just say, if you want to know how this transmission line behaves, here's the data, use it in your simulation. This actual, measured behavior is often referred to as a "behavioral model". More often than not, when we use a behavioral model, rather than using the impedance data, we use the frequency domain reflected and transmitted data, which we call the return and insertion loss. These two terms are

becoming more common as general behavioral models of specific transmission lines.

But a behavioral model doesn't give us any insight into why the transmission line behaves the way it does, nor if we make a geometry or material change, how will its electrical performance change. It's too much work to carry around all this data to describe the electrical behavior of the transmission line. Alternatively, we can approximate the real physical transmission line with ideal circuit elements that have precise, well defined properties.

The most important ideal circuit element to describe a real, physical transmission lines, is an ideal, lossless transmission line. It is a brand new, fundamental, ideal circuit element, distinct and separate from other ideal circuit elements, such as a capacitor, inductor or resistor.

It has two fundamental properties every simulator understands. First, if you send a signal into one end, there is a time delay, TD, before the signal comes out the other end.

The second property is that as the signal propagates down the line, each step of the way, it sees a constant, instantaneous impedance, which is characteristic for the transmission line. We give this impedance the special name, characteristic impedance, Z0. These two terms fully characterized an ideal, lossless transmission line.

How well does the predicted performance of an ideal transmission line model actually match the measured performance of a real, physical transmission line? The only way to know is to compare the measured data to the simulated data. In Figure 4, we show the measured and simulated impedance looking into the front of a transmission line.
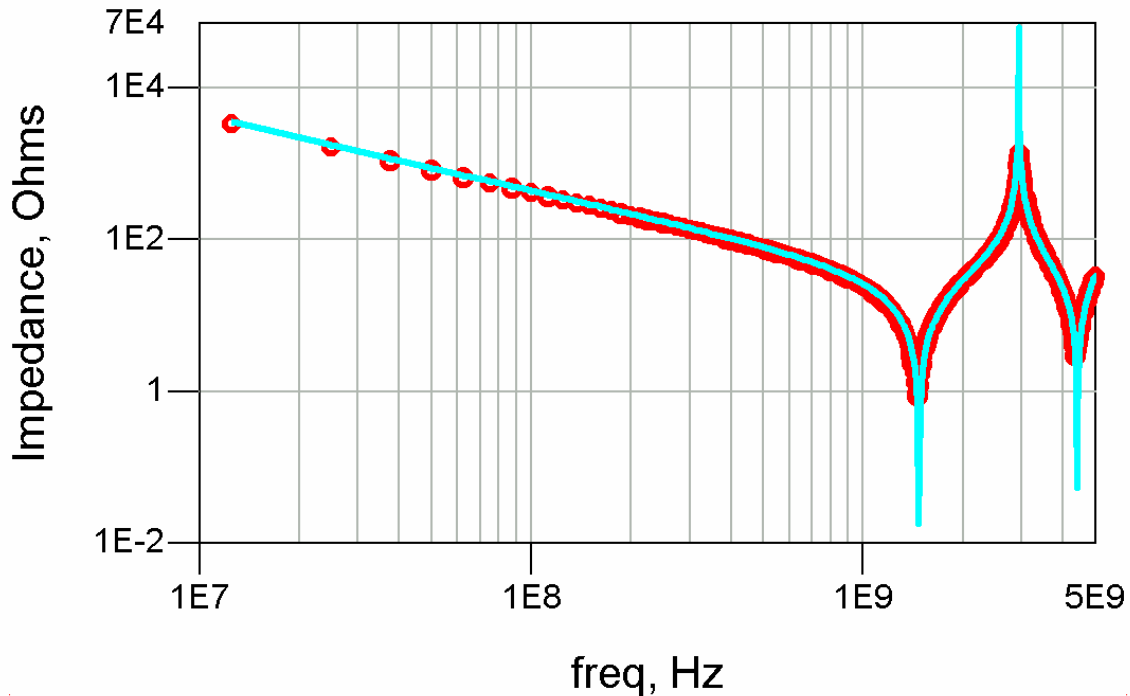
Figure 4. The measured impedance of the real, physical transmission line is the circles. The simulated impedance of the ideal, lossless transmission line, with a TD = 0.16 nsec and Z0 = 47 Ohms, is the blue line.

The impedance of a real, physical transmission line can be very accurately simulated by an ideal, lossless transmission line. An ideal lossless transmission line model is a very good approximation to a real transmission line, from frequencies near DC up to very high frequencies. This measured data only goes up to 5 GHz. Much above 5 GHz lossy effects play a bigger role, and a better model for a real transmission line is an ideal lossy transmission line.

This demonstrates that a real physical transmission line, ALWAYS behaves like an ideal lossless transmission line model, even down to very low frequencies. A transmission line model is ALWAYS a good approximation for a real transmission line on a circuit board. You can never go wrong using an ideal lossless transmission line model. A transmission line is always a transmission line.

A Simpler Approximation
At the lowest frequencies, there is another ideal electrical circuit element that can be used to approximate the impedance of a real, physical transmission line. The measured impedance of the real transmission line starts high and drops as we go up in frequency. The impedance of an ideal capacitor also behaves this way. Its impedance is high at low frequency and drops as frequency increases.

For this specific case of a 1 inch long, nearly 50 Ohm transmission line built with FR4, an ideal capacitor with a capacitance of 3.9 pF would have a similar

impedance, at low frequency. Figure 5 is a comparison of the measured impedance of this real, physical transmission line and the simulated impedance of an ideal 3.9 pF capacitor.
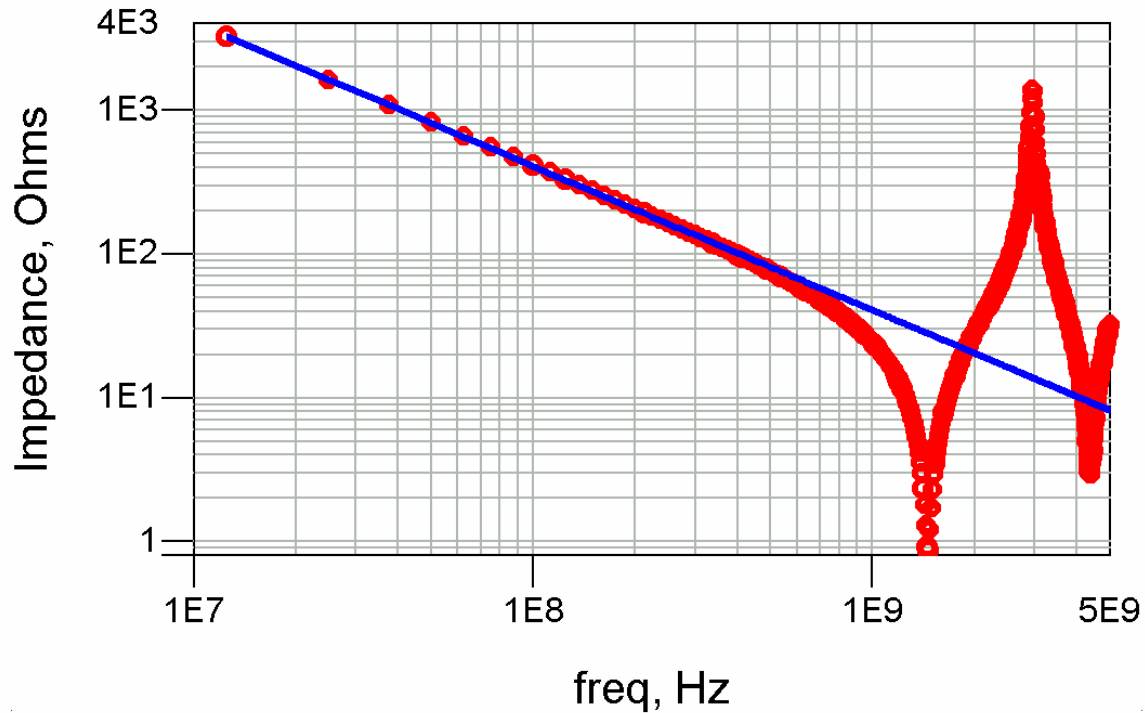

Figure 5. Measured impedance of a roughly 50 Ohm, characteristic impedance, real, physical transmission line, 1 inch long, on FR4, as circles, and the simulated impedance of an ideal 3.9 pF ideal capacitor, as the solid blue line.

As long as we only look at really low frequency, the predicted impedance of an ideal capacitor is an excellent approximation to the measured impedance of a real transmission line. In this specific example, we get excellent agreement below about 0.6 GHz. As long as all the important frequency components of a signal are below 0.6 GHz, this real, physical transmission line will behave exactly like a capacitor, and this real interconnect can be modeled as an ideal capacitor.

This is reasonable because a transmission line is nothing more than two conductors with some dielectric between them. At low frequency, this is exactly what a capacitor is. However, there is a limit to how high a frequency the real interconnect still behaves like an ideal capacitor.

We call the highest frequency at which this ideal capacitor model can be used to accurately describe this real physical transmission line, the bandwidth of the model, BW. It doesn't say this is the highest frequency the interconnect will work, it says, this is the highest frequency we can use this model to describe the electrical properties of the interconnect.

As a rough rule of thumb, the bandwidth of the capacitor model is roughly:

$$BW < 1 \times 1/10 \times 1/TD.$$

where

BW = the highest sine wave frequency where a single ideal capacitor is a good approximation for a real physical transmission line

TD = the time delay of the real physical transmission line

When TD is in nsec, BW is in GHz.

There is a simple relationship between the rise time of a signal and the highest frequency component in it:

$$BW = 0.35/RT$$

where

BW = the highest sine wave frequency component in the signal

RT = the rise time of the signal

With a little algebra, we find,

$$RT > 3 \times TD.$$

$$Or$$

$$TD < 1/3 \times RT$$

This is a very important relationship. It says if we want to approximate the properties of a transmission line as a simple capacitor, where reflections are not important, termination is not important, and the only thing that influences the important electrical properties of the interconnect is its capacitance, we can do this only if the rise time of the signal is at least three times the time delay of the interconnect, or if the time delay of the interconnect is short enough, shorter than 1/3 the rise time.

For example, if the time delay of a real interconnect is 1 nsec, it will behave like a simple, ideal lumped circuit capacitor, as long as the rise time of the signal is greater than 3 nsec.

If the rise time of a signal is 1 nsec, a real physical transmission line will act like a simple, ideal lumped circuit capacitor, provided the time delay is shorter than 1/3 nsec. Of course this interconnect can also be modeled as an ideal transmission line. The voltages simulated, as long as the rise time is longer than 1 nsec, will be exactly the same the same whether we model the real, physical interconnect as an ideal lossless transmission line or as an ideal capacitor.

Interconnects and Critical Lengths

For most real physical transmission lines built in FR4, with a dielectric constant of roughly 4, the speed of a signal is about 6 inches/nsec. This means we can translate the time delay of an interconnect into its physical length, Len, with:

$$Len = 6 \text{ inches/nsec} \times TD$$

With a little more algebra, we can restate how short a real, physical transmission line needs to be for a given rise time so it looks electrically like a capacitor. The condition is:

$$TD < 1/3 \times RT$$

and

$$TD = Len/6 \text{ inches/nsec}$$

so

$$Len/6 \text{ inches/nsec} < 1/3 \times RT$$

Or

$$Len < 2 \times RT$$

with Len in inches and RT in nsec.

If the length of a real physical transmission line is shorter than this critical length, it will look like an ideal capacitor and can be modeled as a simple ideal capacitor. For example, if the rise time is 1 nsec, any real, physical transmission line shorter than 2 inches will act like a capacitor, and though the reflections will still happened, they will happened during the rise time and may be smeared out and not be significant.

While a real physical transmission line can always be modeled as an ideal lossless transmission line, if the length of the line is shorter than this critical length, it can also be modeled as a simple capacitor.

When typical rise times are on the order of 0.5 nsec, the critical length is about 2 x 0.5 nsec = 1 inch. Most interconnect on a circuit board are longer than 1 inch, and for all these lines longer than 1 inch, their transmission line properties will be important, and a termination strategy is essential.

As device technology advances, rise times of drivers will always get shorter, and the critical length above which an interconnect does not behave like a capacitor will get shorter. For a greater and greater percentage of the traces on a board, the transmission line properties are important. If they are not designed for controlled impedance, and a termination strategy implemented, the product may not work.

Dr. Eric Bogatin
President, Bogatin Enterprises