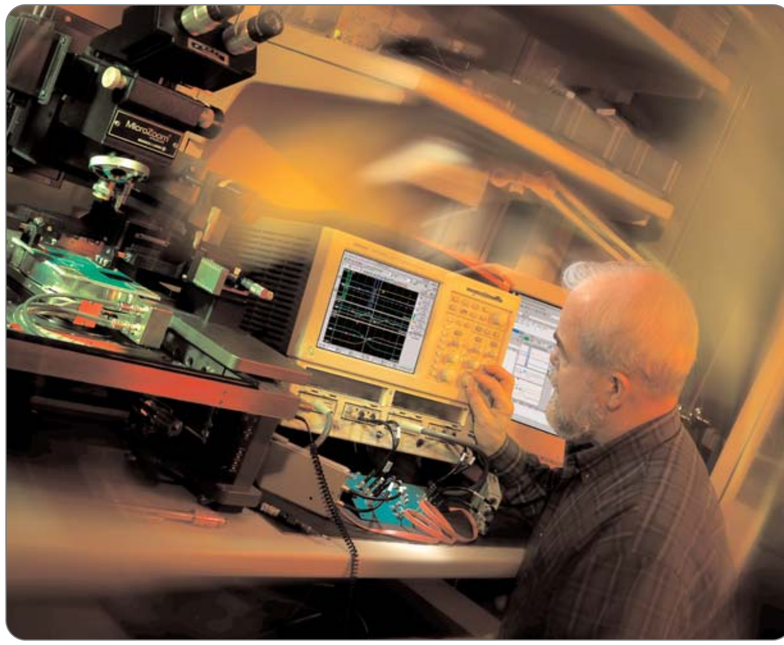
Time Domain Methods for Measuring Crosstalk for PCB Quality Verification



This application note discusses the elements of crosstalk, and demonstrates how you can measure crosstalk on a single-layer PCB using the TDS8000B Series Sampling Oscilloscope or the CSA8000B Series Communications Signal Analyzer.

The increasing speed of digital systems in communications, video, networking and computer technologies increase the quality requirements of the Printed Circuit Boards (PCB's) for these systems. Earlier generations of PCB design cannot guarantee performance and operation in the face of the increasing signal frequencies and rise times.

Today's PCBs and their elements (edge connectors, micro-strip lines, and component sockets), must be modeled using transmission-line methodology. Understanding the forms, mechanisms, and consequences of crosstalk on your PCBs, and employing techniques that minimize it, help you improve the reliability of the systems using your PCB designs. And, although this document is written around PCB design, the topics covered can also be useful for other applications such characterization of cables and connectors.

Consequences of Crosstalk

PCB designers care about crosstalk because it can cause the following performance problems:

- increased noise levels
- unplanned spikes
- jitter on data edges
- reflections of undesired signals

Which, and how many, of these performance problems plague your PCB design depends on several factors, such as the properties of the logic family used, board design, mode of crosstalk (reverse or forward), and the terminations on both ends of the aggressor and victim lines. The information that follows can help focus your investigation into crosstalk, so that you can minimize its impact on your design.

Methods for Investigating

To minimize crosstalk in your PCB designs, you seek balance between capacitance and inductance, and you target nominal impedance levels—after all, manufacturable PCBs require controlled impedance transmission lines. Once such a board is designed, components, connectors and terminations define which type, and how much, crosstalk affects the circuit. Use of time-domain measurements, calculating the knee frequency, and understanding Crosstalk-on-PCB Model can help set boundaries for your crosstalk analysis.

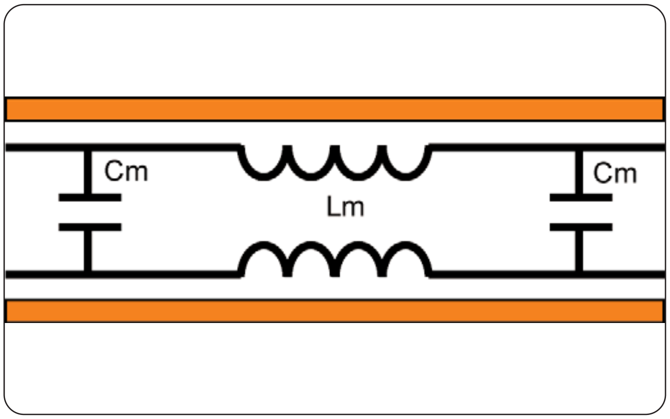


Figure 1. *Mutual Impedance between lines on PCB*

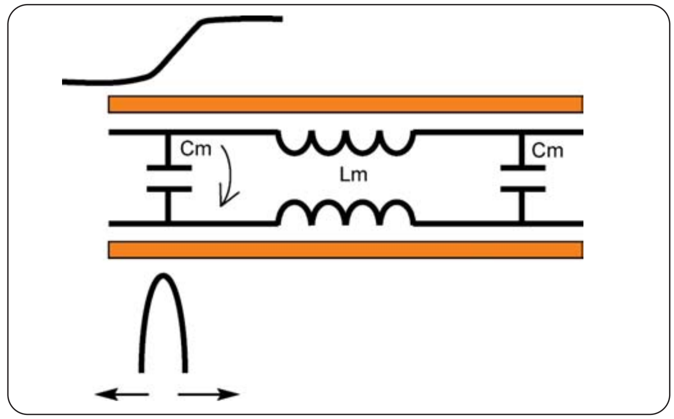


Figure 2. *Capacitively coupled crosstalk*

Time-domain Measurements

To measure and analyze crosstalk, you can use frequency-domain techniques to observe the clock harmonics located in the frequency spectrum relative to the EMI limit levels at these frequencies. However, a time-domain measurement of the digital-signal edge—the rise time from 10% to 90% level—offers these advantages:

- ▶ The speed of the digital-signal edge or the rise time directly describes how high the levels are at each frequency.
- ▶ The definition of speed-by-signal-edge (rise time) also helps explain the mechanisms of crosstalk.
- ▶ Rise time can be used to directly calculate the Knee Frequency, as explained below.

This application note demonstrates and measures crosstalk using rise-time measurements.

Knee Frequency

To guarantee reliable operation of a digital system, you must develop and verify the circuit design for frequencies below the Knee Frequency. Frequency-domain analysis of a digital signal shows that frequencies higher than the Knee Frequency are attenuated, so they have no practical effect on crosstalk, while frequencies below the Knee Frequency have high enough power to affect the circuit operation. Knee Frequency is calculated with the formula:

$$f_{knee} = \frac{0.5}{t_{rise}}$$

Crosstalk-on-PCB Model

The following model sets the stage for exploring the different forms of crosstalk and illustrates how mutual impedance between the micro-strip lines causes crosstalk on a PCB. Figure 1 shows the conceptual model of the mutual impedance, which is evenly distributed along the length of the two lines.

Crosstalk begins as a digital gate outputs a rising edge to the aggressor line, which starts to propagate along the line:

1. Both the mutual capacitance, Cm, and the mutual inductance, Lm, couple or "crosstalk" a voltage into the adjacent victim line.
2. The crosstalk voltage appears on the victim line as a narrow pulse with a width equal to the pulse rise time on the aggressor line.
3. On the victim line, the pulse divides into two pulses, and each starts to propagate in opposite directions, effectively dividing crosstalk into two parts:

- ▶ Forward Crosstalk, propagating in the direction of original aggressor pulse, and..
- ▶ Reverse Crosstalk, propagating in the opposite, source direction.

Crosstalk Types and Coupling Mechanisms

Based on the model just discussed, the information that follows illustrates the coupling mechanisms of crosstalk and discusses the two types of crosstalk.

Capacitively Coupled

Mutual capacitance in circuits enables crosstalk as follows:

- ▶ As the pulse on the aggressor line arrives at the capacitor, the capacitor couples a narrow pulse to the victim line.
- ▶ The amplitude of the coupled pulse is defined by the value of the mutual capacitance.
- ▶ The coupled pulse divides into two parts, and each starts to propagate in opposite directions along the victim line.

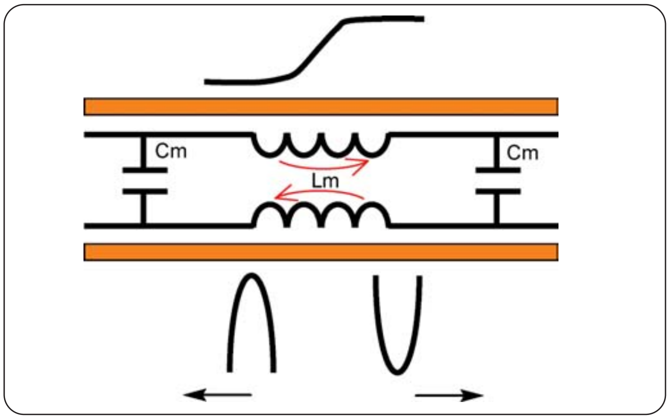


Figure 3. *Inductively coupled crosstalk*

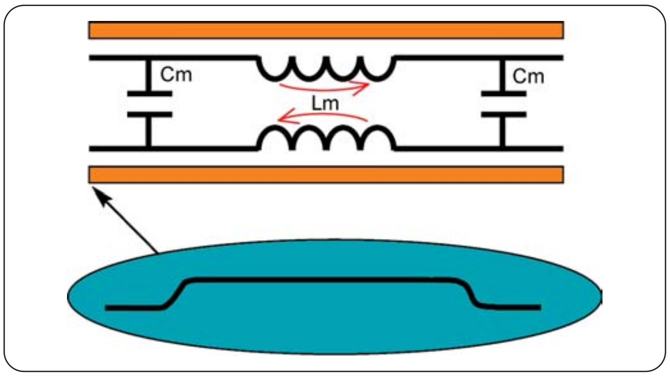


Figure 4. *Reverse Crosstalk*

Methods for investigating

To minimize crosstalk in your PCB designs, you seek balance between capacitance and inductance, and you target nominal impedance levels —after all, manufacturable PCBs require controlled impedance transmission lines. Once such a board is designed, components, connectors and terminations define which type, and how much, crosstalk affects the circuit. Use of time-domain measurements, calculating the knee frequency, and understanding Crosstalk-on-PCB Model can help set boundaries for your crosstalk analysis.

Inductively, or Transformer-coupled

Mutual inductance in circuits enables crosstalk as follows:

- ▶ The pulse propagating on the aggressor line charges the next location with a current spike.
- ▶ This current spike induces a magnetic field, which in turn induces a current spike on the victim line.
- ▶ The transformer generates two opposite-polarity voltage spikes on the victim line: the negative spike propagates in the forward direction and the positive spike propagates in the reverse direction.

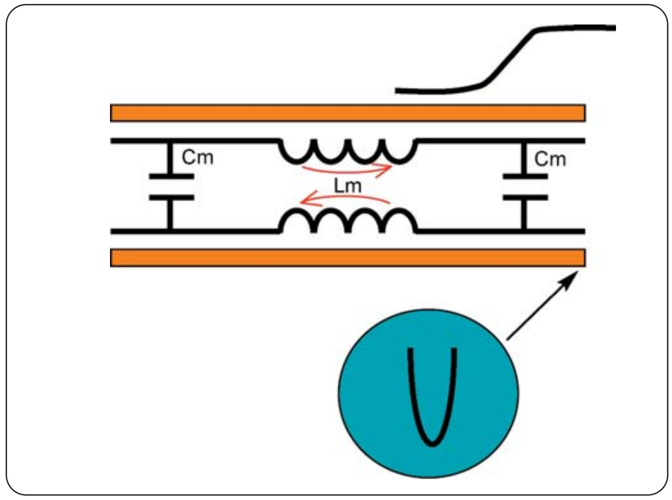


Figure 5. *Forward Crosstalk*

Reverse Crosstalk

The models just described result in the capacitively and inductively coupled crosstalk voltages summing in the victim line at the crosstalk location. The reverse crosstalk that results includes the following characteristics:

- ▶ Reverse crosstalk is the sum of two same polarity pulses.
- ▶ As the crosstalk location propagates with the aggressor-pulse edge, reverse crosstalk is seen at the source of victim line as a low level, wide pulse, with the width relative to the line length.
- ▶ Reverse crosstalk amplitude is independent of the aggressor-pulse rise time but depends on the mutual-impedance value.

Forward Crosstalk

Again, the capacitively and inductively coupled crosstalk voltages sum in the victim line at the crosstalk location. Forward crosstalk includes the following characteristics:

- ▶ Forward crosstalk is the sum of two opposite-polarity pulses.
- ▶ Because the polarities are opposite, the sum depends on the relative values of the capacitance and inductance.
- ▶ Forward crosstalk is seen at the end of the victim line as a narrow spike with width of the aggressor rise time.
- ▶ Forward crosstalk depends on the rise time of the aggressor-pulse rise time—the faster the rising edge, the higher the amplitude and narrower the shape.
- ▶ Forward crosstalk amplitude also depends on the paired lines length: as the crosstalk location propagates along the aggressor-pulse edge, the forward-crosstalk pulse in the victim line receives more energy.

Characterizing Crosstalk

The information that follows explores the crosstalk mechanisms and types just described by making several example measurements on a single-layer PCB by making example measurements.

Note: To become familiar with the crosstalk issues and consequences that come with multilayer PCBs and their ground layers, refer to the reference materials and other sources at the end of this application note.

Instrumentation and Setup

To effectively measure crosstalk in a laboratory, use a wide-bandwidth oscilloscope with 20 GHz measuring bandwidth. Drive the circuits under test from a high-quality pulse generator that outputs a pulse rise time that equals the rise time of the oscilloscope. Use high-quality cables, termination resistors, and adapters with your PCB under test.

The Tektronix 8000B Series instrument, with the 80E04 Electrical Sampling Module installed, makes an ideal combination for successfully measuring crosstalk. The 80E04 is a dual-channel sampling module contains a TDR step generator that generates 17 ps rise-time pulses with a 250 mV amplitude from a 50 Ω source impedance. You need only connect the PCB that you wish to test.

Measuring Forward Crosstalk

To measure forward crosstalk only, all the lines are terminated to eliminate reflections. The measurement is made at the end of the terminated victim line. The setup, shown in Figure 6, follows.

If the mutual inductance couples more crosstalk than the mutual capacitance, the pulse is negative at positive-aggressor edge. The width is the rise time of the aggressor edge. The instrument displays negative pulse (C4) with 48.45 mV amplitude. The aggressor amplitude is 250 mV, and the crosstalk is almost 50 mV, so this fast edge causes 20% crosstalk on these lines. See Figure 7.

Because the input step from 80E04 is an extremely fast edge, the measured crosstalk that results is too high to represent driving signals present in practical logic families. For example, if the drive signal was from a 1.5 ns CMOS gate, the crosstalk pulse would be much wider and lower. To represent this case, the Define Math feature of the instrument is used to create a low-pass filter after the acquisition. The M1 waveform (white) in Figure 7 shows the results. Note that the vertical setting for M1 is 10 times more sensitive than that for the nonfiltered waveform.

Although mathematical analysis proves the technique just described leads to the same result as physically filtering an agressor pulse connected to the line, the following steps further validate the equivalence:

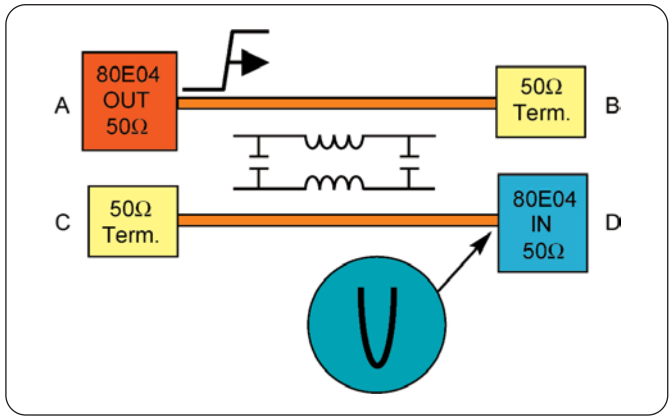


Figure 6. *Forward Crosstalk Measurement*

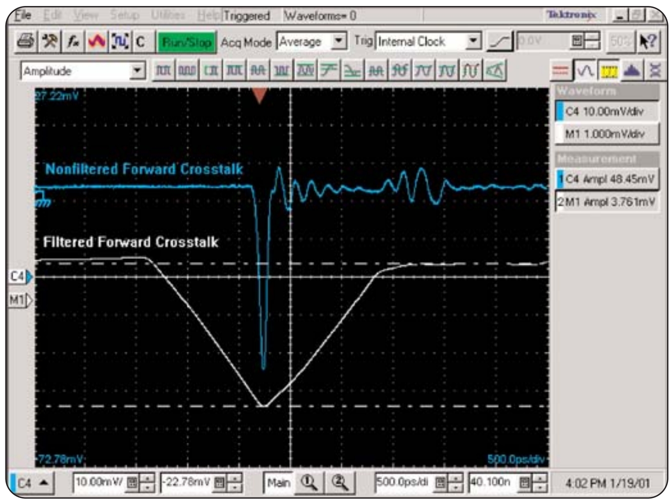


Figure 7. *Forward Crosstalk Measured*

- ▶ Measure the crosstalks caused by a fast and a slow edge with the same amplitude.
- ▶ Then low-pass filter the crosstalk from the fast edge to the rise time of the slow edge, and verify the results.

The resulting measurements are displayed on the instrument screen shown in Figure 8, and are as follows:

- ▶ The red waveform (R3) is the crosstalk caused by the slow generator pulse, which is the yellow waveform (R2).
- ▶ The white waveform (R4) is the crosstalk caused by the fast TDR pulse, which is the green waveform (R1).
- ▶ The blue waveform (M1) is filtered from the white waveform to slow down the pulse rise time, and represents the crosstalk using post-filtering. These two crosstalk traces are displayed at the same voltage scale.

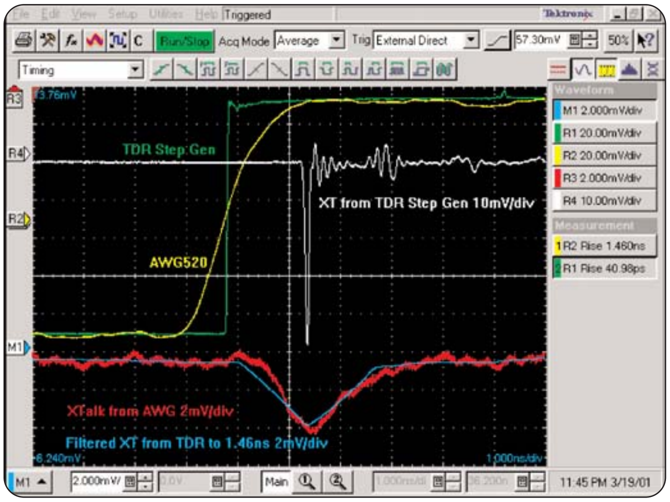


Figure 8. Post-Filtering of Forward Crosstalk

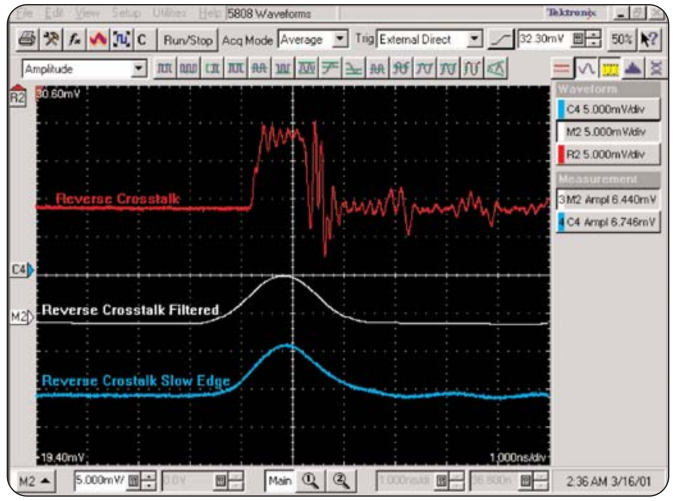


Figure 10. Reverse Crosstalk Measured

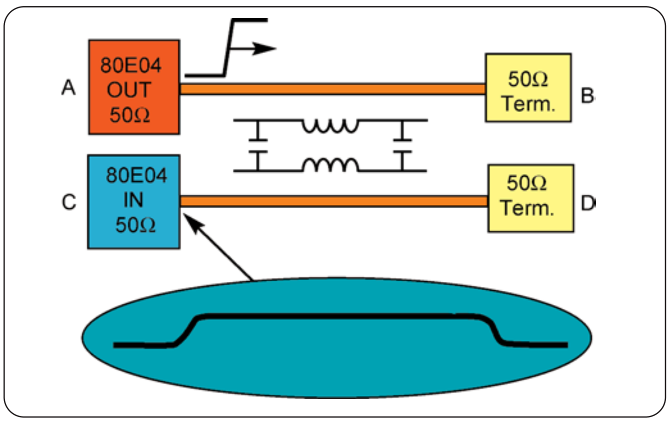


Figure 9. Measurement of Reverse Crosstalk

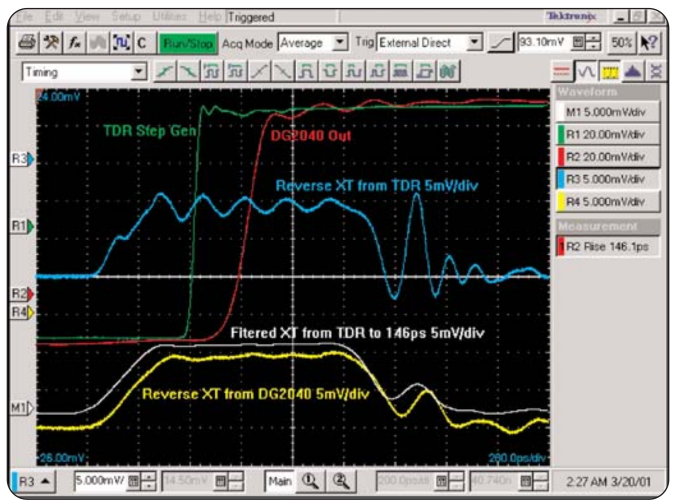


Figure 11. Reverse Crosstalk is independent of rise time

Measuring Reverse Crosstalk

To measure reverse crosstalk only, both lines are terminated with a 50 Ω resistor to eliminate reflections, with the measurement taken at the left end of the victim line, as shown in Figure 9.

The amplitude of the returning pulse is low and its width represents twice the length of the line, because the crosstalk from the end of the line must travel back to the source. Figure 10 displays this measurement, where crosstalk from fast edge is about 10 mV, which equals 4%.

The amplitude of the reverse crosstalk is independent of the aggressor rise time. The two lower waveforms in Figure 10 are crosstalk from a slow pulse and the post-filtered crosstalk of the fast pulse. These both have about 6.5 mV amplitude. The length of the line compared to the rise time causes the lower amplitude of this slow pulse. In this case, the rise time is longer than the line, and the edge propagates through the line before the edge reaches full amplitude. Figure 11 shows crosstalk measurements from a 200 ps rise-time generator (DG2040) and from the 17 ps generator of the 80E04 sampling module.

The three crosstalk waveforms in Figure 11 are at the same voltage scale, 5 mV/div. The white waveform is the result of the 17 ps crosstalk, post-filtered by a waveform math function to 200 ps rise time. These results confirm that aggressor rise time does not affect reverse crosstalk, unless the rise time is longer than the line. If the aggressor rise time is longer than the line, the crosstalk will be lower in amplitude since the edge does not reach full amplitude over the line.

Effects of Circuit Design on Crosstalk

Although careful design of the PCB reduces crosstalk and reduces or removes its effects, some crosstalk will likely remain on PCBs. Careful circuit design should apply proper line-end terminations, because these terminations affect the amount of, and time decay of, crosstalk. The measurement examples that follow illustrate how line terminations at the end of the line and at logic gate output attenuate crosstalk and its causes.

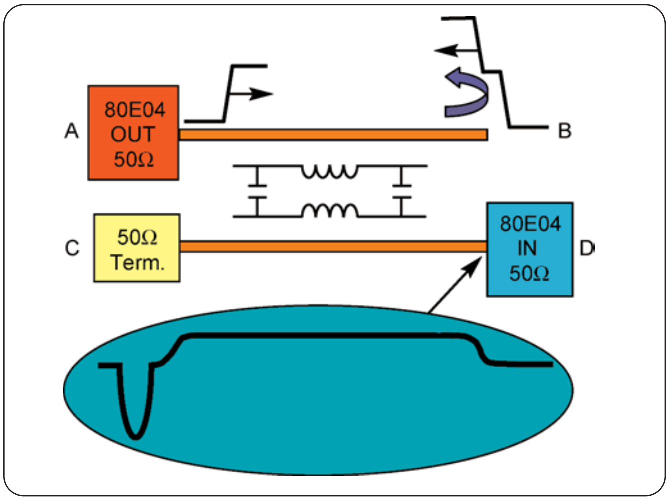


Figure 12. *Crosstalk without end termination*

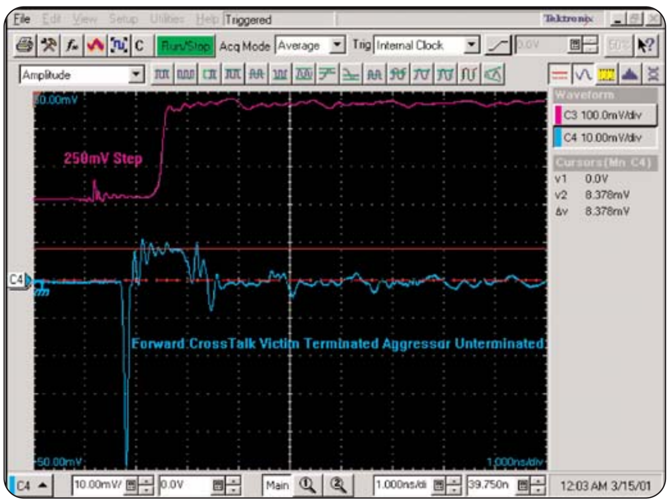


Figure 13. *Measured crosstalk without end termination*

Effects of No End Termination

To measure one case of no end termination, the aggressor line is left unterminated. This setup simulates a line without a terminating resistor driving a CMOS gate, since the CMOS gate has a very high input impedance compared to the 50 Ω nominal line impedance of the line, as shown in Figure 12.

The circuit responds by reflecting the arriving pulse from the open end of the transmission line back to the source, with full amplitude and the same polarity. If the source is terminated, no second reflection occurs there. The measurement at the end of the victim line includes two basic phenomena: the original forward crosstalk, a narrow spike, followed by reverse crosstalk manifested as low and wide pulse caused by the reflected pulse. Figure 13 displays these pulses together (C4), with the aggressor pulse reflection measured at the source of the aggressor line (C3).

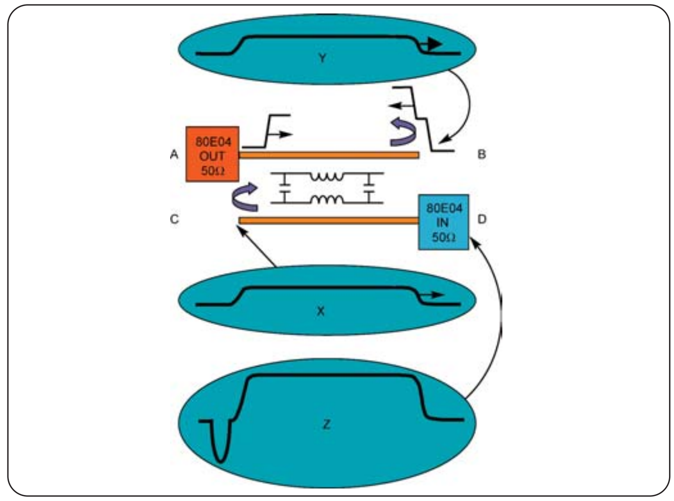


Figure 14. *Crosstalk with both ends unterminated*

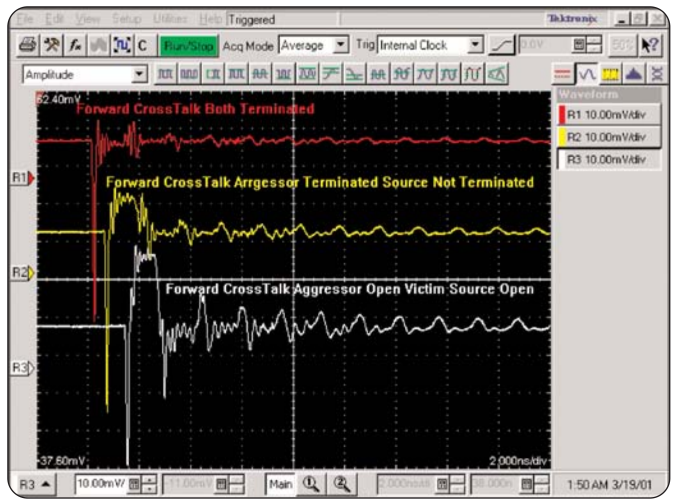


Figure 15. *Measured crosstalk with both lines unterminated*

Effects on No Source or End Terminations

To examine a second case of no termination, both the aggressor line is left open, with no end termination, and victim line is left open, with no source termination. In this case, reverse and forward crosstalk and the reflections accumulate, causing an increase of noise voltage on the victim line, as shown in Figure 14. (Similar voltages can be assumed to occur on adjacent lines as well.)

Victim line end (Z) has a spike from the original forward crosstalk, followed by the reverse crosstalk from the first reflection in the aggressor line (X). The original victim line reverse crosstalk reflected from the open source (Y) will then sum up at the same time with (X) causing double voltage to the wide pulse! In addition, all the forward crosstalk narrow spikes will bounce back and forth from the open ends. Figure 15 displays these waveforms.

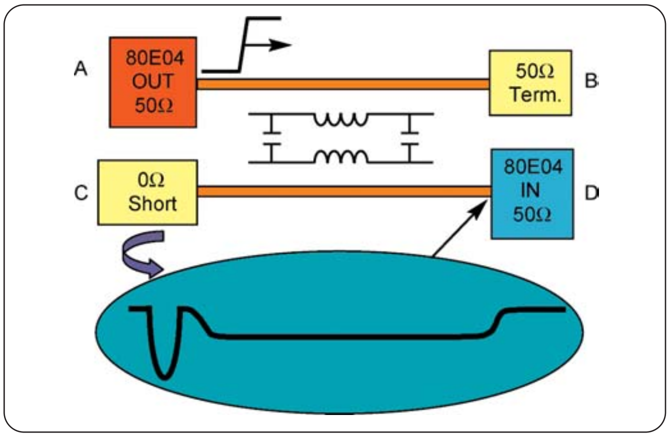


***Figure 16.** Crosstalk with low impedance source*

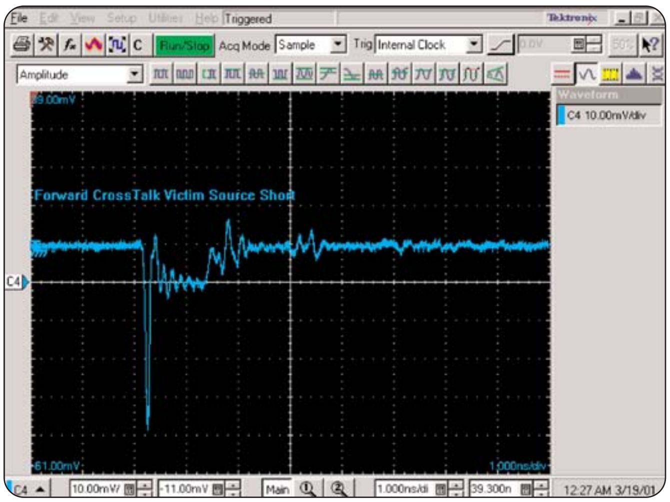


***Figure 17.** Measured crosstalk with victim source shorted*

Note. When making measurements like just described, terminate all unused lines to keep noise level low. Otherwise, crosstalk pulses from these lines will couple to, and create further crosstalk in, their victim lines.

Effects of Low Impedance Source

To examine the case of a low impedance source on the victim line, the victim line is driven by an ECL gate. The gate is simulated in the measurement setup using a shorting termination. (Fast ECL gate output impedance ranges from 15 Ω to 25 Ω). The measurement setup is shown in Figure 16.

The ECL gate impedance and line impedance mismatch results in negative reflections in the aggressor line. If the aggressor line carries a pulse, its reverse crosstalk will reflect to its victim line with negative polarity. The reflection appears as a negative pulse at the end of the victim line, as shown Figure 17.

Conclusion

TDR-capable instruments, such as 8000B series instruments equipped with the 80E04 Electrical sampling module, used with the methods and approaches explored in this application note, can meet the design challenges presented by crosstalk. Using the measurements discussed here on your prototype will help verify that your design handles these challenges. Careful measurements of crosstalk effects, and application of correct working terminations, are keys to eliminating the consequences of crosstalk.

Tektronix CSA8000B Series Communication Signal Analyzers and TDS8000B Series Sampling Oscilloscopes support design and verification of extremely fast electronic circuits. Some of these applications follow:

- Crosstalk measurements on PCB's and cablings, using the 80E04 Electrical Sampling Module to generate 17 ps rise-time steps and the mathematical functions of the 8000B Series instruments to simulate practical circuit speeds.
- Impedance measurement and analysis of the interconnects, transmission lines, and micro strip lines, using TDR technology. The 8000B series provides 17 ps rise time and 20 GHz bandwidth, resulting in 3-mm resolution on ordinary PCB materials.
- AC parameter measurements of electronics to verify fundamental operation of extremely high speed logic gates. A +70 GHz bandwidth and multi-channel construction with a very stable time base enable accurate and flexible measurements, including jitter down to less than 1 ps.
- Measurements of optical interfaces in communication technologies, using standard receivers and optical sampling inputs. The 8000B Series instruments feature onboard automatic measurements for optical signals, when used with 80C00 Series Optical Sampling Modules.

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