BROOKSPEAK

Crosstalk, Part 1:
The Conversation We Wish Would Stop!

By Douglas Brooks, President
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Let's talk about crosstalk again, something that is not well understood by many designers. Consider the trace, A-B shown in **Figure 1**. We call that a 'driven' line. Let's assume that a pulse is traveling down that line from A to B and is now at the point defined by the 'X'. There is a nearby trace, C-D, which we will call the 'victim' trace. A signal may couple between the driven and victim traces at the point 'X'.
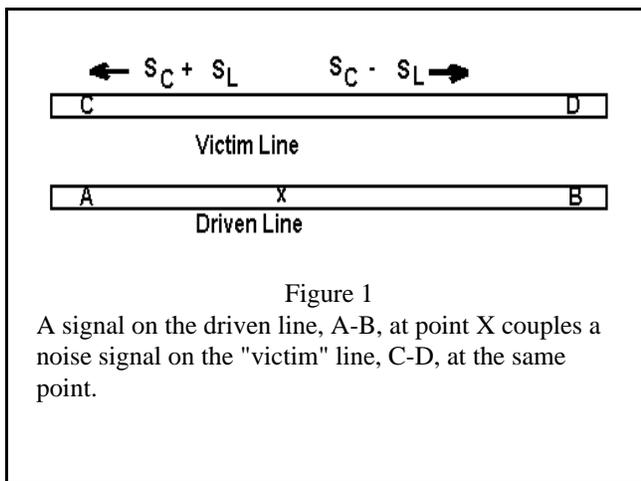

Figure 1
A signal on the driven line, A-B, at point X couples a noise signal on the "victim" line, C-D, at the same point.

Now let's think about what is intuitive. There is likely some capacitive coupling between the two traces. It may be small, but there is likely to be some. Since parallel traces sort of look like a transformer, there is probably some inductive coupling between the traces, also. In most PCB applications, however, the material between the traces is probably a very good insulator, so there is probably no (purely) resistive coupling between the traces. Since capacitive and inductive effects reduce with distance, any coupling probably reduces as the separation between the traces increases. This leads to:

General Rule #1: If we are concerned about crosstalk, greater separation between traces is better.

If a signal along trace A-B is going to couple noise into trace C-D, we must be looking at an AC phenomenon. That is, a steady state DC signal on one trace will not couple into the other one. But if an AC signal will, then, intuitively, the coupling will be greater (or more efficient) the higher the frequency (or frequency components of the harmonics of the underlying signal.) More about the specific effects of frequency (and rise time) next month. But this observation leads to:

General Rule #2: If we are concerned about crosstalk, lower frequency harmonics and slower rise times are better.

The effects of coupling can be summarized as follows:

Mutual Capacitive Coupling--a signal, S_C, caused by capacitive coupling between the two traces, which travels along the victim trace in both the forward and backward direction with the same polarity.

Mutual Inductive Coupling--a signal, S_L, caused by inductive coupling between the two traces, which travels along the victim trace in both the forward and backward direction with opposite polarity.

Directionality--Crosstalk goes in both the forward and backward direction. Mutual capacitive and inductive *forward* crosstalk are approximately equal and opposite and tend to cancel. They are approximately equal and reinforcing in the *reverse* direction, and therefore tend to be additive.

Magnitude--Forward crosstalk tends to look like the driven signal, and (at least in theory) continues to grow larger the longer is the coupled length A-B (and C-D). Reverse crosstalk tends to have a rectangular shape (in response to a step function) that reaches a maximum and then does not increase further regardless of coupled length.

Environment--If the two traces are contained within a homogeneous material (as they are in a stripline environment), the inductive and capacitive *forward* crosstalk components are almost exactly equal and cancel. Therefore, we generally don't worry about forward crosstalk in stripline environments. If the surrounding material is NOT homogeneous (as it is not in a microstrip environment), the inductive component tends to be larger than the capacitive component.

General Rule #3: Therefore, if we are concerned about crosstalk, keep the sensitive traces in stripline environments. (Thus ends the discussion on forward crosstalk!)

Figure 2 helps us understand why the reverse crosstalk waveform tends to be longer than the driven pulse. Consider a simple signal as it travels down a trace. We will take a "snapshot" of it at seven points in time, labeled t=0 through t=6. In order to simplify the analysis, we will assume the signal is a pulse with zero width, even though in Figure 2 it is shown with a finite width.

At time t=0 the pulse just starts down the trace. The reverse crosstalk signal in the victim line reflects off C with a negative reflection coefficient (Footnote 1) and begins traveling down the victim line towards D. At time t=1 the driven pulse causes a coupled signal in C-D to travel in the reverse direction towards C, while the coupled pulse from time t=0 has traveled to position t=1.

Skipping to time t=4, the driven signal couples into C-D at position t=4, but the pulses coupled at times t=3 and t=2 are moving backwards (reverse direction) towards C. Pulses at times t=0 and t=1 have reflected off the end at C and are now moving with a negative polarity towards D. In this manner it can be seen that the driven signal creates a coupled signal in the victim line that (1) travels in a reverse direction (towards C) until it reflects off C and then travels the length of the line towards D.

Now, instead of thinking about snapshots in time, consider the signal in real time as it travels from A to B. The "front edge" of the signal at each increment of its travel will couple a noise signal in C-D that will travel towards C, reflect off C, and travel towards D. The coupled signal will have a magnitude (to be discussed next week) and a width equal to the propagation time from D to C and then back to D (twice the propagation time of the coupled length.)

The above analysis assumes that the reverse coupled signal travels towards C and then reflects towards D. But what if the end at C is terminated in the characteristic impedance of the trace? In that case it is tempting to say that there would be no reflection of the reverse crosstalk waveform. Then, if points B and D were also terminated in their characteristic impedance, there would be no reflections at that end, either. Does this mean that we wouldn't have to be concerned about reverse crosstalk. And, further, if we are in a stripline environment so that we don't have to worry about forward crosstalk, would this mean that the entire crosstalk problem would go away? Never say "never", but next month we will talk about how to calculate crosstalk, taking terminations into account.
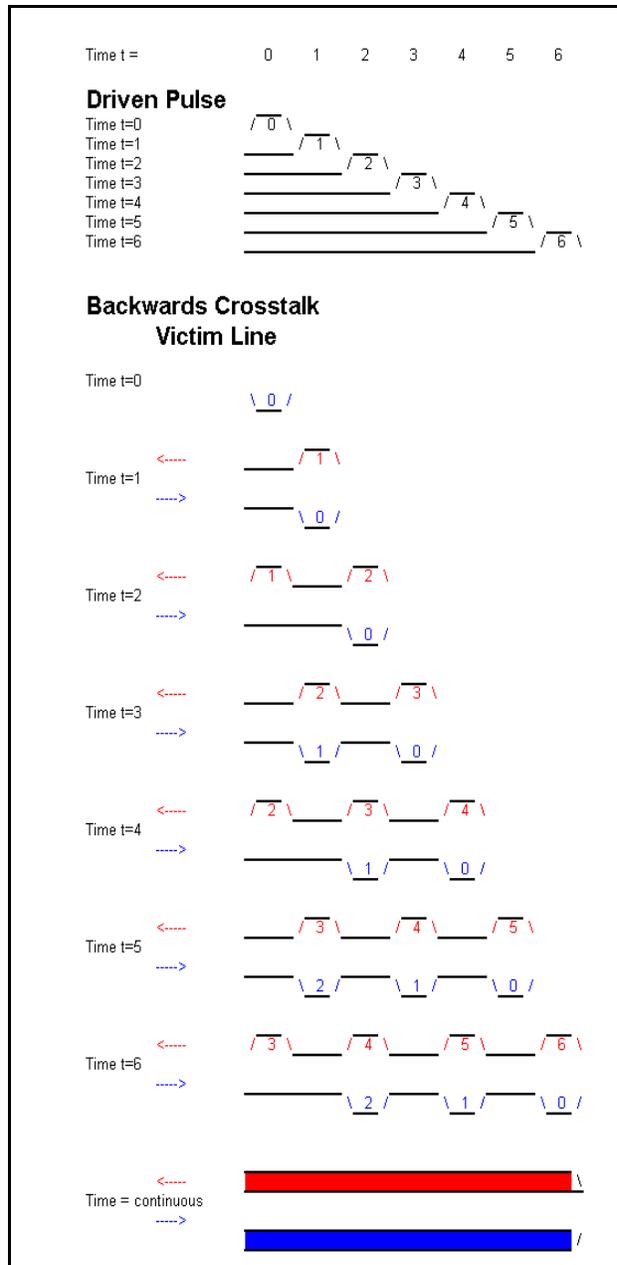

Figure 2:
Backwards crosstalk as the driven signal propagates down the trace.

Footnote 1. Remember that the reflection coefficient is (Rs-Zo)/(Rs+Zo) where Rs is the source resistance at C and Zo is the characteristic impedance of the trace. Since Rs is normally much less than Zo, the reflection coefficient can approach -1.

BROOKSPEAK

Crosstalk, Part 2:
How Loud Is Your Crosstalk?

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Last month's column focused on what crosstalk is and attempted to provide an intuitive understanding of the principles involved. It also concluded that forward crosstalk is usually not a problem in stripline environments. This month I will provide a means of (approximately) quantifying backwards crosstalk.

Estimating crosstalk can be difficult. The approach shown in this column depends on several simplifying assumptions, and will lead to results that are close, but not necessarily precise. The reader would be wise to *calibrate* this technique by applying it to boards that have been designed in the past and are known to be either "good" or "bad" with respect to crosstalk performance. That will provide insight into how future boards will perform, based on the results of these calculations.

Three concepts are involved in the measurement approach:

1. Electromagnetic coupling between two traces.
2. The parallel distance over which that coupling occurs.
3. The effectiveness of any terminations, if they exist.

Electromagnetic coupling:

Howard Johnson shows in his book "High Speed Digital Design: A Handbook of Black Magic" (page 192) that the crosstalk coupling coefficient in parallel traces is proportional to, and does not exceed, **Equation 1a** (see **Figure 1**.) Equation 1a is re-expressed in **Equation 1b**. It is clear from Equation 1b what we already intuitively know: to minimize crosstalk, you minimize H and maximize D.

If the parallel traces are at different heights, the H^2 term really becomes the product of the two heights, as shown in **Figure 2** and **Equation 2**. D becomes the direct distance between the centerline of the traces.

Finally, if the traces are between two planes, as shown in **Figure 3**, find *each* H by using a parallel combination of the heights to each plane, as shown in **Equation 3**.
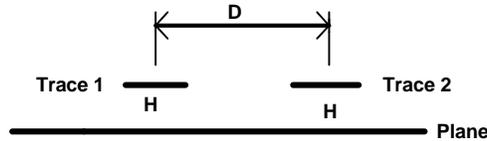

Figure 1
Typical crosstalk configuration

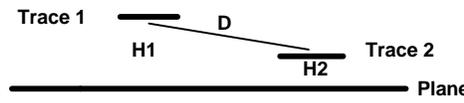$$\frac{1}{1+(D/H)^2}$$

Eq. 1a

$$\frac{H^2}{H^2+D^2}$$

Eq. 1b

Figure 2
Trace heights are different

$$\frac{1}{1+\left(D^2/H1*H2\right)}$$
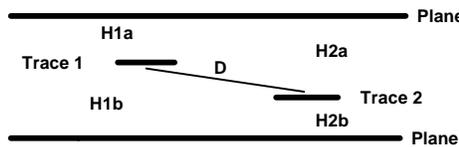
Eq. 2

Figure 3
Use parallel combination to calculate H in stripline environments

$$\frac{Hna*Hnb}{Hna+Hnb}$$

Eq. 3

Coupling Distance:

Backwards crosstalk starts out small and increases as the length of parallel coupling increases --- to a point. It reaches a maximum magnitude and then stays constant at the so-called "critical length"; the length where the round trip propagation time (T_{RT}) equals the rise time (T_R) of the driving signal. So for short traces ($T_{RT}/T_R =< 1$) crosstalk is proportional to the *ratio* of T_{RT}/T_R. We calculate T_{RT} with **Equation 4**. For long traces, ($T_{RT}/T_R > 1$) calculate crosstalk independent of length.

$$T_{RT} = 1.017\sqrt{a\varepsilon_r + b} \ * \ \text{Parallel Length} \ * \ 2$$

Where:
ε_r = Relative dielectric coefficient
$a = 1$, $b = 0$ for Stripline
$a = .475$, $b = .67$ for Microstrip

Equation 4
Use this equation to calculate T_{RT}

Terminations:

If the coupled trace is *perfectly* terminated at the near end with the characteristic impedance of the trace (Zo), there will be no reflection at the near end and no backwards crosstalk reflecting back down the line. Correspondingly, if the driven trace is *perfectly* terminated at the far end, there will be no reflection at the far end that will induce crosstalk in the victim trace. Thus, if there are terminations at both ends of the traces, crosstalk will be reduced, and will be proportional to the reflection coefficient (measured at the end with the worst mismatch):

$$r = \frac{(R_L - Z_0)}{(R_L + Z_0)}$$

Assume, for example, the tolerance for Zo is 10% and the tolerance for R_L is 3%. The worst case reflection coefficient, then, would be:

$$r = \frac{(.97 - 1.1)}{(1.1 + .97)} = .063$$

Here is a simplifying trick. For small tolerances like this, the worst case reflection coefficient can be *approximated* with [Tol(Zo) + Tol(RL)]/2. Using the illustration above, this would become
[10 + 3]/2 =.065

Result:

The final result, now, is that the backwards crosstalk coupling coefficient can be approximated as:

$$\frac{1}{1 + (D/H)2}(T_{RT}/T_R)\frac{Tol(Zo) + Tol(R_L)}{2}$$

Where the T_{RT}/T_R term cannot exceed 1.0, and the final term applies *only* if there are terminations at both ends of the traces.

People sometimes like to express coupling in decibels (db's). To convert this coupling coefficient to db's, take the common log (log to base 10) of the coupling coefficient and multiply it by 20.

Example:

As a final example, suppose we have the configuration shown in **Figure 4**. Let εr be 4.5, the rise time of the coupled pulse be 1 nsec, the parallel length be 10 in. and no terminations. The calculated coupling coefficient would be .05195 (-26 db).
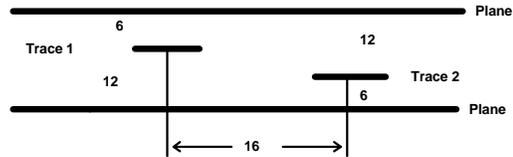

Figure 4
Example

Calculator:

UltraCAD has written a Windows software calculator for calculating the crosstalk coefficient. It is distributed as freeware and can be downloaded from our web site (www.ultracad.com --- follow the link to technical papers). Download the file ultra_ct.zip, and unzip it in its own directory.
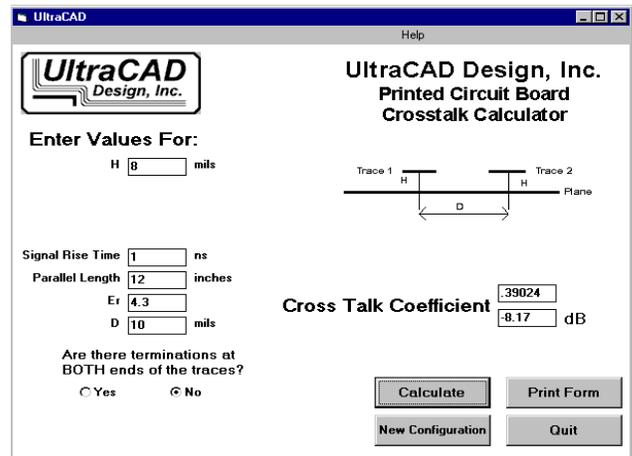

Figure 5
UltraCAD's Crosstalk Calculator