

Chip-Scale Transmission Lines

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This winter brought lots of snow and cold weather to our region. I can't say we enjoyed the storms, but the skiing has been terrific.

Over the holidays, I have been preparing for a busy spring season teaching my new Advanced High-Speed Signal Propagation course, in addition to maintaining and re-arranging some of the material in my original course, High-Speed Digital Design. Thanks to all who have written with questions or discussion about these courses (and many other topics).

This month's letter concerns an important topic from the advanced class: the difference between chip-scale and pcb-scale transmission lines.

The original course deals with a broad spectrum of high-speed phenomena. It builds a solid understanding of ringing, crosstalk, ground bounce, and power supply noise as they exist on printed circuit boards. It emphasizes basic circuit configurations where these effects may be easily understood and learned. It treats supplementary subjects including chip packages, oscilloscope probes, and power systems for high-speed digital products.

The new **Advanced** course, and the book that accompanies it, is more highly specialized, delving into issues relevant to transmission at the upper limits of speed and distance. If you need to transmit faster and further than ever before, especially if you are contemplating systems above 1 GHz on printed circuit boards or long cables, this is a terrific course for you.

Chip-Scale Transmission Lines

The key differences between chip-scale transmission lines and pcb-scale transmission lines can be gleaned from examination of the propagation function H .

Signals propagating along any transmission structure, whether on-chip or off-chip, experience a certain degree of attenuation H as they pass through each unit length section of the structure. The value of H varies dramatically between different types of transmission structures and also as a function of frequency, but, within any particular structure, at any one particular frequency, you may assume the attenuation H remains the same in each section of that line.

Suppose you inject a sine wave into a long transmission line having an attenuation factor (at your sine wave frequency) of H per meter. As your signal passes through many meters of transmission line, each with a predefined attenuation of H , the overall amplitude of your propagating signal clearly decreases exponentially with distance. The value of H determines *how rapidly* the signal decays as it moves along the line.

YMTC
Exhibit 2014
Micron v. YMTC
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The value of H is a complex number. The magnitude of H specifies the gain of each unit length of the line, while the phase of H specifies the phase shift. A long transmission line acts like a cascade of filters H , with each filter contributing to the overall attenuation and phase shift of your signal.

Let's look next at two particular examples of H . First, consider an RC line model, shown Figure 1. The circuit shown represents the behavior of one short section of an RC transmission line.

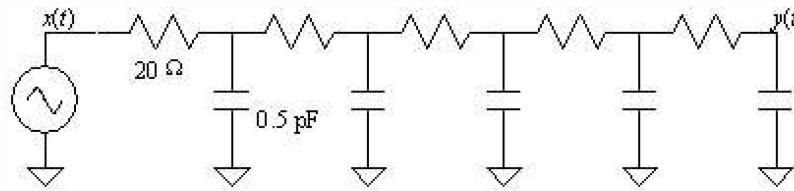


Figure 1-A sine wave voltage source drives an RC line model. The line model comprises five stages, each having twenty ohms in series with the signal followed by 0.5 pF shunting the signal to ground. The voltage $x(t)$ is measured at the source; $y(t)$ is measured after the fifth stage.

If you remember nothing else from this discussion, *remember this*: when the RC filter delays an input signal, making $y(t)$ substantially different from $x(t)$, there must at that time exist a substantial voltage drop across the chain of resistors. The voltage drop thus developed causes each resistor to dissipate a significant amount of power. That loss of power translates ultimately into attenuation of the input signal amplitude.

In the example of Figure 1, at a sine wave frequency of 1 GHz the circuit produces a phase delay of 47 degrees with a 2-dB loss of signal amplitude. The moral of this story is that you can't build much phase delay using an RC circuit without losing a lot of your signal amplitude.

Next let's consider a different line model: the LC circuit (Figure 2). This circuit, like figure 1, also forms a low-pass filter, but with one key difference. In this circuit, you can accumulate plenty of phase delay without loss of signal amplitude. At a frequency of 1 GHz, this circuit produces the same 47 degrees of phase delay but with negligible loss of signal amplitude. Even larger phase shifts are possible at higher frequencies. This difference between this and the previous circuit is that here the voltage differences from stage to stage are sustained by inductors, not resistors. The inductors dissipate zero net power; therefore, all the signal power transmitted by the source is conveyed faithfully to the load. *Remember this*: an LC circuit can provide a very large phase shift (i.e., time delay) with little or no signal attenuation.

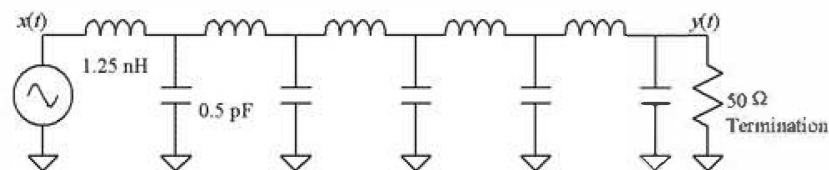


Figure 2-A sine wave voltage source drives an LC line model. The line model comprises five stages, each having 1.25 nH in series with the signal followed by 0.5 pF shunting the signal to ground. The last stage is followed by a 50-ohm termination to ground. The voltage $x(t)$ is measured at the source; $y(t)$ is measured across the termination resistor.

Practical transmission circuits always combine some amount of both resistance and inductance; they are never purely one or the other. It is, however, useful to consider the pure RC and LC forms because they approximate what happens in two very important cases.

On-chip, the interconnections are so tiny (i.e., have such a small cross-section) that the resistance of the connections, at modest operating speeds, overwhelms the effect of series inductance. Series resistance, not inductance, mostly dominates on-chip interconnections in a 130-nm chip architecture.

On-board, the cross-section of a pcb trace is huge by comparison to a chip interconnect. Scaling the cross-section makes the per-unit length resistance of a pcb trace a whole lot smaller but doesn't affect the per-unit length inductance that much. As a result, the roles of resistance and inductance in a pcb trace are swapped-in a pcb trace, the inductance matters most. At any digital logic speed above 10 MHz, typical pcb traces act mostly like LC structures.

Now comes the conclusion of this article: on-chip interconnections rarely require termination, but pcb traces often do. This conclusion is directly related to the properties of RC and LC transmission lines.

In an RC structure, any time you make a line long enough to build up a substantial phase shift (or round-trip delay), the line naturally provides a corresponding amount of signal attenuation. In such an environment you can't produce the round-trip reflections necessary to cause problems with ringing and overshoot. Long lines naturally come with their own built-in damping.

In an LC structure, you can easily construct a low-loss line with huge amounts of phase shift (or round-trip delay). In this environment, a signal can bounce many times from end to end within your transmission structure without degrading. The only cure for objectionable bouncing in an LC line is a termination at one end of the line, the other, or both.

Best Regards,
Dr. Howard Johnson

Extra for Experts

Those of you already conversant with the propagation function H may recognize that this discussion applies only to linear, time-invariant, TEM-mode systems with propagation occurring in one direction.

The calculation of line resistance and inductance, and the determination of the effective mode of operation, is included in the new Advanced High-Speed Signal Propagation course. The course contemplates other modes of operation including the skin-effect-limited mode, the dielectric-loss-limited mode, and the waveguide mode.

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