Electronic System Design
521405A

Noise

PART 1: Crosstalk

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Bibliography


Crosstalk, which is the coupling of energy from one line (i.e., source) to another (i.e., victim), will occur whenever the electromagnetic fields from different structures interact. Crosstalk will occur on the chip, on the PCB board, on the connectors, on the chip package and on the connector cables. In multiconductor systems, excessive line-to-line coupling, or crosstalk, can cause two detrimental effects. First, crosstalk will change the performance of the transmission lines in a bus by modifying the effective characteristic impedance and propagation velocity, which will adversely affect system level timings and the integrity of the signal. Additionally, crosstalk will induce noise onto other lines, which may further degrade the signal integrity and reduce noise margins.

Mutual inductance is one of the two mechanisms that cause crosstalk. Mutual inductance $L_M$ will inject a voltage onto the victim proportional to the rate of changes of the current on the driver line. The magnitude of this noise is calculated as:

$$u_{noise} = L_M \cdot \frac{di_{driver}}{dt}$$

Mutual capacitance is the other mechanism that causes crosstalk. Mutual capacitance is simply the coupling of two conductors via the electric field, which is presented in a circuit model by a mutual capacitor. Mutual capacitance $C_M$ will inject a current onto the victim line proportional to the rate of change of voltage on the driver line:

$$i_{noise} = C_M \cdot \frac{du_{driver}}{dt}$$

Again, since the induced noise is proportional to the rate of change, mutual capacitance becomes very significant in high-speed digital applications.

In systems where significant coupling occurs between transmission lines, it is no longer adequate to represent the electrical characteristics of the line with just an inductance and a capacitance. It becomes necessary to consider the mutual inductance and mutual capacitance to fully evaluate the electrical performance of a transmission line. This can be done using inductance and capacitance matrices known collectively as the transmission line matrices.
Field simulators are typically used to model electromagnetic interactions between transmission lines. The outputs are typically matrices that represent the effective inductance and capacitance values of the conductors. These matrices are the basis for all equivalent circuit models and are used to calculate characteristic impedance, propagation velocity and characteristic impedance. The two-dimensional, or electrostatic, simulators will give the inductance and capacitance matrices as a function of conductor length, which is usually most suitable for interconnect analysis and modeling. The matrices are shown here for the two-line system of Fig.2.

**Inductance matrix**

\[
\begin{bmatrix}
L_s & L_M \\
L_M & L_v
\end{bmatrix}
\]

**Capacitance matrix**

\[
\begin{bmatrix}
C_s & C_M \\
C_M & C_v
\end{bmatrix}
\]

\[C_s = C_{sG} + C_M\]
\[C_v = C_{vG} + C_M\]

Crosstalk noise can be divided into *near-end noise* and *far-end noise*. The near end is the part of the victim line, which is closest to the source line driver end. The far end is correspondingly the farthest end of the victim line from the source line driver end. The crosstalk is graphically presented in Figures 3-4.

**Fig. 3** At the driver end; \(t = 0\).

**Fig. 4** At the middle of the transmission line; \(t = TD/2\).

**Fig. 5** At the end of the transmission line; \(t = TD\).

The conclusions are as follows: The near end crosstalk will begin at \(t = 0\) and have a duration of \(2TD\). The far end crosstalk will occur at \(t = TD\) and have a duration approximately equal to source signal rise or fall time.
Crosstalk Induced Noise

The magnitude and shape of crosstalk noise depend heavily on the amount of coupling and the termination. Some approximations on the maximum crosstalk noise are given in Figures 6-8. These equations should be used only to estimate the magnitude of crosstalk noise and to understand the impact of a particular termination strategy.

**Fig. 6** Perfect termination.

**Fig. 7** High Impedance at Far End.
If the terminations are nonideal, the resultant crosstalk signal can be calculated as follows, where $V_x$ is the crosstalk signal at near or far end, $R$ is the impedance of the termination, $Z_o$ the characteristic impedance of the transmission line, and $V_{crosstalk}$ the value calculated in Figures 6-8.

$$V_x = V_{crosstalk} \cdot (1 + \frac{R - Z_o}{R + Z_o})$$

Equivalent circuits are the most general method of simulating crosstalk. The number of segments (N) required such that model will behave as a transmission line can be approximated in such a way that the propagation delay of a segment should be less than one-tenth of signal rise or fall time. The mutual inductance is typically modeled in Spice-type simulators with a coupling factor $K$:

$$N \geq 10 \cdot \frac{\sqrt{L_s C_v}}{t_r} \text{ or } 10 \cdot \frac{\sqrt{L_v C_s}}{t_r}; \quad K = \frac{L_M}{\sqrt{L_s L_v}}$$

Where $L_M$ the mutual inductance between the source and victim line, $L_s$ and $L_v$ the self inductance values of the source and victim line, $C_s$ and $C_v$ the capacitance values of source and victim line, respectively.
Equivalent Circuit for Spice

Inductance matrix  Capacitance matrix
\[
\begin{bmatrix}
    L_s & L_M \\
    L_M & L_v
\end{bmatrix}
\begin{bmatrix}
    C_s & C_M \\
    C_M & C_v
\end{bmatrix}
\]

Simulation model

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