# Basic Transmission Lines

## *Why Use 'Em At All?*

### REFLECTIONS AND TRANSMISSION LINES

Figure 1 illustrates what we sometimes call a "general communication model." Any time communication occurs, we can think in terms of a sender of that communication, a message that is being sent, the media over which the message is being sent and the intended receiver of the message.

**General Communications Model**

**Message**

**Sender** <     > **Receiver**

**Media**

Figure 1.
General Communications Model

For example, at this moment you are reading something "sent" by Doug Brooks, author of this article. The message is what is written on this page. The media is the page you are reading, and the receiver is you, the reader.

The evening news is "sent" by the news anchor (and his or her team behind the scenes). The message is what you see on TV, and might be designed to be entertaining as well as informative. The media can be thought of in simple terms as the television system. But in reality it can be thought of as a much more complex system of microphones, cameras, switchers, satellites, retransmitters, etc. The receiver(s) are those watching the program.

This model can be applied equally well to circuit boards. On PCBs, the sender is the driver, the message is typically the change in state from and high to a low signal (or from a low to a high signal), the media is the trace, and the receiver is the receiving circuit.

Now, I want you to think about these two communication problems. First, picture yourself sitting down at the end of a high school gym at assembly time. The coach is at the other end handing out the football team awards. He is speaking through a hand-held PA system. The floor is made of hardwood, the walls are concrete, the ceiling is metal, and the echoes are awful! The echoes make it almost impossible to understand what the coach is saying. The media is the primary cause of this particular communications problem.

Next, picture yourself positioned along a PCB trace. The driver is sending a signal down the trace and you are trying to "hear" it. But here is the problem:

***Any time a signal travels down a wire or a trace, it reflects. Period!***

Notice what I said and what I didn't say. I did not say, *often* reflects. I did not say *sometimes* reflects. I did not say *under certain circumstances it* reflects. It ***always*** reflects. (Well, it turns out there is one, *very special* case when it doesn't. But this special case doesn't happen by accident, as you will see.)

In both of these examples, the high school gym and the PCB trace, there are reflections and echoes that can interfere with the receiver understanding the message that is being sent. Here are some solutions to these communications problems:

1. We can encode the message, so we can pull it from the noise level. There is an entire science related to encoding and decoding message in noise environments, and this a certainly a legitimate solution. But, it's not a particularly practical one in the gym environment, and probably not in our PCB environment either.
2. We can listen "harder," or become better listeners. In the gym, we can concentrate harder on what the coach is saying. On our boards we can use better, more selective, but probably more expensive receivers. Again, these are legitimate solutions, but perhaps not desirable.
3. We can shorten the distance the message travels. In the gym, we can get up and move closer to the coach. We can shorten the trace on the board. On the circuit board, this is usually a highly desirable alternative. But, we probably have already designed the traces about as short as they can be, so further shortening them is no longer an alternative.
4. A particularly interesting solution is to slow down the message. The coach can speak more slowly. It will clearly be easier to understand him if he does. The analogy on our boards is to use signals with slower rise and fall times. And this, too, is a desirable solution. Many people recommend using circuits with the slowest rise and fall times we can get away with to avoid the reflection (and most other high-speed design) problem. The problem is, (a) we may not have control over the rise time of the circuits we are using, and (b) we may have already chosen the fastest rise time circuits available in order to meet other circuit requirements. (See Footnote 1.)

Therefore, there are four legitimate solutions to our communications problem, but none of them may be practical for our specific situation. But there is one more:

5 We can acoustically engineer the gym to absorb reflections. Next time you are in a hotel or convention center conference room or hall, look closely at the surroundings. Chances are very good the room has been acoustically engineered to absorb echoes and reflections. It will have a soft carpet, cloth paneled walls, and sound absorbing ceiling tiles. The PA speakers are probably placed where there will be no phase shift between the sound coming from the speaker (wherever he or she is) and where you are sitting.

Similarly, we can (not acoustically, but) electrically engineer our trace to absorb reflections. Then, there will be no reflections going back and forth on the trace to interfere with the receiver's ability to receive and understand the message the sender is sending.

The problem is: in general, we don't know how to do that. We do know how to acoustically engineer a room. But we don't know how to electrically engineer a wire or trace to absorb reflections — with one very special exception. We *do* know what to do if we are dealing with a very special case we call a "transmission line."

**Transmission lines:** So what makes transmission lines so special? Consider a long straight wire or trace with its return wire or trace nearby. The wire has some inductance along its length. There is also some capacitive coupling between the wire and its return. Figure 2 shows what we call a "lumped" model of the wire pair, because we show the capacitors and inductors as lumped components. In reality, the inductance and capacitance are spread continuously along the wires. But we don't know how to show that in a drawing, so we approximate it with a lumped model. Every incremental inductance is equal to every other one, and every incremental capacitance is equal to every other one. On the other hand, we are going to think of this wire as being infinitely long. Therefore, the part shown in Figure 2 is just an infinitely small part of the total length!

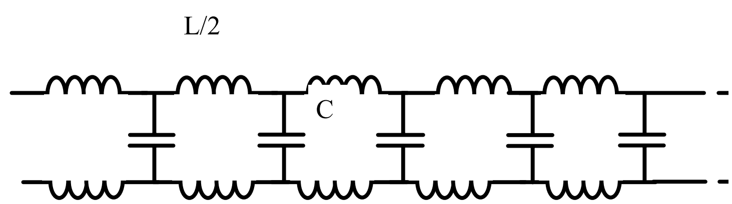


Figure 2.
A transmission line is made up of an infinitely long network of capacitors and inductors.

Now, if these wires are infinitely long, there will be no reflection at all! At least, if there is a reflection, it will take an infinitely long time for it to return, so for all practical purposes we can assume it doesn't exist.

However, it takes at least one other thing to avoid reflections — the wires must be absolutely uniform. If they are not uniform, then we can consider them to be two different (sets of) wires, each with different characteristics. These two individual (sets of) wires will not be infinitely long, and therefore there *will* be reflections. So, the way to avoid reflections is to use an infinitely long, absolutely uniform wire or trace pair. We give such a wire or trace pair the special name "transmission line."

If we look into the front of this wire pair, there is an input impedance we can mathematically calculate. We give it the symbol Zo, and call it the "intrinsic" or "characteristic" impedance of the line. If we could calculate the "lumped" values of inductance (L) and capacitance (C ), the impedance would then be calculated as:

$$Zo = \sqrt{L / C}$$

Now here is a little slight-of-hand. If you look into the transmission line at the front, it looks like it has an impedance of Zo. Let's take our infinitely long transmission line and break it in two parts. If we look into the second part, it also looks like an infinitely long transmission line with an input impedance of Zo. So, what if we simply substituted the second part of the line with an impedance equal to Zo? (see Figure 3.) From the front of the first line, it still looks exactly the same —— i.e. it looks like an infinitely long line. And it turns out it behaves that way too. A transmission line of finite length, terminated in its characteristic impedance, Zo, looks like an infinitely long transmission line. Therefore, even though it has a finite length, it still will have no reflections. In this case it is not the infinite length that makes reflections irrelevant, it is the fact that *all* of the energy traveling down the line is exactly absorbed (dissipated) in the termination. There is no energy left to reflect back. The net effect is the same thing —- there are no reflections to worry about.

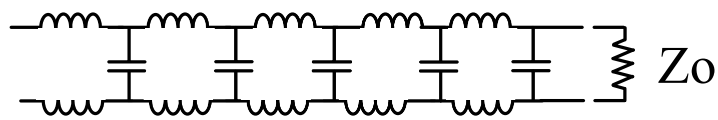


Figure 3.
If we terminate an infinitely long transmission line in its characteristic impedance, it still looks infinitely long.

This is the trick we need if we want to control reflections on PCBs. We need to make our traces *look like* transmission lines, and we need to terminate them in their characteristic impedances, Zo. (Unless, of course, we can make our traces short enough that reflections don't interfere with the receiver's ability to hear the signal, or we slow down the rise time enough that the receiver can hear through the echoes.)

There are certain types of transmission lines that are commonly around us every day. The coaxial cable leading to our cable TV is a 75 Ohm transmission line. If you use 10Base2 coax cable for networking, that is a 50 Ohm transmission line. The 300 Ohm twin lead cable from your TV rabbit ear antenna to your TV is a transmission line. And it is no accident that those high power electrical lines from the power generating plant to our cities are called "transmission lines," strung between transmission line towers. Even power system engineers need to worry about reflections if the lines are long enough (about 480 miles or so!)

**Conclusion:** Some people look at the question of transmission lines as something "bad." They are somehow an unfortunate consequence of high-speed design that we wish we didn't have to worry about. Actually, transmission lines are the *solution* to the problem of reflections on our traces. They are not "bad" things, but are in fact "good" tools that help us maintain clean signals. Our job is to learn how to use them and to benefit from them in our designs. Subsequent articles in this series will examine how to do that.

Footnotes:

1 UltraCAD has placed three audio files on its web site that illustrate these three points. The first, testwave1.wav, is a simple phrase. The second, testwave2.wav, is the same phrase with considerable (admittedly forced) echoes (reflections) added. The third, testwave3.wav, is the same expression with the same echoes, but the phrase is spoken more slowly. The three files illustrate how reflections can obscure a message, and how slowing down the message can help improve the receiver's ability to understand it. The three files can be found here. *(You may get better results if you right-click on these links and save the files on your local computer, then play them locally.)*

http://www.ultracad.com/mentor/testwave1.wav (76k)
http://www.ultracad.com/mentor/testwave2.wav (76k)
http://www.ultracad.com/mentor/testwave3.wav (376k)

About the author:

**Douglas Brooks** has a B.S and an M.S in Electrical Engineering from Stanford University and a PhD from the University of Washington. During his career has held positions in engineering, marketing, and general management with such companies as Hughes Aircraft, Texas Instruments and ELDEC.

Brooks has owned his own manufacturing company and he formed UltraCAD Design Inc. in 1992. UltraCAD is a service bureau in Bellevue, WA, that specializes in large, complex, high density, high speed designs, primarily in the video and data processing industries. Brooks has written numerous articles through the years, including articles and a column for *Printed Circuit Design* magazine, and has been a frequent seminar leader at PCB Design Conferences. His primary objective in his speaking and writing has been to make complex issues easily understandable to those without a technical background. You can visit his web page at http://www.ultracad.com and e-mail him at doug@ultracad.com.