Signal Integrity in Digital Circuits

Lesson 1: Crosstalk

Goal

The exchange of information in an electronic system can be compromised by signal degradation and by disturbances generated either outside or inside the systems itself. The signal integrity addresses these problems: it enables the designer to guarantee correct signaling within a system, taking into account the physical laws of electrical signal propagation, and in spite of disturbance and noise originated within the system itself.

Current high-speed digital systems require designers able to think not only in terms of “0” and “1” (standard Boolean algebra), but also in terms of current, mutual inductance, transmission lines, parasitic parameters. Signal integrity involves skills from digital and analog electronics, and electromagnetic wave propagation theory and practice. An understanding of these problems is now mandatory for any digital system designer.

After this course you will know what “Signal Integrity” means and how to deal with these problems in high speed digital systems, by using proper design techniques, by proper selection of the logic family, and applying some PCB layout design rules.

Content and organization

The Signal Integrity in Digital Circuits course is structured in 5 lessons:

Crosstalk
Capacitive and inductive coupling, Crosstalk Model, Forward and Backward crosstalk.

Design Guide to reduce Crosstalk.
Effects of PCB layout. Signal and ground routing. Filtering

Ground bounce and switching noise
Ground Bounce, simultaneous switching noise, totem-pole current spike.

Design guide for Ground and Power planes.
Decoupling Capacitors, PCB layers stacking. Ground and power distribution. Clock distribution

Measurements
Laboratory experience to show and measure signal integrity effects in digital systems.

Prerequisites

To follow these lessons you must already know
- circuit theory: R-C cells, transient response,
- loss-less transmission lines.
- structure of digital logic circuits, static parameters
- dynamic interfacing of digital circuits
- function and use of basic electronic instruments (pulse generator, oscilloscope).
References

A reference textbook with both general and detailed discussion of signal integrity problems is:

H.W. Johnson, M.Graham:  
High Speed Digital Design (A Handbook of Black Magic),  

The same author has a web site, with several articles and pointers:

http://www.signalintegrity.com/ftrecord.htm

Other more specific references are provided in each lesson.

Other textbooks with general references on this subject are:

M.I. Montrose:  
PCB Design Techniques for EMC Compliance,  

Henry W. Ott  
Noise Reduction Techniques in Electronic Systems  
John Wiley&Sons, 1988

James E. Buchanan  
Signal and Power Integrity in Digital Systems: TTL, CMOS and BiCMOS  
McGraw-Hill, 1996

For this lesson, the related sections in the reference book are: 3.9 and 5.7.

Acknowledgements

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Summary

Conductors running side-by-side (e.g., bus tracks) exhibit capacitive and inductive coupling. Due to these coupling, a signal driven on one line can induce noise on the other ones; this behavior is called crosstalk.

The first lesson answers to the following questions:

- What does "signal integrity" mean?
- Which are typical signal integrity problems
- Which are the effects of mutual coupling among PCB conductors?
- How can mutual coupling cause false signaling?

Examples of signal integrity problems

1) In a bundle of wires only some of them are active (that is carry logic transitions), but signals appear also on not-active conductors. This is a crosstalk problem, and can be handled by proper selection of driving devices and wiring layout.

![Fig 1.1 Crosstalk from capacitive and inductive coupling.](image1.png)

2) A pulse is applied to one input of a buffer; the other inputs of the same package are fixed at High or Low levels. The voltage at the outputs corresponding to steady inputs change state when other devices in the same package switch. This can be caused by ground bounce noise – a common-path crosstalk problem – and can be avoided by proper layout and decoupling of the power supply.

![Fig 1.2 Crosstalk caused by ground bounce.](image2.png)
Simplified Model for Crosstalk Analysis

The reference model for a first approximation analysis of crosstalk consists of two wires (or PCB tracks) running close each other, as in figure 1.3.

![Fig. 1.3 Two coupled tracks.](image)

For this analysis the wires are modeled as two transmission lines with characteristic impedance $Z_0$ and both capacitive ($C_M$) and inductive ($L_M$) coupling. To avoid multiple reflections, both lines have matched terminations $R_T = Z_0$. (figure 1.4).

![Fig. 1.4 Transmission line model for crosstalk analysis.](image)

The driven line (or active line, always drawn in the upper part of the diagram) carries a signal moving at speed $U$. This signal is a voltage step with rise time $t_r$ and slope $dv/dt = \Delta V/t_r$. (Figure 1.5).

![Fig. 1.5 Disturbing signal.](image)
The effects of capacitive coupling can be evaluated with the model shown in figure 1.6. The equivalent circuit includes a voltage generator $V_m$, the coupling capacitance $C_m$, and the impedance $Z_0/2$, which models the resting (or passive) line.

![Fig 1.6 Model for capacitive crosstalk](image)

If the voltage change $V_{SC}$ on the passive line is small, the whole step $V_S$ appears through the capacitor $C_m$. A current $I_{CM} = C_m \frac{\partial V}{\partial t}$ flows from the capacitor to the load $Z_0/2$. This rectangular current pulse generates a voltage pulse with the same duration $t_r$ and amplitude $V_{SC} = I_{CM} Z_0/2$. In summary:

$$V_{SC} = I_{CM} \frac{Z_0}{2} = C_m \frac{\partial V}{\partial t} \frac{Z_0}{2} = C_m \frac{\Delta V}{t_r} \frac{Z_0}{2}$$

This pulse propagates on the passive line towards the two ends of the passive line, thus making the Backward Capacitive (BC) and Forward Capacitive (FC) terms of crosstalk (figure 1.7).

![Fig 1.7 Forward and backward propagation of the capacitive term](image)

The inductive coupling causes on the passive line a voltage proportional to the concatenated magnetic flow change, and therefore again to $\frac{\partial V}{\partial t}$. The induced voltage is $V_{SL} = L_m \frac{\partial I}{\partial t}$.

![Fig 1.8 Model for inductive crosstalk](image)
Also this voltage propagates on the passive line towards the two ends with opposite polarity in the two directions: Backward Inductive ($B_L$) and Forward Inductive ($F_L$) terms of crosstalk (figure 1.8). In this case, since the induced disturbance can be modeled by a voltage generator serially connected along the passive line, the backward and forward pulses have opposite polarity.

![Diagram of Forward and Backward Inductive Crosstalk](image)

**Forward and backward crosstalk**

In summary, the disturbing signal propagating on the active line puts on the passive line four noise signals or crosstalk terms, all with amplitude proportional to $dv/dt$ and duration $t_r$:

1. crosstalk caused by coupling through $C_M$, which propagates towards the termination (right side): Forward Capacitive crosstalk $F_C$;
2. crosstalk caused by coupling through $C_M$, which propagates towards the driver (left side): Backward Capacitive crosstalk $B_C$;
3. crosstalk caused by coupling through $L_M$, which propagates towards the termination (right side): Forward Inductive crosstalk $F_L$.
4. Crosstalk caused by coupling through $L_M$, which propagates towards the driver (left side): Backward Inductive crosstalk $B_L$.

The total crosstalk moving towards the right end (far end, termination), in the same direction of the disturbing signal is the forward crosstalk $F_T = F_C + F_L$. Forward crosstalk is the sum of terms 1 and 3 above; since they have the same polarity, if $dv/dt > 0$ (for the disturbing signal), the forward crosstalk is always positive.

The total crosstalk moving towards the left end (near end, driver), in the opposite direction of the disturbing signal is the backward crosstalk $B_T = B_C + B_L$. Backward crosstalk is the sum of terms 2 and 4 above; since they have opposite polarity; the actual polarity of backward crosstalk depends on prevalence of capacitive (2) or inductive (4) term.

The above mentioned disturbance are generated on each elementary section of line: the actual voltage $v(x,t)$ at any point of the line is the sum of all these contributions. The disturbing pulse moves towards the far end with speed $U$, and the forward term moves in the same direction at the same speed. At any point along the line all the forward terms previously generated arrive at the same time, and sum up to make a single pulse of width $t_r$ and increasing amplitude as it moves along the line towards the far end. The forward term at different points along the line is visualized in figure 1.10. These are the signals which can be observed on a scope connected to the resting line, when an edge travels along the disturbing line.
Backward terms sum in the time domain and make a pulse with fixed amplitude and width related to position along the line.

When the disturbing edge reaches the far end at $t = t_p$, it is absorbed by the matched termination, and the corresponding noise generators turn off. The forward term ends immediately; the various points along the line return to the resting voltage as the "turn off" propagates backwards towards the driver.

Fig 1.11 Backward term of crosstalk.
Examples

The following drawings are taken from an algorithmic simulator, which separates the waveforms of forward and backward crosstalk components for different capacitive and inductive coupling. This split is not possible in a real systems, where the voltage in any point of the line is the sum of forward and backward waves. The three diagrams are snapshots of the voltage on the disturbing line (upper diagram), and of forward and backward terms on the resting line (respectively second and third diagram from the top). Note that these diagrams represent $v(x)$ at a given $t$; they are not $v(t)$ diagrams taken at given points on the line, like the scope diagrams in figure 1.10 and 1.11. The waveforms are idealized (rectangular pulses); in real systems edges are rounded, and rise/fall times of crosstalk signals are not zero.

The first diagram (Fig 1.12) shows the crosstalk voltages at $t = t_p/3$, for a given combination of $dV/dt$ (rise time $t_r$ of the disturbing edge), $C_M$, and $L_M$ (the values of these parameters shown in the box at the bottom right corner are only for comparison of different situations).

![Fig 1.12 Crosstalk noise at $t = t_p/3$.](image)

Figure 1.13 shows the same waveforms for the same system at a later time $t = 2 \cdot t_P/3$. The forward term amplitude increases (due to summation of contributions along the line), but the duration is still $t_r$, while the backward term keeps the same amplitude but longer duration.

![Fig 1.13 Crosstalk noise at $t = 2 \cdot t_P/3$.](image)
In the third diagram (Fig. 1.14), the ratio among capacitive and inductive coupling is inverted: the capacitive term overcomes the inductive one, and the polarity of resulting forward term is reversed.

![Diagram showing capacitive and inductive coupling](image)

Fig 1.14. Crosstalk noise at $t = t_p/3$, with higher capacitive coupling.

The effects of edge slope are shown in figure 1.15. All parameters are the same in both cases, the only difference being the slope of the disturbing signal rising edge. Since crosstalk amplitude is proportional to the slew rate, the steep edge causes a higher noise. The disturbance lasts for the duration of the edge, and is close to 0 when the active line does not change state.

![Graphs showing steep and slow edges](image)

Fig. 1.15 Crosstalk pulses for steep and slow edges.
Near-end and Far-end crosstalk

The actual crosstalk signals in a real system are the sum of all contributions (inductive, capacitive, forward and backward terms). Due to different propagation directions, the waveforms depend from the observation point: a scope connected to different points shows different wave shapes. Summarizing the previous analysis:

At the near end all terms start for \( t = 0 \); the backward term ends when the disturbing pulse reaches the far end, and the induced noise generator is turned off (at \( t = t_\text{p} \)). This information (or the negative edge caused by turning off the disturbing pulse at the far end) needs another \( t_\text{p} \) to reach the near end, therefore the total duration of crosstalk noise at the near end is \( 2 \ t_\text{p} \) (track A in figure 1.16).

The disturbing pulse (and induced noise) reaches the far end at \( t = 2 \ t_\text{p} \) (nothing can be seen before). The forward term (narrow pulse with width \( t_\text{r} \)) is the sum of all contribution along the line; the backward term ends almost immediately, as the disturbing pulse reaches the far end at the same time end at \( t = 2 \ t_\text{p} \). Therefore the far-end crosstalk is a narrow pulse, occurring at \( t = 2 \ t_\text{p} \), with sign and amplitude related with the actual \( L_{\text{M}} \) and \( C_{\text{M}} \) values (track C in figure 1.15). At intermediate position (track B in figure 1.16) we can observe the forward term (narrow pulse, variable height), followed by the backward term (rather flat pulse, width depending on the position).

Fig. 1.16  Measurement of total crosstalk.
Review questions

1) A processing system suffers intermittent failures; the error rate changes (but never goes to 0) when the power supply voltage changes of a few %, some IC are replaced, or interface boards are moved to other slots. The correct countermeasure is:

- rewrite the program in another language,
- analyze the OS interfaces,
- revise the electrical design, focusing on dynamic interfacing and signal integrity aspects,
- put a voltage regulator on the power supply.

These symptoms reveal random errors, which cannot depend from the SW (repeating the operations with the same data should give identical results), nor from the power supply. Too narrow electrical interfacing margins make the system sensitive to noise and disturbance, which cause small changes in signal levels and power supply voltage.

2) The term which best describe the problem addressed by signal integrity is

- static compatibility of logic circuits
- power consumption of logic circuits
- *dynamic behavior of logic signals and circuits
- correctness of Boolean operations performed by logic gates

Static compatibility is also a condition to fulfill, but the correctness of dynamic behavior requires also static compatibility.

3) The amplitude of crosstalk noise is

- proportional to the slew rate (dV/dT) of the disturbing signal
- inversely proportional to the slew rate (dV/dT) of the disturbing signal
- not affected by the slew rate of the disturbing signal
- proportional to the duration of the disturbing signal

The crosstalk is directly proportional to mutual coupling (capacitive and inductive) and on slew rate of signals. Steep edge, with fast slew rate push more noise through capacitive and inductive coupling.

4) The backward crosstalk noise term at the near end has:

- fixed amplitude, duration $t_f$
- fixed amplitude, duration proportional to line length
- amplitude proportional to line length, fixed duration
- amplitude and duration proportional to line length

The backward term can be seen as the sum of all contributions along the line, originated when the disturbing pulse travels towards the far end. When the pulse reaches the far end (for a matched line), it is absorbed by the termination. The backward pulse duration is therefore twice the propagation time, which in turn depends from line length.
5) The forward crosstalk noise at the far end has:

- fixed amplitude, duration $t_r$,
- fixed amplitude, duration proportional to line length,
- *amplitude proportional to line length, fixed duration,
- amplitude and duration proportional to line length.

The forward term can be seen as the sum of all contributions along the line, originated when the disturbing pulse travels towards the far end. Since these elementary contribution travel towards the far end at the same speed of the disturbing pulse, their amplitude increases as the signal moves toward the far end. The final peak value is therefore proportional to the length of the line.

6) At the near end we can observe a crosstalk noise pulse with duration

- $t_r$,
- $2\ t_r$,
- $t_P$,
- *$2\ t_P$.

The total width of the near end crosstalk pulse depend from the time required by the disturbing signal edge to travel along the line ($t_P$), plus the time require by the negative edge (the crosstalk noise turn-off) to come back to the near end (another $t_P$).

7) At the far end we can observe a crosstalk noise pulse with duration

- *$t_r$,
- $2\ t_r$,
- $t_P$,
- $2\ t_P$.

The far end crosstalk pulse is the sum of all elementary contributions along the line, which move towards the far end at the same speed of the disturbing signal. They sum in the amplitude domain, and the pulse width corresponds to the width of each elementary contribution ($t_r$).

8) If the characteristic impedance $Z_0$ of the disturbed line increases, the capacitive term of crosstalk:

- does not change,
- *increases,
- decreases.

The amount of capacitive crosstalk depends on the partition among the mutual capacitance $C_M$ and the line characteristic impedance $Z_0$. As $Z_0$ goes up the attenuation decreases, and the noise transferred through capacitive coupling to the resting line increases.
9) Connecting a scope at the middle point of the disturbed line we will observe:

- a pulse with duration \( t_p \) followed by a spike of duration \( t_r \),
- a pulse with duration \( 2t_p \) followed by a spike of duration \( t_r \),
- a spike of duration \( t_r \) followed by a pulse with duration \( t_p \),
- a spike of duration \( 2t_r \) followed by a pulse with duration \( 2t_p \).

The signal at any point is the sum of the forward term (a spike of duration \( t_r \)) and the backward term (a pulse with duration twice the fly time from that point to the far end, that is \( t_p \) for the line middle point).

10) If the length of a couple of lines is doubled (and all other parameters per unit length remain unaffected):

- the amplitude of near-end crosstalk doubles,
- the amplitude of far-end crosstalk doubles,
- the width of far-end crosstalk doubles,
- the amplitude and the width of near-end crosstalk doubles.

The far end crosstalk pulse is the sum of all elementary contributions along the line, which move towards the far end at the same speed of the disturbing signal. Therefore the amplitude of far end crosstalk is proportional to the line length.