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Transmission Line Basics

Why Use 'Em At All

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It is not often understood that when electrical signals travel along a wire or trace --- they reflect. Always!

We intuitively understand that when we send audio waves across a room, a field or a canyon, they reflect. We call those "echoes." Echoes can happen in a great many places, even in small rooms. But we have a harder time understanding that electrical signals reflect also. We call that, well, reflections!

Illustration

Imagine this environment. Picture yourself in a high school gym during an assembly. The football coach is at the far end handing out the year-end awards. He is using a hand-held PA system. You are sitting at the far end of the gym. Like all typical gyms, this gym has a hardwood floor, concrete brick walls, and a steel or wood roof; and it is very hard to hear him because of all the echoes.

Imagine this environment. You are an electrical receiving circuit at the end of a trace or wire. The driver at the other end is sending a signal to you. Like along all wires and/or traces, the signals "bounce" off the ends and reflect back and forth. It can be very hard for you to figure out what is the "signal" the driver is sending you right now, and what is a reflected signal for part of the message that was sent a little bit earlier. The earlier parts of the message can interfere with the current message and result in confusion over what the current message really is.

Possible Solutions

Well, there are some solutions to these communication "problems." Here is a few that, conceptually at least, will work in each case.

1. We can encode the message so that it is easier to pull it from the surrounding noise level. Coding algorithms are readily available to do this. The problem is, for us humans in the gym, this causes extra work and resources. For our circuits it means more processing power and activity. So, while this is a viable solution, it is probably not practical unless there are other, more compelling reasons for increased security.
2. We can listen "harder." For us as individuals, this is something we can do in the gym, at least within limits, without too much trouble. In our circuits it means we might select "better" receivers with better noise rejection capabilities. This, in fact, and within limits, might be a viable solution.
3. We can shorten the distance the message travels. As the distance shortens, the echoes are closer together and it is easier to discriminate between the primary message and its echo or reflection. For us as individuals, this means getting up and moving closer to the coach, a very viable solution. In our circuits it means shortening our traces, moving the receiver closer to the driver. This is something we should usually do if we can (for several good reasons.) The practical problem, however, is that our wires and/or traces are probably already as short as reasonable, and the option to shorten them further isn't practical.
4. A particularly interesting solution is to slow down the message! In the gym that means having the coach speak more slowly. If he slows down his speech, it is easier to pick out the individual words.
   The signal on our traces is often the transition between "states," i.e., the transition between a logical zero and a logical one, or between a logical one and a logical zero. Slowing down the signal means *slowing down the rise time*! This is an excellent solution and many references will suggest that we should *always* use the slowest rise time circuits we can that will still meet our purposes for several reasons: among them are reflections, EMI and crosstalk. But the practical problems are that:
   a. We may need the fastest rise time we can obtain in order to achieve the results we want, or
   b. We may not have a choice of the rise times for the circuits that are available, or
   c. The manufacturer may change the rise time of the devices available on the market, sometimes without our being aware of it.
5. The four alternative solutions above are viable, but not necessarily practical. There is a fifth. We can *acoustically* engineer the gym to absorb the echoes so that it is easier to hear the coach. Just look around most conference rooms to see examples of careful acoustical engineering making the rooms more functional for people assembled in them. In the same way, we can (electrically) engineer our wires and traces to absorb reflections.

But here's the rub. In general, we don't know *how* to engineer our traces to absorb reflections! But we DO know how to do that in one, very special case. In the *very special case* of "transmission lines" we know that if we engineer the line and then terminate it properly, we can prevent reflections. So, here is the solution to our reflection problem on traces on circuit boards:

1. Design the traces carefully to look like transmission lines, and then
2. Terminate them properly.

Transmission Lines

We are all familiar with various types of transmission lines. Coaxial cable is perhaps the most familiar, used in both cable TV and networking environments. Some of us may remember the old 300 Ohm "twin lead" used in earlier TV, rabbit ear antennas and FM antennas.

One characteristic of a transmission line is that it has an input impedance, defined as its "characteristic impedance," usually represented by the symbol Zo. A well-designed transmission line (among other things) is one whose characteristic impedance is uniformly *constant* over its entire length, without any discontinuities. This is perhaps the *most* important design rule for PCB designers to follow when designing transmission lines.

What may not be so obvious at first glance is that the characteristic impedance of a transmission line is almost totally dependent on its materials and its physical geometry. There are no electrical parameters that have an appreciable effect on the impedance of a transmission line (unless we call the relative dielectric coefficient of the insulating materials an "electrical" parameter.)

Therefore, when we say that the characteristic impedance must be constant over the length of the transmission line, we are saying that the *geometry* of the line must be constant over its length. By inspection, we can observe that coax cables have uniform geometry over their length, and we may have found from experience that it doesn't work to cut and splice a coax cable! This creates a geometric discontinuity (that causes an impedance discontinuity) that causes ghosts on TV screens or (usually) stops a network from functioning correctly.

Termination

There is well defined and understood characteristic of transmission lines: if they are terminated in their characteristic impedance, there will be no reflection from that termination point.

What that means is this. Assume we design a trace so that it looks like a transmission line with particular characteristic impedance, say 50 Ohms. Now place a 50 Ohm resistor across the end of the line (i.e. we terminate it with a resistor equal to the characteristic impedance.) There will be no reflection from the end of the trace. This is the equivalent to acoustically engineering our gym to absorb sound waves and prevent echoes.

Precisely *how* to design the transmission line to a particular characteristic impedance is beyond the scope of this paper. And there are several different termination schemes that can be used to terminate traces that are designed to look like transmission lines.

The Impact of Distance

In the illustrations above, it was suggested that distance plays a role in the communication problem. Reflections (echoes) are not too bad a problem if the receiver is close enough to the sender. And, there is less of a problem if the message is slowed down (the rise time is slowed down, or lengthened.) If we think of a signal traveling down a trace, these two things are actually equivalent! The issue is, what is the length of the signal path (in propagation time) relative to the rise (or fall) time of the signal?

For example, consider Figure 1. There are two cases shown, Driver A is driving a signal to receiver B1, or to both receivers B1 and to B2. B2 is much further away from the driver than is B1.

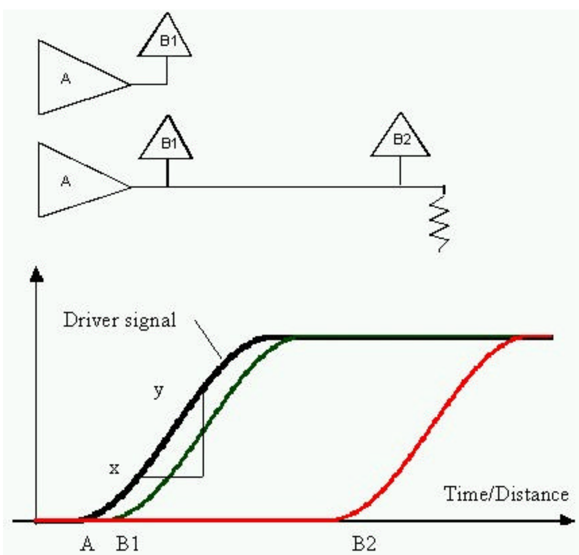

Figure 1 - Two Cases Shown, Driver A is Driving a Signal to Receiver B1

Receiver B1 is much closer to driver A, than is receiver B2. As a result, reflections are a more serious problem for the circuit containing B2, unless the trace is designed to look like a transmission line and is terminated properly.

The driver signal propagates down the trace. The horizontal axis represents both distance and time, since all signals on a particular trace layer (usually) propagate at the same, constant speed. Pick a spot (x) on the lower portion of the rising edge of the driver signal. Now move horizontally from that spot to the slope representing B1. This horizontal distance represents the propagation time between the driver and B1. Move horizontally an equal distance again, and then move up vertically to the driver slope (point y). Notice that the driver is still driving at this point in time. We can think of the driver having "momentum" and overpowering the reflection, so the reflection has no effect on the circuit. B1 is "close" to the driver in this example.

On the other hand, move horizontally from the same point, x, to the point representing B2. This represents the propagation time to B2. Now, extend beyond B2 another equal increment in time, and then rise up vertically to the driver signal. Now, the driver signal has long since stabilized at its upper value, and the reflection may be significantly apparent on the trace, possibly disrupting the operation of the circuit. B2 is a long way away from the driver in this example.

The distance from the driver to B1 is intuitively short in this example, and the distance to B2 is intuitively long. Reflections have minimal impact on short traces and may have significant impact on long traces. So how do we define the difference between a "short" trace and a "long" trace?

"Long" Traces

The general "rule of thumb" accepted by most people goes like this:

1. If the propagation time down the trace and back again is less than the rise time of the signal, then we can consider the trace to be "short."
2. If the propagation time down the trace and back again is longer than the rise time of the signal, then we must consider the trace to be "long" and must therefore consider whether terminations might be necessary.

The boundary between these two lengths is called the "critical length" and is usually defined as the length where "the two way delay of the line is less than the rise time of the pulse."

You can think of that this way: Signals travel at approximately 6" per nanosecond in FR4. The rule says that the "round trip" of the signal, down the trace and back, should happen in less time than the rise time of the signal, or 1 nanosecond. So the "round trip" length should be 6". Or, the length of the trace should be (half that, or) 3".

This rule defines the "generally accepted" boundary between "short" traces (where reflections are not considered to be an issue) and "long" traces (where reflections *are* considered to be an issue.) Of course the world is not that clear cut. Reflections exist with any length trace, and so this boundary simply represents some people's opinion of when we need to become concerned. Other people, for example the engineers you work with, might have different opinions! As designers, we simply do what the customer (the engineer) asks, and our role is to *understand* why he/she asks for it.

Conclusion

Signals traveling down wires and traces reflect. These reflections, like echoes related to speech, can interfere with proper information communication within our circuits. This problem is not too serious for short wires and traces, but becomes more problematic for longer traces. In one specific area of engineering, transmission line analysis, we know that we can control or eliminate such reflections by (a) designing our traces to look like transmission lines, and then (2) terminating them properly. We control the transmission line properties of our traces by controlling their geometry. Several different termination strategies then become available to us for controlling and/or dealing with any reflections that might exist.