Handling differential skew in high-speed serial buses

Arnold Frisch - October 26, 2006

Until recently, wide synchronous buses were the method of choice for high-data-rate digital communications because digital logic could not support the switching rates for required bandwidth on a single lane. Unfortunately, wide synchronous buses become problematical at high clock rates. As speeds increase and buses become wider, it becomes increasingly difficult to obtain required setup-and-hold times on all the lines in a wide bus. These facts have driven the use of very-high-bit-rate serial buses with embedded clocks. Embedded clocks are implicit in serial buses, and the clock frequency is 1/UI (unit interval) of data change. This article assumes an 80-psec UI and, therefore, a 12.5-GHz clock frequency (Figure 1).

A little-regarded phenomenon, differential skew, has become a fundamental performance-limiting issue for high-speed serial-communications links. "Differential skew" refers to the time difference between the two single-ended signals in a differential pair. The operation of such links involves significant amounts of signal processing to recover clocks, reduce the effects of high-frequency losses, reduce ISI (intersymbol interference), and improve SNR. Skew limits the bandwidth of these links, adds data-dependent jitter, and limits the possibility of equalizing links to compensate for high-frequency skin effect and dielectric losses.

Skew arises from a variety of sources. The most common and universal cause of skew is the difference in the effective lengths of the two transmission lines in the lane connecting a transmitter to a receiver (Figure 2). Figure 3 illustrates the effects of that skew. The right side of Figure 3 represents the skew in the differential signal. The small amount of skew in Figure 2 and Figure 3, about 0.2 UI, or 16 psec, can result from a length difference of less than 1/8 in. (3 mm).

You can add various amounts of skew to a sophisticated analog FIR-filter equalizer (Figure 4). Figure 5 shows the simulated effects of adding this skew. This filter equalizes the frequency-dependent loss of dielectrics, which predominates in pc-board interconnects at frequencies of 5 GHz and greater. For the zero-skew-input case, the 12-UI burst exhibits minimum ISI and maximum output amplitude, and, with small amounts of skew, both the ISI and the output amplitude degrade significantly.

Even perfectly matched lengths do not guarantee zero skew. Many media— from cables to pc-board materials— have nonuniform dielectric constants, which can cause skew in perfectly matched path lengths as short as a few inches. A prime example is fiberglass-reinforced epoxy, such as G10. In this case, the dielectric constant of the fiberglass differs from that of the epoxy, and the fiber bundles are spaced at a distance that is comparable to the width of conductors in stripline or microstrip interconnects. Random placement of the fiberglass bundles with respect to the location of the conductors on the pc board results in uncontrolled differential skew. This skew can be as large as 25 psec in 4 in. (10 cm) of interconnect (Reference 1).
New solutions

You can correct differential skew by improving control of the manufacturing process to reduce the variation of effective dielectric constant as a function of location. You could use irregular angular relationships between the direction of the fiber bundles or other causes of anisotropic dielectric constants and the conductors in the lanes. If each conductor of length $L$ crosses the same number of fiber bundles, the delay associated with each conductor should be the same. Alternatively, you can measure the skew and replace a conductor link with a link containing the inverse of the measured amount of skew—an expensive proposition. Creating a library of precisely known differential delays involves a significant amount of test time, and it requires the accurate assembly, measurement, and cataloging of many cables or other forms of interconnect.

Another, more promising, approach is to detect differential skew and adjust the delay in one, the other, or both paths to reduce the skew to near zero. This approach involves detecting the skew and then adjusting the delay.

Detecting skew

Modern oscilloscopes have timing resolutions of 1 psec or less, but connecting an oscilloscope to the differential inputs of a receiver IC can typically introduce systematic skew of 2 or 3 psec. Uncertainties associated with the probe positioning, the location of the ground connections, and the differences between the load impedances of the two probes cause this skew. US Patent 6,909,980 describes a method for deciding how a piece of test equipment should adjust the timing of input differential signals to obtain optimal skew values in an eye diagram (Reference 2). The patent uses independently programmable "paired independent skew circuits" for the true and complementary versions of a differential input, thereby letting you deskew the signal circuit. The patent assumes that the differential skew arises as a consequence of problems in the interconnection to the test equipment. The invention does not deal with skew introduced by interconnection between a source and the input circuit of a remote IC that is not a part of such test equipment. The patent gives a good approach for displaying eye diagrams, not for measuring skew.

Observe the received signals inside the receiver. You can determine the skew with a NOR latch. If there is no skew, the average value of the output waveforms from $Q_p$ and $Q_n$ will be the same. Any skew adds to the average value of one waveform and subtracts from the average value of the other waveform. This situation makes it easier to detect small amounts of skew.

Figure 6 shows a circuit-level simulation for a system having 1 psec of skew. At 50% duty factor, the skew is zero, so 1 psec of skew is easily detectable.

Observe the reflection from the input of the receiver. If the receiver is differentially terminated, the virtual center of the termination is at ac ground when no skew exists. When skew exists, large reflections launch at the receiver during the skew interval. The first signal to arrive at the line-to-line termination "sees" the value of that termination resistor in series with the characteristic impedance of the transmission line that connects to the opposite side of the termination resistor. During the skew interval, the termination appears to be $3 \times Z_n$ instead of $Z_n$. This fact results in a reflection coefficient of $(Z_T-Z_n)/(Z_T+Z_n)=(2 \times Z_n)/(4 \times Z_n)=0.5$. This large reflection coefficient persists until the arrival of the second signal at the end of the skew interval. At that time, the voltages at the opposite ends of the termination resistor are equal and opposite in sign. So the line-to-line
termination has the same effect as two resistors, each of value $Z_N$, providing ideal terminations to the two lines.

The reflections are easy to detect at the transmitter, and they indicate not only the presence of skew, but also which of the two signals arrived at the receiver first. Figure 7 shows the model for the skew detector and the corresponding waveforms. It's important to note that, in this case, the indicated skew could be the result of some transmitter skew and some interconnect skew, but the skew-detection method determines the final resulting skew, no matter where the contributions came from. (I have filed a patent application in this area.)

**Adjusting skew**

If the required skew resolution is several picoseconds long, the skew adjuster can insert active delay into a path using a multiplexer. This time-tested and proven methodology is largely in the public domain. For skew requirements of approximately 1 psec or less, you can use an interpolator to interpolate between two fixed delays whose difference is approximately 10 psec. Many timing interpolators are in the public domain. For smaller target amounts of skew requiring subpicosecond resolution in the timing adjuster, a programmable-delay line using current control or varactors is a good choice. Patent applications exist for this type of system.

Resolving small amounts of skew is not too difficult. Ensuring that the skew exists and is not an artifact of the measurement is more difficult. Two paths typically exist between the device under test and the measurement device. One connects each of two points whose differential skew you are determining to corresponding inputs of the measurement device or skew detector. If these paths have a differential delay, an error will appear in the measurement result. If the two paths have different rise times or bandwidths, a differential delay will result. If the measurement device is an oscilloscope that uses a probe for each input, the skew of the probes, their cables, and the difference in their rise times can cause a significant amount of skew.

Also, when measuring the relative duty factors of the output of a latch-based skew detector, bias or leakage current in the input of the dc amplifier can cause significant errors.

**References**