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Signal Integrity Basics: Digital Signals on Transmission Lines

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The physical effects of a signal traveling along a circuit conductor affect the shape of a digital waveform, potentially causing errors and ambiguities in the transmitted data.

Signal Integrity is one of the "hot topics" in digital circuit design. SI, as it's called, involves the quality degradation and timing errors of digital signal waveforms as they travel on conductors that make up the path, such as p.c. board traces, package structures and interconnects.

These conductors are transmission lines, a term completely familiar to RF/microwave engineers, but not understood in the same terms by digital engineers. Also, the behavior we're concerned with is referenced to the time domain, which is the normal environment of digital engineering, but is typically dealt with indirectly by RF/microwave engineers. Understanding SI requires both perspectives.

Transmission Line Characteristics

A transmission line has the following key attributes:

Loss

Resistive Loss—The I^2R loss due to finite conductivity of any metal. In addition, as frequency increases, skin effect confines the currents to a smaller portion of the metal thickness, increasing the effective resistance and corresponding loss.

Dielectric Loss—This is the additional loss caused by the reduction in velocity of the signal, plus any energy absorbed by the dielectric material. The apparent increase in conductor length increases the loss as if the conductor were physically longer.

Radiation Loss—In a closed system, such as a coaxial cable, radiation loss is small, but as shown in Figure 1, circuit and package conductors more closely resemble microstrip when they are single conductors over a ground plane, stripline when they are embedded between "ground" layers of a p.c. board, parallel lines in air or dielectric, or conductors passing through layers. These transmission line structures allow coupling to adjacent conductors and components via the electric and magnetic fields, as well as radiation (and reception) like antennas.

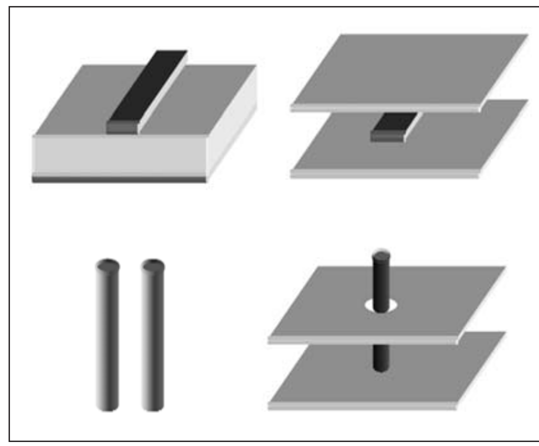

Figure 1 · Signal path conductors in electronic circuits are transmission lines, and may have any of the above configurations.

Crosstalk

The coupling and radiation noted above gives rise to crosstalk, where energy from one signal line is transferred to another line. Just like interference in the radio environment, excessive crosstalk can impair the quality of the desired digital signal.

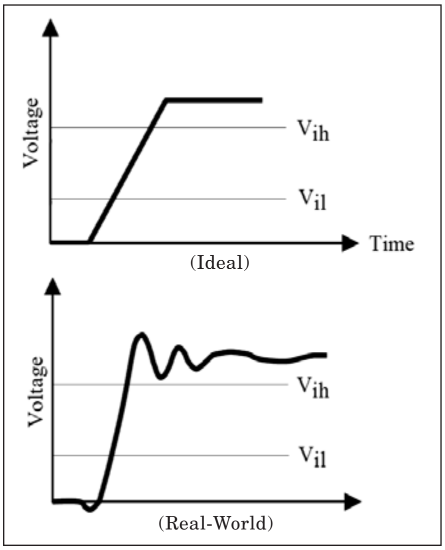

Figure 2 · The Signal Integrity problem: An ideal waveform (top) has variations due to the effects of the signal path, such as the ringing shown in the bottom waveform. Also note that the ringing may reach the HI logic level threshold, causing data errors.

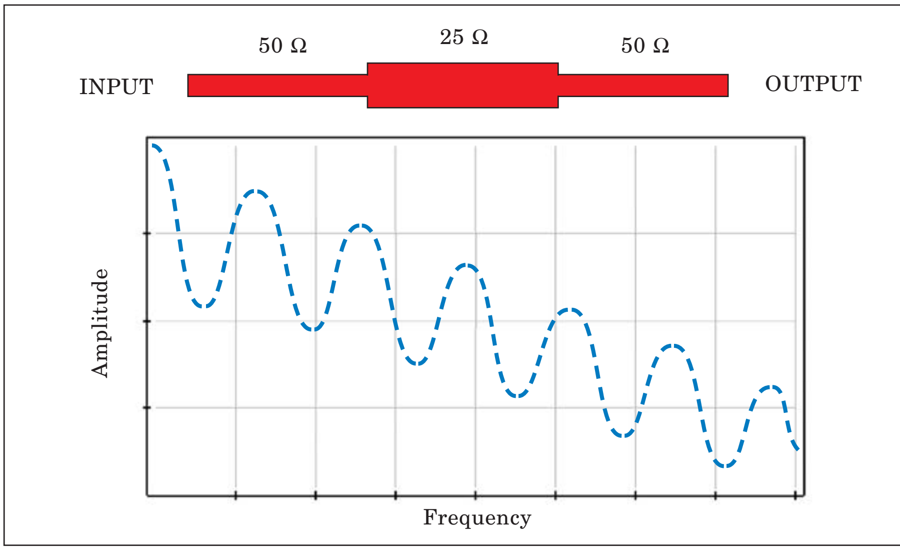

Figure 3 · Transmission characteristics of a test transmission over a wide frequency range. Resonance effects are clearly visible, along with an overall reduced amplitude with increasing frequency.

Time Delay

Delay—Any conductor requires a certain amount of time for a signal to travel from one end to another. With a repetitive waveform (e.g, RF sine wave), that delay can also be characterized as a phase difference between the input and output. With a train of digital pulses, the actual transit time is a more appropriate measure.

Reflection

Impedance—Impedance is a frequency-domain-based term, which digital signal engineering has not traditionally used. It is the amplitude ratio of the voltage and current, along with the phase difference, expressed either as a magnitude and angle ($R \angle \theta$) or in Cartesian real/imaginary coordinates ($R \pm jX$).

Characteristic impedance of a transmission line is a function of physical size, nature of the ground, and the intervening dielectric material. For example, narrow p.c. board traces will have a higher impedance than wide traces.

Discontinuities—A mismatch between a device's impedance and the impedance of the transmission line creates a point of discontinuity. These can occur at the device pins, or at any variation in the p.c. trace along its route, such as a bend or transition through a via hole. When the traveling wave meets a discontinuity, a portion of the energy is reflected back toward the source. If there is also a mismatch at the source, a further reflection will occur, with energy "bouncing" between discontinuities.

These reflected signals are summed with the desired signal, and if large enough, can greatly distort the waveform. Minimizing reflections and maintaining an impedance match between source and load is required for robust SI design.

Resonance—When a reflection has a time delay equal to a multiple of 1/2-wavelength at a corresponding frequency, there is a perfect alignment for partial cancellation of a signal. This is a critical issue in the time domain, because a digital "square" waveform contains the fundamental clock frequency plus significant energy at several of the odd-numbered harmonics. A resonance at 3× clock frequency will result in a greatly distorted waveform and potential data errors. Because resonance is a function of time, there is no amplitude-based equalization scheme that can remove its effect.

Figure 3 shows some of the reflection effects. At the top is the test circuit, a line section with 50 ohm lines at the input and output, and a section of 25 ohm line placed in the center. The line lengths are chosen so that reflection, mismatch and loss effects can be analyzed over the desired frequency range. The plot shown covers a range of six harmonics of the primary resonance. The deep reductions in amplitude show the signal cancellation, while the overall level falls off with increasing frequency, due to the various loss mechanisms.

Conclusion

This has been a brief introduction to the physical effects of signals on transmission lines. Hopefully, these basics will serve as a foundation for greater understanding of the issues involved in engineering for good signal integrity.