TECHNICAL PUBLICATION

Adjusting Signal Timing (Part 2)

Crosstalk effects in serpentine traces

Douglas Brooks, President
UltraCAD Design, Inc.

January 2004

ABSTRACT

When a signal passes through a serpentine trace with coupling between the legs, there is an apparent speed-up of the signal. That is, the signal appears to pass through the serpentine section faster than the trace length would otherwise indicate. This apparent speed-up is caused by crosstalk coupling between the legs of the serpentine traces. The amount of apparent speed-up is directly related to the coupling strength between the legs and inversely related to the rise time of the signal passing through the section. The apparent speed-up of the signal is not directly related to the coupled length. For long coupled lengths (those longer than the critical length) signals may become distorted as they pass through the serpentine section, but the degree of distortion is a complex function of the frequency of the signal. Signals pass relatively undistorted through short coupled serpentine sections.

BACKGROUND

Part 1 of this series[1] discussed signal timing issues in general, and why and how we can tune trace lengths to achieve certain timing objectives. Ordinarily, it does not matter much what type of pattern we use to tune traces. But there can be unexpected signal timing and integrity effects if we use timing loops that are closely spaced. It is often convenient to add trace length by extending a trace some distance and then allow it to fold back on itself, perhaps several times. We typically call this type of serpentine pattern "tromboning." When the loops are closely spaced, crosstalk can occur between them that has interesting consequences.

It is generally known that these crosstalk effects can exist. Howard Johnson has observed, "Short, coupled switchbacks produce smaller delays than the total trace length would indicate. Long, coupled switchbacks distort the signals."[2] It is interesting to explore why this happens. And when we do so, some interesting conclusions result.

HOW CROSSTALK OCCURS

Consider the trace pattern illustrated in Figure 1. The trace extends out and then doubles back upon itself. A signal starts to propagate down the trace and is shown in three possible positions, (a), (b), and (c), respectively.

When the signal first starts down the trace (traveling to the right), it couples into the return leg of the trace directly opposite the signal. This coupling exists as "backward crosstalk"[3] and it travels toward the left. As such, this backward crosstalk signal is clearly now in front of the main signal. When the main signal travels to point (b), it is still coupling a backward crosstalk signal into the opposite trace segment, still in front of the main signal.

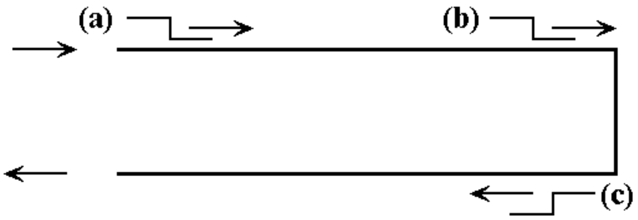


Figure 1: When a trace loops back upon itself, crosstalk can occur between the two legs of the trace.

When the signal "rounds the corner" to position (c), and begins moving to the left, it begins coupling a backward crosstalk signal into the opposite trace segment, now behind the signal. As the signal continues on, it continues to couple into the opposite trace segment, generating a backward crosstalk signal behind the main signal. Since this situation is symmetrical, these two coupled backward crosstalk signals, one in front of the main signal and one behind it, will be almost identical in shape.

Thus, when the signal reaches the end of the entire trace (arriving at the receiver), there will be three components to it. There will be a crosstalk component that arrives earlier than the signal, the main signal itself, and then a crosstalk component that arrives later than the signal.

WHAT THE CROSSTALK COMPONENTS LOOK LIKE

When one trace couples into another (for "long" lengths), the backward crosstalk signal looks roughly trapezoidal (see Figure 2). It is truly trapezoidal if the aggressor signal is a perfectly linear ramp (modeled in Hyperlynx, below.)

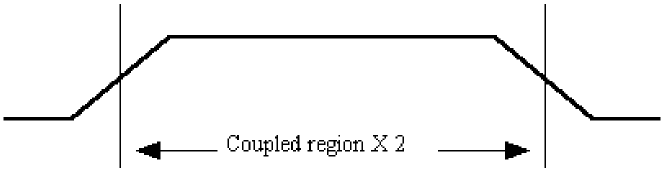


Figure 2: A backward crosstalk signal looks roughly trapezoidal.

The crosstalk signal rises from zero to some peak value, then holds at the peak value throughout its length, and then returns to zero. The width of the pulse is generally understood to be twice the propagation time through the coupled region. It is important to note that the magnitude of this peak value does not change with coupled length (for "long" coupled lengths). But the width of the pulse (twice the propagation time down the coupled length) does change with coupled length.[4] The pulse looks more rounded for "short" lengths. The boundary between "long" and "short" lengths is called the "critical length."

The backward crosstalk pulse reaches a maximum value (for any given set of circumstances) when the coupled region is longer that the "critical length." This is the same critical length we refer to in transmission line analyses.[5] It is a length of trace where the propagation time along the length equals one-half the rise time of the aggressor signal. For example, in FR4, the propagation time is typically about 6"/ns. One half of that is 3". So the critical length for a one-ns rise time signal would be 3". A 2.0 ns rise time signal would have a critical length of 2 x 3" or about six inches.

Figure 3 illustrates a HyperLynx model of a coupled trace and Figure 4 illustrates the results from this model. The aggressor signal (a) is a linear ramp taking 2 ns to rise from zero to full value. The coupled traces are assumed to be in a stripline environment (so there is no forward crosstalk) with FR4 dielectric whose relative dielectric is such that the propagation time is 6"/ns. The backward crosstalk signal reflects off the front (left) end of the victim line and arrives at the far end of the line one propagation delay after the aggressor signal enters the coupled region. Figure 4 illustrates the results of this model for three coupled lengths, 12" (d) (twice the critical length), 6" (c) (the critical length), and 3" (b) (one-half the critical length).

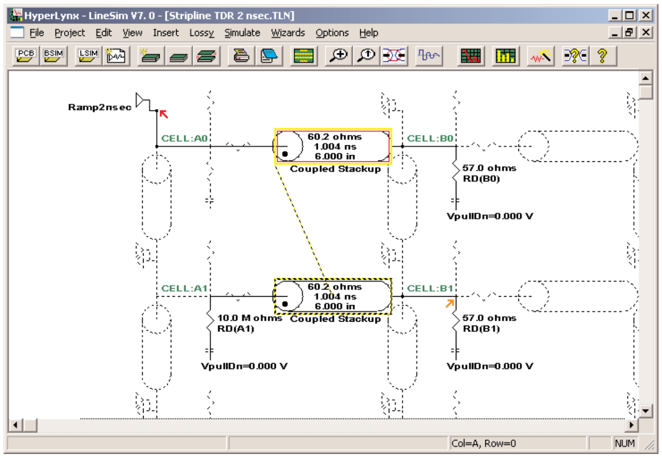
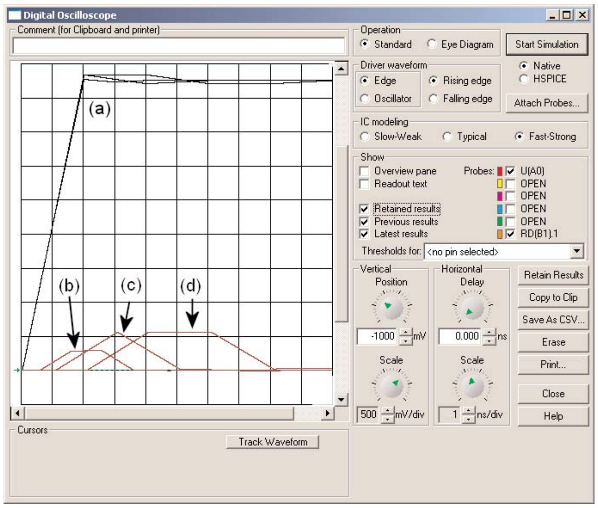


Figure 3: Model for evaluating backward crosstalk response to a ramp aggressor signal

The results show clearly that the backward crosstalk signal for coupled regions longer than the critical length resembles a trapezoid when the aggressor signal is a linear ramp. This reduces to a triangle (with the same magnitude) when the coupled region is exactly the critical length. For coupled regions less than the critical length, the shape resembles a trapezoid again, but it is more accurately described as a "flattened" triangle.

Rise time: In general, the backward crosstalk signal continues to increase as long as the aggressor signal is increasing (i.e. as long as di/dt is positive). It stops increasing as soon as the aggressor signal stops increasing. Thus the rise time of the backward crosstalk signal is the same as the rise time of the aggressor signal. This can be seen in traces (c) and (d) in Figure 4, where the rise time of these signals is the same as the rise time of the aggressor signal, 2 ns. The slope of the backward crosstalk signal when the coupled length is less than the critical length is the same as in the other cases; but the signal does not have time to rise to the same magnitude as when the coupled length is greater than the critical length.



Operation: ● Standard ○ Eye Diagram

Driver waveform: ● Edge ○ Oscillator ● Rising edge ○ Falling edge

● Native ○ HSPICE

IC modeling: ○ Slow-Weak ○ Typical ● Fast-Strong

Show: ☐ Overview pane ☐ Readout text ☑ Retained results ☑ Previous results ☑ Latest results

Probes: ☑ U(A0) ☐ OPEN ☐ OPEN ☐ OPEN ☐ OPEN ☑ RD(B1).1

Thresholds for: <no pin selected>

Vertical Position: -1000 mV

Horizontal Delay: 0.000 ns

Vertical Scale: 500 mV/div

Horizontal Scale: 1 ns/div

Figure 4: Model response for an aggressor signal (a) rising in a ramp-like pattern in 2 ns inducing a backward crosstalk signal in coupled regions of 3" (b), 6" (c), and 12" (d), respectively.

Pulse width: The width of the backward crosstalk pulse is twice the length of the coupled region. This width is measured from the approximate midpoint of the rise and fall times of the pulse. (Alternatively, it could be measured between the points where the pulse just starts to rise [where the aggressor just starts to rise entering the coupled region] to the point where the pulse just starts to fall at the far end [where the aggressor just stops rising and levels off at the far end of the coupled region]). So if we had a main signal (which plays the role of an aggressor signal in this type of situation) with a 2 ns rise time, and a coupled length of 12 inches (2.0 ns), then the dimensions of this backward crosstalk signal would be as shown in Figure 5. The rise time is 2 ns and the width (as defined) is 4.0 ns (twice the length of the coupled region). The total width of the backward crosstalk pulse, from beginning to end, would be 6.0 ns (2 x the coupled length plus one rise time). This result can be seen in the modeled results shown in traces (c) and (d) in Figure 4.

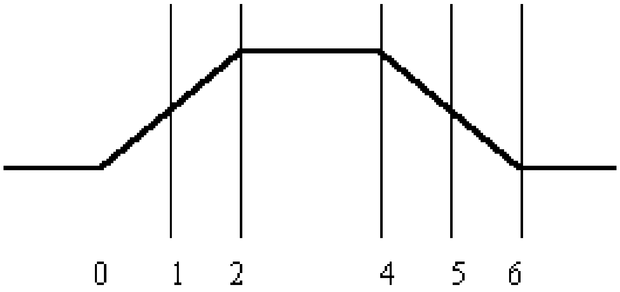


Figure 5: Timing diagram (in ns) for a backward crosstalk signal when the aggressor signal has a 2.0 ns ramp rise time and the coupled region is 2 ns (12 in) long.

Why do we measure the pulse width between the midpoints on the rise and fall times? The answer is somewhat subtle. Consider the rise time of an "aggressor" pulse. The very first part of the rise time of the aggressor pulse begins to couple into the victim pulse and begins generating a backward pulse whose length is twice the coupled length. This is the very beginning of the backward pulse. The very last part of the rise time also couples into the victim trace and it also generates a backward pulse whose pulse width is twice the coupled length. The very end of this component of the backward crosstalk pulse is the end of the total backward pulse. So the entire backward crosstalk pulse length, from its beginning to its end, is twice the coupled length plus the rise time of the aggressor signal.

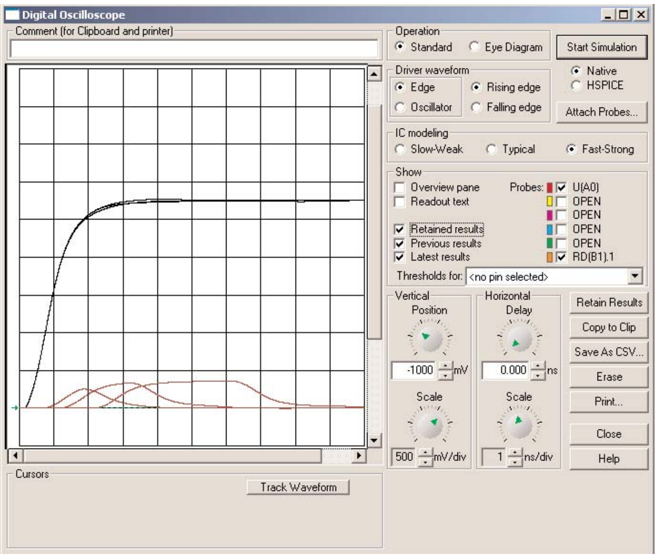
Pulse Magnitude: For coupled regions longer than the critical length, the magnitude of the backward crosstalk signal rises to a maximum constant value and then increases no further. This is shown in curves (c) and (d) in Figure 4. For coupled regions shorter than the critical length, the backward crosstalk pulse does not have time to rise to this magnitude.

Howard Johnson shows that the maximum magnitude of a backward crosstalk pulse is proportional to[6]

$$\frac{1}{1+(D/H)^2}$$

We can consider this to be a crosstalk coupling coefficient. We multiply this coupling coefficient times the magnitude of the aggressor signal to get an approximate worst-case backward crosstalk magnitude. This is approximately the magnitude of the pulse if the coupled length exceeds the critical length. For coupled regions shorter than the critical length, the approximate maximum magnitude is proportionally less.

Reality: These signal patterns have been represented as trapezoids and triangles for convenience and understanding. Real signals would look very much like these figures if the aggressor signal had absolutely linear rise and fall times. In truth, of course, that isn't the case. Real signals are much more rounded in their appearance, as shown for reference in Figure 6.



Operation: ● Standard ○ Eye Diagram

Driver waveform: ● Edge ○ Oscillator ● Rising edge ○ Falling edge

● Native ○ HSPICE

IC modeling: ○ Slow-Weak ○ Typical ● Fast-Strong

Show: ☐ Overview pane ☐ Readout text ☑ Retained results ☑ Previous results ☑ Latest results

Probes: ☑ U(A0) ☐ OPEN ☐ OPEN ☐ OPEN ☐ OPEN ☑ RD(B1).1

Thresholds for: <no pin selected>

Vertical Position: -1000 mV; Scale: 500 mV/div

Horizontal Delay: 0.000 ns; Scale: 1 ns/div

Figure 6: The same model results as Figure 4 when the aggressor signal is a more typical TTL driver.

CONCEPTUAL RESULTS

We can now sketch a conceptual view of what the result might be of a signal flowing through a trace that folds back on itself (as shown in Figure 1). Figure 7 illustrates the signal components of Figure 1 when the rise time is fast relative to the coupled length (i.e. the coupled length is greater that the critical length).

Trace (a) is the signal as it enters the coupled region at the left side of Figure 1. Trace (b) is the same signal (component) after it rounds the corner and leaves the coupled region. This is what the signal would look like at the end of the trace if there were no coupling. Trace (c) is the leading crosstalk component of the signal and trace (d) is the lagging crosstalk component of the signal. The true signal is the sum of components (b), (c), and (d). This is drawn as trace (e).

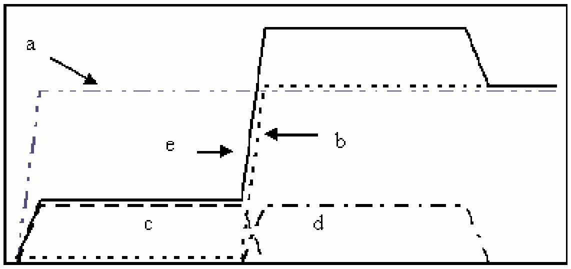


Figure 7: Conceptual results.

If we expand the central region of Figure 7 (see Figure 8) the arrows point to the apparent decrease (speed-up) in propagation time of the signal through the serpentine trace. The signal is not actually speeded up at all. It is the magnitude (level) of the signal that is increased by the addition of the leading and lagging crosstalk signal components that causes the effect of decreasing propagation time. We will see that the degree of apparent speed-up is related to the "tails" of the leading and lagging crosstalk signal components (inside the circle), which are in turn related to the coupling and to the rise time of the signal itself. Conceptually the situation is the same for shorter coupled regions, although that is a little more difficult to draw.

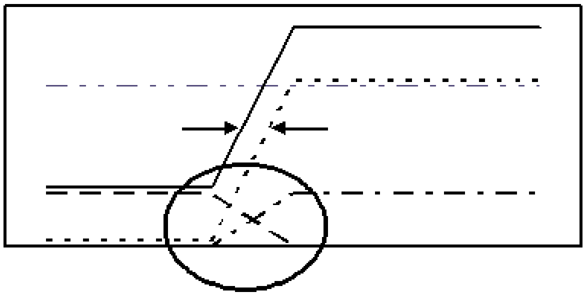


Figure 8: Close-up of the central section of Figure 7.

ESTIMATING THE DEGREE OF SPEED-UP

Conceptually, the degree of speed-up can be estimated with the help of Figure 9. This is the same as Figure 8 with different labels. The degree of speed-up is shown in the figure by the symbol t. The rise time is shown by Tr. The magnitude of the signal is V, and the magnitude of the backward crosstalk pulse is h. The ratio, h/V is simply the crosstalk coupling coefficient.

By similar right triangles we have the relationship that t/Tr is the same as h/V, the coupling coefficient. So, the speed-up, t, is found from:

$$t/Tr = h/V, \text{ or}$$
$$t = Tr * \text{coupling coefficient}$$

Therefore, stronger coupling and longer (slower) rise time lead to greater apparent speed-up of the signal.

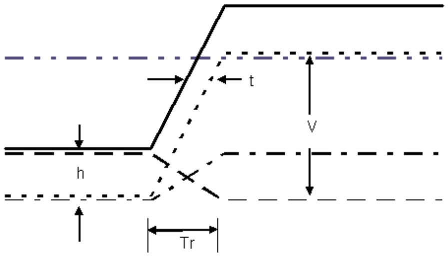


Figure 9: The degree of speed-up is related to the rise time and the coupling coefficient.

Just as we have printed circuit design guidelines for controlling crosstalk (by effectively controlling the crosstalk coupling coefficient), we can develop similar PCB design guidelines for controlling the percentage speed-up (t/Tr * 100) by controlling the crosstalk coupling coefficient.

MODELING THE EFFECTS

The Hyperlynx™ LineSim software is a powerful tool that allows us to model the effects of crosstalk when we have closely spaced serpentine traces. But more than modeling the result, Hyperlynx can also be used to model the individual (three) components that can exist when traces fold back on themselves. Looking at the three components individually can give us much better insight into what is happening.

Figures 10 and 11 show the basic form of the Hyperlynx models used in this paper. Figure 10 illustrates the model for looking at the individual crosstalk components. The individual components can be summed together to represent the model for the complete result. Figure 11 models the complete result directly.

Individual Models: Figure 10 is a model of the serpentine trace shown in Figure 1 that allows us to look at the three components (the leading crosstalk signal, the signal itself, and the trailing crosstalk signal) individually. This particular model shows the driver to be an ultra-fast CMOS driver with a very fast rise time. The driver signal immediately enters a length of (serpentine) trace that is coupled to (the return) trace. The two lengths of trace (the outgoing length and the serpentine return) are the same length, 3", and have, in the model, an impedance of 45.8 Ohms. The propagation time through each length is 527 ps.

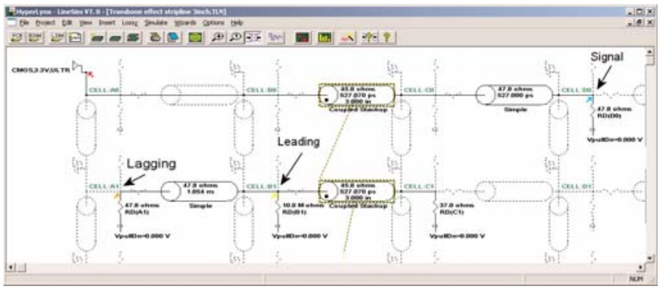


Figure 10: Modeling the individual components of the serpentine trace.

When the signal enters the coupled region, it immediately couples to the other side. The arrow labeled "Leading" shows where the leading crosstalk signal can be seen. At the point in time when the signal exits the coupled region, we have only seen the first half of the leading crosstalk signal (remember it has a pulse width twice the coupled region.) And the signal itself does not show up at the same point until it completes the return loop 527 ps later. Therefore, to get the signal component and the leading crosstalk component to line up correctly, we must delay the signal another 527 ps through an uncoupled line to a point labeled "Signal". Finally, since the trailing crosstalk signal looks exactly like the leading one, if we delay the leading one another 527 ps (1,054 ps total) we can have signals in the model lined up exactly as we want them. The point labeled "Lagging" in Figure 10 shows where we can see this in the model.

Combined model: Figure 11 illustrates the combined model for the same circuit. The signal simply passes down through one length of coupled trace and back through the other length of the same trace. We look at the result at the point where the arrow labeled "Model" points.

The difference between, and advantage of, these two different models of the same trace is that one gives us the single, complete result while the other allows us to look at the individual components making up the result. Each should lead to the same overall conclusion for any given set of assumptions.

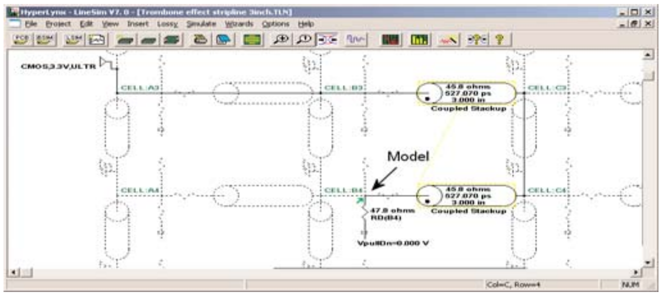

HyperLynx - LineSim V7.0 - [Trombone effect stripline 3inch.TLN]

Figure 11: Modeling the serpentine trace directly.

MODEL RESULTS

Influence of relative coupled length: The following sets of figures (Figures 12-14) illustrate the results of the model for three different assumed drivers, the generic "USERMOD" CMOS 3.3V drivers with three different rise times (speeds.) The coupled length (3") is the same for every case. The relative coupled length (compared to the critical length) changes in each case because the rise time changes in each case. The left panel (a) of each figure shows the driven signal as it enters the beginning of the serpentine trace and the three individual components (leading crosstalk signal, the signal itself, and the lagging crosstalk signal) at the other end of the trace. The right-hand panel shows the driven signal as it enters the beginning of the serpentine trace as well as the true signal at the end of the trace compared to what the signal would have looked like without any serpentine crosstalk. Figure 12 illustrates the case where the coupled length is much greater than the critical length (relatively fast rise time), Figure 13 illustrates the case where the coupled region is roughly equal to the critical length, and Figure 14 illustrates the case where the coupled region is much shorter than the critical length (relatively slow rise time).

For long coupled regions (compared to the critical length), the effect of the leading and lagging crosstalk pulses are very pronounced. The signal at the far end of the region shows a pronounced step before rising, and a pronounced overshoot before returning to its normal value. These effects become more gradual as the length of the coupled region decreases (relative to the rise time).

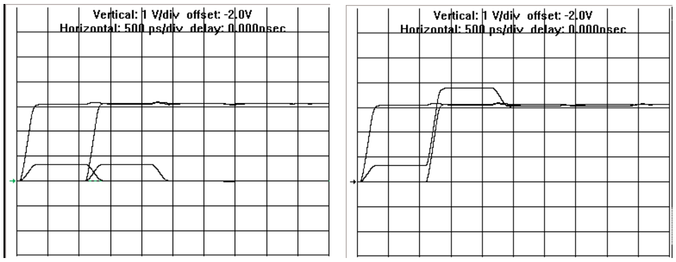


Figure 12a & 12b: Here the coupled region is much longer than the critical length. The rise time is about 160 ps and the apparent speed-up is about 40 ps.

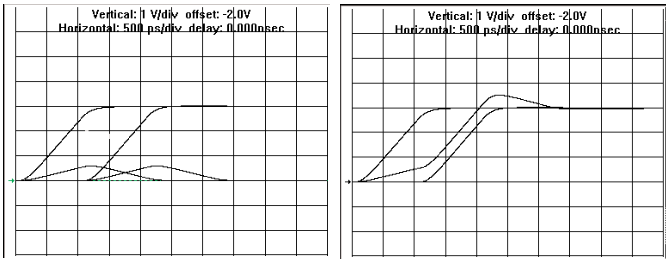


Figure 13a & 13b: Here the coupled region is approximately the same as the critical length. The rise time is about 900 ps and the apparent speed-up is about 210 ps.

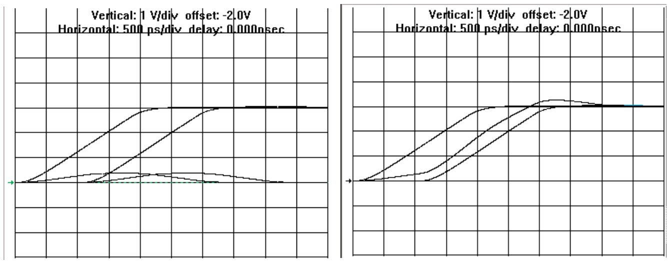
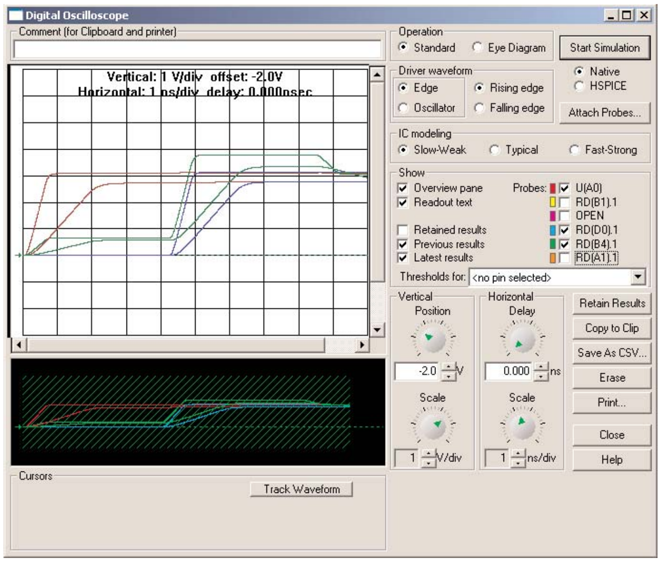


Figure 14a & 14b: Here the coupled region is much shorter than the critical length. The rise time is about 1.50 ns and the apparent speed-up is about 310 ps.

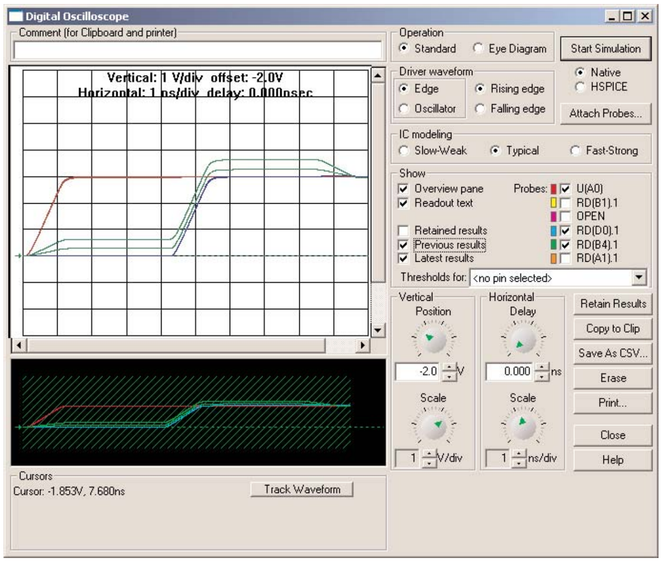
Determinants of apparent speed-up: For any given trace configuration, the degree of apparent speed-up is directly related to coupling and to rise time (as was described in Figure 9). Figures 15 and 16 illustrate these effects. They both reflect a relatively long trace length (longer than the critical region) in order to eliminate the effects that shorter traces may introduce.

For coupled lengths longer than the coupled region, the apparent speed-up of the signal does not change as coupled length changes. This is shown in Figure 17. Even though the coupled length has increased significantly, the apparent speed-up of the signal doesn't change at all. For traces shorter than the critical length, the apparent speed-up of the signal does appear to change with coupled length, but this is totally explained by the fact that the effective coupling is changing.



Operation: ● Standard ○ Eye Diagram
Driver waveform: ● Edge ○ Oscillator ● Rising edge ○ Falling edge ● Native ○ HSPICE
IC modeling: ● Slow-Weak ○ Typical ○ Fast-Strong
Show: ☑ Overview pane ☑ Readout text ☐ Retained results ☑ Previous results ☑ Latest results
Probes: ☑ U(A0) ☐ RD(B1).1 ☐ OPEN ☑ RD(D0).1 ☑ RD(B4).1 ☐ RD(A1).1
Thresholds for: <no pin selected>
Vertical Position: -2.0 V; Scale: 1 V/div
Horizontal Delay: 0.000 ns; Scale: 1 ns/div

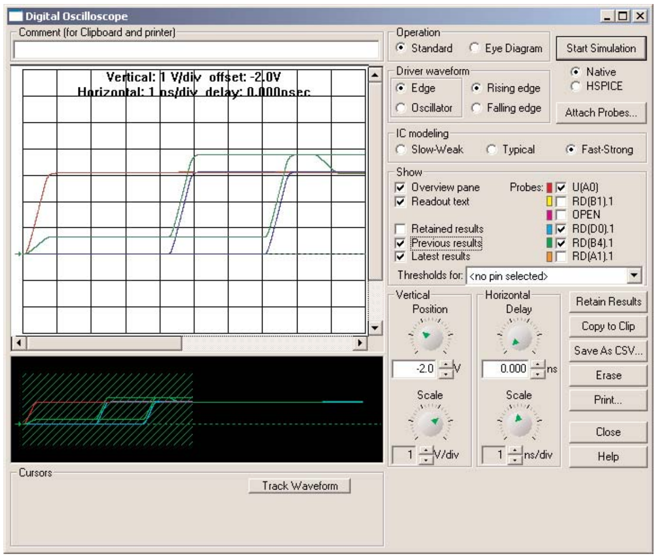
Figure 15: Influence of rise time on the apparent speed-up of the signal. Slower rise times, everything else equal, lead to a greater apparent speed-up of the signal.



Operation: ● Standard ○ Eye Diagram
Driver waveform: ● Edge ○ Oscillator ● Rising edge ○ Falling edge ● Native ○ HSPICE
IC modeling: ○ Slow-Weak ● Typical ○ Fast-Strong
Show: ☑ Overview pane ☑ Readout text ☐ Retained results ☑ Previous results ☑ Latest results
Probes: ☑ U(A0) ☐ RD(B1).1 ☐ OPEN ☑ RD(D0).1 ☑ RD(B4).1 ☐ RD(A1).1
Thresholds for: <no pin selected>
Vertical Position: -2.0 V; Scale: 1 V/div
Horizontal Delay: 0.000 ns; Scale: 1 ns/div
Cursor: -1.853V, 7.680ns

Figure 16: Influence of coupling on the apparent speed-up of the signal. Tighter coupling, all other things equal, leads to increased apparent speed-up of the signal and increased overshoot.

Influence of wave shape: It is interesting to see what happens as we send a more typical wave shape (a clock square wave, for example) through a serpentine trace. The following figures illustrate the results of the model for various combinations of signal rise time and frequency.



Digital Oscilloscope

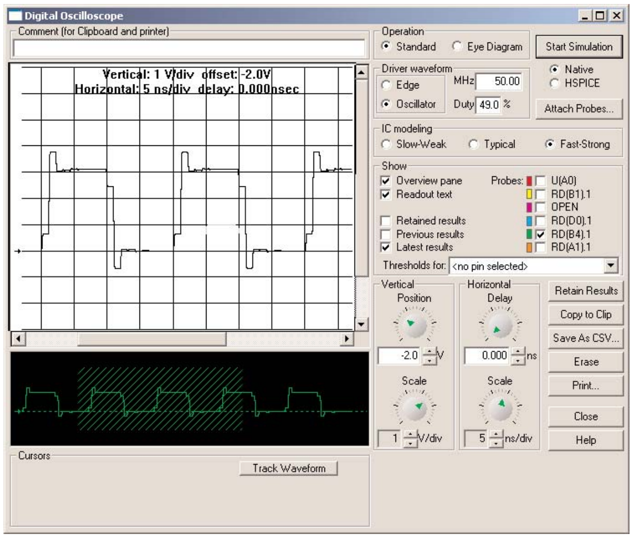
Comment (for Clipboard and printer)

Vertical: 1 V/div offset: -2.0V
Horizontal: 1 ns/div delay: 0.000nsec

Operation: ● Standard ○ Eye Diagram
Driver waveform: ● Edge ○ Oscillator ● Rising edge ○ Falling edge
● Native ○ HSPICE
IC modeling: ○ Slow-Weak ○ Typical ● Fast-Strong
Show: ☑ Overview pane ☑ Readout text ☐ Retained results ☑ Previous results ☑ Latest results
Probes: ☑ U(A0) ☐ RD(B1).1 ☐ OPEN ☑ RD(D0).1 ☑ RD(B4).1 ☐ RD(A1).1
Thresholds for: <no pin selected>
Vertical Position: -2.0 V
Horizontal Delay: 0.000 ns
Scale: 1 V/div
Scale: 1 ns/div

Figure 17: Changing the coupled length has no effect on the apparent speed-up of the signal.

Figure 18 illustrates the very fast rise time signal through the 3" coupled region with a relatively slow frequency (50 MHz). In this context, the coupled region is long. If the frequency of the square wave is 50 MHz, the distortion is probably not too great (which is, of course, a decision for the circuit design engineer to make). On the other hand, at higher frequencies the distortion can be quite complex, depending on the interaction of the rising and falling edges of the signal through the coupled region. For example, Figure 19 illustrates what happens to the signal for the three relatively closely spaced frequencies of 500, 700 and 900 MHz, respectively. The serpentine trace becomes almost tuned to specific frequencies. This is one of the very few instances in the area of signal integrity where the issue is truly frequency, not rise time!



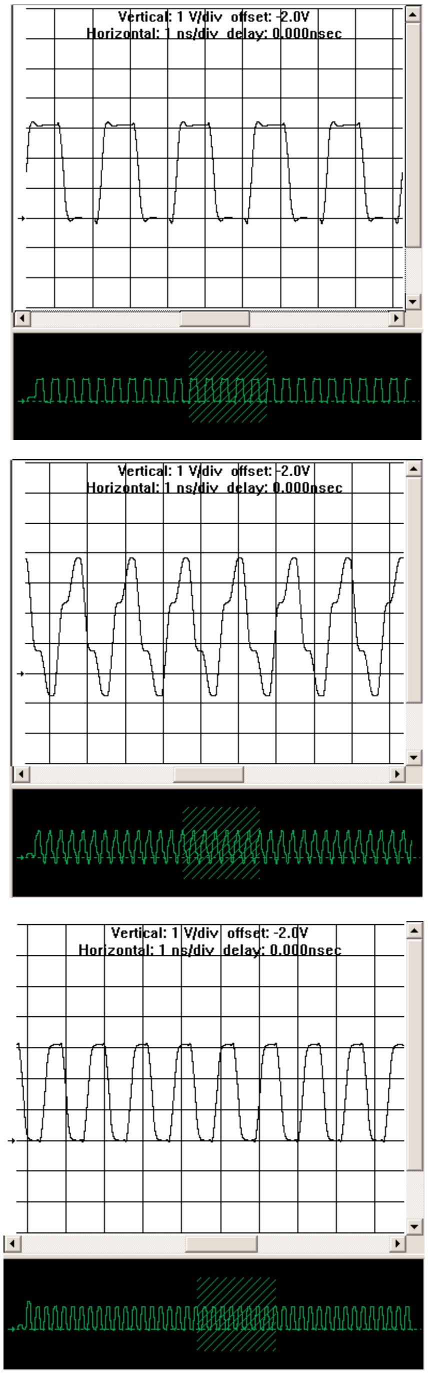
Digital Oscilloscope

Comment (for Clipboard and printer)

Vertical: 1 V/div offset: -2.0V
Horizontal: 5 ns/div delay: 0.000nsec

Operation: ● Standard ○ Eye Diagram
Driver waveform: ○ Edge ● Oscillator MHz 50.00 Duty 49.0 %
● Native ○ HSPICE
IC modeling: ○ Slow-Weak ○ Typical ● Fast-Strong
Show: ☑ Overview pane ☑ Readout text ☐ Retained results ☐ Previous results ☑ Latest results
Probes: ☐ U(A0) ☐ RD(B1).1 ☐ OPEN ☐ RD(D0).1 ☑ RD(B4).1 ☐ RD(A1).1
Thresholds for: <no pin selected>
Vertical Position: -2.0 V
Horizontal Delay: 0.000 ns
Scale: 1 V/div
Scale: 5 ns/div

Figure 18: Distortion of a 50 MHz signal through a long serpentine region



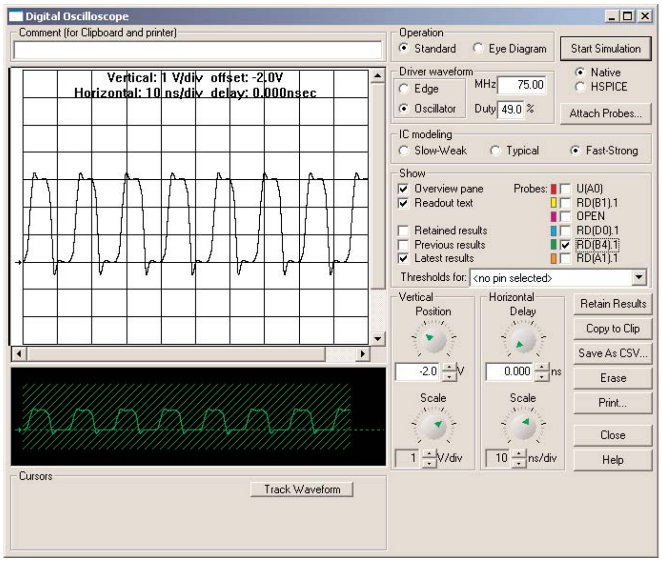
Vertical: 1 V/div offset: -2.0V
Horizontal: 1 ns/div delay: 0.000nsec

Vertical: 1 V/div offset: -2.0V
Horizontal: 1 ns/div delay: 0.000nsec

Vertical: 1 V/div offset: -2.0V
Horizontal: 1 ns/div delay: 0.000nsec

Figure 19a & 19b & 19c: Waveform distortion through a coupled serpentine section depends dramatically on frequency

For short coupled regions (shorter than the critical length), a square wave waveform passes through without too much distortion. Figure 20 illustrates the result of a simulation with a 75 MHz square wave through the 3" serpentine section driven with a relatively slow rise time driver (about 1.5 ns). The distortion around the rising and falling edge is not too severe.



Vertical: 1 V/div offset: -2.0V
Horizontal: 10 ns/div delay: 0.000nsec

Operation: ● Standard ○ Eye Diagram

Driver waveform: ○ Edge ● Oscillator; MHz 75.00; Duty 49.0 %

● Native ○ HSPICE

IC modeling: ○ Slow-Weak ○ Typical ● Fast-Strong

Show:
☑ Overview pane
☑ Readout text
☐ Retained results
☐ Previous results
☑ Latest results

Probes:
🟥 ☐ U(A0)
🟨 ☐ RD(B1).1
🟪 ☐ OPEN
🟦 ☐ RD(D0).1
🟩 ☑ RD(B4).1
🟧 ☐ RD(A1).1

Thresholds for: <no pin selected>

Vertical: Position -2.0 V; Scale 1 V/div

Horizontal: Delay 0.000 ns; Scale 10 ns/div

Figure 20: Waveforms through serpentine sections whose length is shorter than the critical length pass relatively undistorted.

SUMMARY

When a signal passes through a serpentine trace with coupling between the legs, there is an apparent speed-up of the signal. That is, the signal appears to pass through the serpentine section faster than the trace length would otherwise indicate. This apparent speed-up is caused by crosstalk coupling between the legs of the serpentine traces. The amount of apparent speed-up is directly related to the coupling strength between the legs and to the rise time of the signal passing through the section. The apparent speed-up of the signal is not directly related to the coupled length.

For long coupled lengths (those longer than the critical length) signals may become distorted as they pass through the serpentine section, but the degree of distortion is a complex function of the frequency of the signal. Signals pass relatively undistorted through short coupled serpentine sections.

FOOTNOTES

1. Brooks, Douglas; Adjusting Signal Timing (Part 1), available at http://www.mentor.com/pcb/techpapers/
2. Howard Johnson: *"Serpentine Delays"*, EDN Magazine, February 2001
3. See Brooks, Douglas; *"Crosstalk, Part 1 - Understanding Forward vs. Backward"*, available at http://www.mentor.com/pcb/techpapers/. Also see Brooks, Douglas, Signal Integrity Issues and Printed Circuit Board Design, Prentice Hall, 2003, Chapter 12.
4. Ibid.
5. Brooks, Douglas; *"Propagation Times and Critical Length; How They Interrelate,"* available at http://www.mentor.com/pcb/techpapers/. See also Brooks, Douglas, Signal Integrity Issues and Printed Circuit Board Design, Prentice Hall, 2003, Chapter 10.
6. Johnson, Howard; <u>High Speed Digital Design, A Handbook of Black Magic</u>, Prentice Hall, 1993, p. 191. See also Brooks, Douglas, Signal Integrity Issues and Printed Circuit Board Design, Prentice Hall, 2003, p. 227.

ABOUT THE AUTHOR

Douglas Brooks has a BS and an MS in Electrical Engineering from Stanford University and a PhD from the University of Washington. During his career has held positions in engineering, marketing, and general management with such companies as Hughes Aircraft, Texas Instruments and ELDEC.

Brooks has owned his own manufacturing company and he formed UltraCAD Design Inc. in 1992. UltraCAD is a service bureau in Bellevue, WA, that specializes in large, complex, high density, high speed designs, primarily in the video and data processing industries. Brooks has written numerous articles through the years, including articles and a column for Printed Circuit Design magazine, and has been a frequent seminar leader at PCB Design Conferences. His primary objective in his speaking and writing has been to make complex issues easily understandable to those without a technical background. You can visit his web page at http://www.ultracad.com and e-mail him at doug@eskimo.com.

For more information, call us or visit: **www.mentor.com/pcb**

Corporate Headquarters
Mentor Graphics Corporation
8005 S.W. Boeckman Road
Wilsonville, Oregon 97070 USA
Phone: 503-685-7000

Silicon Valley Headquarters
Mentor Graphics Corporation
1001 Ridder Park Drive
San Jose, California 95131 USA
Phone: 408-436-1500
Fax: 408-436-1501

Europe Headquarters
Mentor Graphics Corporation
Deutschland GmbH
Arnulfstrasse 201
80634 Munich
Germany
Phone: +49.89.57096.0
Fax: +49.89.57096.40

Pacific Rim Headquarters
Mentor Graphics (Taiwan)
Room 1603, 16F,
International Trade Building
No. 333, Section 1, Keelung Road
Taipei, Taiwan, ROC
Phone: 886-2-27576020
Fax: 886-2-27576027

Japan Headquarters
Mentor Graphics Japan Co., Ltd.
Gotenyama Hills
7-35, Kita-Shinagawa 4-chome
Shinagawa-Ku, Tokyo 140
Japan
Phone: 81-3-5488-3030
Fax: 81-3-5488-3031

Printed on Recycled Paper

01-04-JC TECH6170-w