Defining Signal Integrity: The Characteristics of High Speed Digital Signals

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Signal Integrity is the process of understanding and controlling the collective effects of "real world" behaviors on an ideal digital signal, to maintain reliable, error-free circuits and systems

Signal integrity, as it applies to high speed digital circuits and systems, is often poorly defined. As a result, the effects that the term attempts to describe may not be completely understood by the engineers designing and testing those systems. In this article, we will try to identify the behaviors that collectively can be defined as *signal integrity*.

The word integrity is defined as: "wholeness; completeness; having unimpaired action." Thus, signal integrity deals with the factors that cause a *deviation* from an unimpaired digital signal. Signal integrity is usually described as relating mainly to the effects of physical structures on ideal digital signals, but other effects are also involved, such as clock signal timing, power distribution and noise.

The magnitude of the effects of physical structures is frequency dependent, increasing with higher operating frequencies. Signal integrity is a relatively recent concern, becoming a critical element in digital design as clock speeds have increased. Digital signals must now be handled like microwave signals, since the bandwidth required to carry those digital signals extends well into the microwave frequency range.

Likewise, high speed reduces the margin of error for clock timing signals. Accurately distributing the system clock to multiple circuits on a large p.c. board requires an unprecedented level of precision. At high speeds, timing errors are magnified, both in timing pulse alignment and in rise/fall times that can cause overlapping signals or violations of digital circuit setup and propagation delay times.

The Core Issues of Signal Integrity

Let's try to group the various causes of signal integrity problems into related areas. These are listed according to the approximate degree of difficulty:

1. *Transmission line effects*—losses and reflections in interconnecting traces, including package leads, vias and connectors, as well as impedance matching to the active devices.

2. *Coupling effects*—crosstalk between signal lines, or between signal and clock lines.

3. *Ground currents*—Signal return currents (the "other side" of transmission lines); propagated signal, clock and noise; plus DC "ground bounce."

4. *Power integrity*—DC supply distribution and decoupling; plus unwanted signal or clock propagation through power distribution circuits.

5. *Electromagnetic Interference (EMI)*—External noise ingress, self-interference, control of radiated emissions.

6. *Circuit design issues*—Clock distribution, timing errors, logic process sequencing.

This last item on the list is certainly not the least important, but was put in that position because it should be a familiar issue for a digital designer. And there are several other factors that might have been included on this list, such as manufacturing tolerances and temperature, humidity and aging effects.

The General Definition

Signal integrity can be defined as the net effect of all the impairments to a digital signal's waveform as it travels between the active devices in a circuit or system. The goal is to remove or greatly reduce those impairments.

Visible Effects of Signal Impairments

When the data stream is evaluated end-to-end, poor signal integrity will result in excessive data errors. Examination of the digital signal waveform with a high speed oscilloscope may show reduced amplitude, droop or tilt; slowed rise/fall times; increased noise floor; and missing pulses or split pulses (missing segments of pulses). Eye diagram analysis will show a closed eye with poor, or non-existent, logic state detection margin.

The next step is identifying the causes of the observed problems. As individual sources of impairment are identified and corrected, smaller effects will become apparent, Eventually, all significant problems should be reduced to levels that result in reliable data transmission throughout the system.

However...

It is much better to avoid the type of troubleshooting noted above! Signal integrity problems are best handled at the earliest stages of design. This is where digital design and microwave design combine to develop interconnections with minimal degradation over a sufficient bandwidth to carry high speed digital signals.

Underlying Principles

Let review the areas of concern listed previously. Items 1, 2 and 3 are related, since they all are types of impairments due to the high frequency effects of physical structures. Classic high frequency effects include:

Frequency-dependent behavior—Capacitance and inductance are frequency-dependent. Capacitive reactance decreases with increasing frequency, while inductive reactance increases. Most capacitive effects are from the signal trace to ground (shunt), which acting alone would attenuate the signal. Most inductive effects are due to the length of the trace (series), where increased reactance also affects signal attenuation.

Combined capacitance and inductance can also create resonances. At low frequencies, those resonances are usually well above the bandwidth occupied by the digital signal, but with increasing frequency they may directly affect the digital waveform. Typical effects include overshoot and ringing.

Transmission line behavior—At high frequencies, the length of an interconnection will eventually become an appreciable fraction of a wavelength. Over that length, the applied waveform will undergo transitions in magnitude and phase, defined by the distributed inductance and capacitance of the trace, ground type and dielectric material. Circuit boards are transmission lines, with a characteristic impedance established by the above parameters.

If the input impedance of a digital device matches the characteristic impedance of the transmission line, all energy will be absorbed by the device, and none will be reflected back toward the source. Thus, the impedance of the p.c. board trace is important, as is the terminating impedance of the device.

Reflected energy resulting from a mismatched condition will cause signal degradation. Note that those reflections are not caused only by the termination; irregularities in the transmission line can create localized variations in its characteristic impedance, referred to as *discontinuities*. These may include bends, transitions to vias, thickened areas where components are soldered, and any other physical deviation from a uniform line structure. And as frequency increases, the magnitude of the deviation increases.

Electromagnetic effects—With increasing frequency, we have the shorter wavelengths and increased AC reactances noted above. In addition, the increasingly rapid fluctuation of high frequency signals means that they contain more energy. When that energy is high enough, we can discern its effects, which include coupling, radiation and surface waves. As we learned in school, these propagating electromagnetic waves are described by Maxwell's equations, which will bring us to the next topic: preventing impairments.

Robust Signal Integrity Design

If we are to avoid signal integrity problems in high speed digital circuits, all of the above characteristics must be considered. Past practices in the tens to low hundreds of Mbps effectively handled frequency-dependent effects and basic transmission line behavior. Today, electromagnetic analysis is essential.

EM analysis is remarkably accurate, and there are a wide range of computer tools available. Unfortunately, the mathematics of EM analysis is complex, requiring manipulation of large matrices and large-scale integrations. These calculations are then repeated over many discrete observation locations, with many frequency steps. Even with powerful computers and multi-core techniques, large problems cannot be solved quickly. At a recent conference, a scientist at a major computer company noted that EM analysis of a typical motherboard or backplane required more than 24 hours computation time. With this time requirement, it would be impractical to use any type of trial-and-error method to solve signal integrity issues.

Current design efforts are focused on more "bite size" problem areas. Connector manufacturers have performed analyses of their products and developed standardized p.c. board patterns. Users can duplicate those patterns and have predictable performance where the connector interfaces to their circuitry. Integrated circuit vendors are beginning to provide performance data out to the pins of the package, not just functional data on the logic operations.

Printed circuit board design tools are addressing the issue with proven solutions for common structures: BGA and other standard IC connections, ground plane “fill” areas, power distribution traces, etc. These tools are currently in development, with some well established, but others less reliable for a user’s specific application. At large OEMs with sufficient resources, designers have developed similar techniques in-house, breaking down the analysis into smaller segments, creating a solution can be re-used whenever a similar circuit is included in another product.

One area of great interest is maintaining signal integrity performance through via holes. A standardized approach is difficult, since there are many variations in the structure surrounding the vias, the number of layers penetrated, and variations in the intervening layers.

Specific problems like vias, IC pin connections, trace parameters, etc., are being addressed by the “general purpose” EM EDA tool vendors as well as be specialized EM-based design tools. Signal integrity is a very active part of both high speed/high frequency engineering and design tool development.

Summary

Maintaining the integrity of the signal waveform is essential for accurate, reliable operation of high speed digital systems. Signal integrity involves a wide range of behaviors that create impairments to a digital signal waveform. This note focused on the range of high frequency effects common to classic “radio” and “microwave” engineering, and which now must be applied to digital design. Much work has been done to analyze and solve signal integrity issues, but much more is needed in this important area of design.