Crosstalk

- Crosstalk (or X-talk) is when the switching on one signal causes noise on an adjacent line.
- The term Crosstalk comes from the early analog phone lines where you could actually hear voices from neighboring lines due to EM coupling.
- Crosstalk is due to the capacitance and inductance between conductors, which we call:
  - "Mutual Capacitance" ($C_M$)
  - "Mutual Inductance" ($L_M$)

Superposition

- Crosstalk is based on the principle of Superposition where:
  1) Multiple signals can exist on the same line without interacting or effecting each other.
  2) An arbitrary signal can be coupled onto a line independent of what may already exist on that line.

Crosstalk Terminology

- We call the switching signal the "Aggressor"
- We call the line receiving the noise the "Victim"

Crosstalk Classes

- There are two main classes of X-talk
  1) Signal X-talk
     - When $C_M$ and $L_M$ produce X-talk noise on the same order of magnitude
     - When the signal path is the reason for the X-talk
     - This is what we see on PCB's and on-chip traces
  2) Switching X-talk
     - When the return path is highly inductive and the inductive noise dominates
     - When the inductance in the return path is the reason for the X-talk
     - This is what we see on packages and in connectors
     - This is also called:
       - "Ground Bounce / Power Supply Droop"
       - "Simultaneous Switching Noise (SSN)"
       - "Simultaneous Switching Output (SSO) Noise"

Crosstalk Location

- There are two locations where we observe and define X-talk
  - Near End - the location closest to the driving source resistor
  - Far End - the location closest to the receiving termination resistor

Crosstalk Definitions

- We define parameters for X-talk based on a double terminated system.
  - Near End Crosstalk Coefficient ($V_{rev}/V_{A}$)
  - Far End Crosstalk Coefficient ($V_{for}/V_{A}$)
Crosstalk

**SPICE Matrices**
- There can be multiple signal lines in a system.
- To keep track of their LC values, we use a matrix.
- Each signal is given an index, where ground is "0".
- We define $C_{ss}$ as the self capacitance of signal $i$.
- We define $C_{mm}$ as the mutual capacitance between signals $i$ and $j$.
- In this system, $C_{ss}$ and $C_{mm}$ are equal.
- We then put all the values in a matrix for easy record keeping.
- We do the same for the inductances.

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**Capacitive Crosstalk**
- As the Aggressor Edge propagates down the line, it will inject current into the Victim line through the Mutual Capacitance following:

$$I_C = C_{mm} \frac{dV}{dt}$$

- As the current is injected, it will see an equal impedance in both the forward and reverse directions (i.e., 50ohms).
- As a result, the current will equally split and half will travel forward and half will travel backwards.

**Capacitive Crosstalk (Near End)**
- Half of the current injected into the victim as the incidence voltage step travels down the aggressor travels back to the Near End.
- At any given time, only a fixed amount of current will be observed at the Near End.
- This means that the Near End voltage will raise to a fixed value and remain there.
- At the point the aggressor edge reaches the end of the line ($T_D$), the injected noise on the victim still needs to travel back to the Near-End (taking another $T_D$).
- This means the fixed noise level at the Near End will remain for $2T_D$.

**Capacitive Crosstalk (Near End)**
- This gives a voltage profile at the near-end as follows:

$$V_{near} = \frac{1}{2} \left( C_{mm} V_{rise} \right)$$

- The maximum amount of current injected is reduced by a factor of 1/2 to account for the injected energy splitting in both the forward & reverse directions.
- This current is further reduced by an additional factor of 1/2 to account for the energy being spread out over $2T_D$.

$$I_C = \frac{1}{2} \left( \frac{1}{3} \right) C_{mm} \cdot \frac{V_{rise}}{T_D} = \frac{1}{2} \left( \frac{1}{3} \right) C_{mm} \cdot \frac{V}{V}$$

**Capacitive Crosstalk (Far End)**
- We can convert this into a ratio of Volts by looking at KCL at an arbitrary point of injection.

As a result, the current will equally split and half will travel forward and half will travel backwards.

- A dV/dt occurs on the aggressor node which is seen across the $C_{ss}$ of the aggressor and $C_{mm}$ of the victim.

(NOTE: we assume the victim line is at 0V for our derivation.)
Crosstalk

- Capacitive Crosstalk (Near End)
  - The change in voltage causes a current to flow through \( C \) given by:
    \[ I_{C} = C \frac{dV}{dt} \]
  - When this current reaches the victim line, it causes a voltage change, \( V_{C} \), given by:
    \[ V_{C} = \frac{C}{C + C_{M}} V_{L} \]
  - This current in \( C \) then creates a change in voltage, \( dV/dt \), given by:
    \[ \frac{dV}{dt} = I_{C} \]
  - This is the total voltage created at the injection point prior to the inductors beginning to conduct and allowing the current to flow in both the forward and reverse directions.

- Capacitive Crosstalk (Far End)
  - We can now relate the magnitude of the voltage observed on the aggressor (\( V_{A} \)) to the voltage on the aggressor (\( V_{L} \)) as:
    \[ V_{A} = \frac{C}{C + C_{M}} V_{L} \]
  - The net voltage at the far end will be the sum of all of the injected current along the length of the coupled lines.
  - The TOTAL amount of current that is injected through \( C \) is proportional to the total length that the lines are coupled.
Crosstalk

- Capacitive Crosstalk (Far End)
  - All of the current that is injected into the victim line will add together and be injected into the last $C_L$ segment of the Victim at the Far-End.
  - The current in the last segment is described as:

$$I_{C_L} = C_L \frac{dV}{dt}$$

$$I_{C_L} = C_L \left( \text{ref. } t_{	ext{rise}} \right) \frac{(0.8) V_L}{t_{	ext{rise}}}$$

- We now apply our factor of 1/2 to account for the forward and reverse traveling current and we get:

$$V_{FE} = \frac{V_L}{2} C_L \left( \text{ref. } t_{	ext{rise}} \right) \frac{(0.8) V_L}{t_{	ext{rise}}}$$

**NOTE:** The magnitude of FE $X$-talk can get very large because it is proportional to coupled length and inversely proportional to $t_{	ext{rise}}$.

Inductive Crosstalk

- Magnetic fields exist as the current travels down the Aggressor line.
- These B-field lines induce B-field lines around the Victim line, which in turn creates current.
- The direction of the B-field lines in the Aggressor follows the Right-Hand Rule.
- The direction of the B-field lines in the Victim are opposite of the Aggressor.

- The B-Field lines induced on the Victim create a current that flows in the opposite direction of the Aggressor current.

- The direction of the induced current creates a Negative Voltage at the Far-End and a Positive Voltage at the Near-End as it flows through the termination impedances.
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- **Inductive Crosstalk (Near End)**
  - Just as in Near End Capacitive X-talk, the currents that are induced by the inductive coupling will travel back to the Source (or Near End) over a time span of $2T_0$.

- **Inductive Crosstalk (Far End)**
  - The exact derivation is applied to the Far End inductive X-talk to derive the maximum amount of noise due to inductive coupling.
  - The only difference is that the magnitude of the Far End noise is NEGATIVE.

\[
\frac{V_{a}}{V_{b}} = -\frac{1}{2} \left( \frac{\Delta I_{a}}{\Delta I_{b}} \right)
\]

\[
\text{Near End Crosstalk Coefficient (NEXT)}
\]

\[
\text{NEXT} = \left( \frac{V_{a}}{V_{b}} \right) - \frac{1}{2} \left( \frac{C_{a}}{C_{b}} + \frac{L_{a}}{L_{b}} \right) \Delta I_{a}
\]

- We define $L_{a}$ as the Backward Coefficient which is only in terms of intrinsic values.
Crosstalk

• **FEXT**
  - We can combine all of the coupling at the Far-End to come up with the

  \[
  FEXT = \left( \frac{V_o}{V_i} \right) \left( \frac{\text{length}}{\text{rise}} \right) \left( \frac{L_{out}}{C_{out}} \right) \left( \frac{L_{in}}{C_{in}} \right)
  \]

  - We define \( k_1 \) as the Forward Coefficient which is only in terms of intrinsic values.
  \[
  k_1 = \frac{1}{2} \left( \frac{C_{in}}{C_{out}} \right) \left( \frac{L_{in}}{L_{out}} \right)
  \]
  where,
  \[
  FEXT = \left( \frac{\text{length}}{\text{rise}} \right) k_1
  \]


Crosstalk

• **Total X-talk**
  - If we look at NEXT, we see that:

  \[
  NEXT = \left( \frac{V_o}{V_i} \right) \left( \frac{\text{length}}{\text{rise}} \right) \left( \frac{L_{out}}{C_{out}} \right) \left( \frac{L_{in}}{C_{in}} \right)
  \]

  - We scale the maximum value that it will reach using:

  \[
  \text{FEXT} = \left( \frac{\text{length}}{\text{rise}} \right) k_1
  \]

  1) Near End X-talk doesn't depend on risetime.
  2) Near End X-talk is always positive (for a rising edge on the Aggressor)

  - If we look at FEXT, we see that:

  \[
  FEXT = \left( \frac{V_o}{V_i} \right) \left( \frac{\text{length}}{\text{rise}} \right) \left( \frac{L_{out}}{C_{out}} \right) \left( \frac{L_{in}}{C_{in}} \right)
  \]

  1) Far End X-talk depends on coupled length and \( \text{rise} \)
  2) FE X-talk can actually cancel if the ratios of Capacitance and Inductance are equal

  - NOTE: this cancellation occurs if all of the field lines are contained within a homogenous dielectric.

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• **Scaling Near-End X-talk**
  - If the coupled length of the T-line is shorter than the risetime, the peak value of NEXT will not reach its maximum value.
  - We scale the maximum value that it will reach using:

  \[
  \text{NEXT}_{scale} = \frac{\text{Length of Coupled Region}}{\text{Length of Routine}}
  \]

  - Risetime is converted to Length/risetime:

  \[
  \text{length}_{scale} = \text{risetime} \cdot \text{risetime}
  \]

Crosstalk

• **Switching Noise**
  - When we derived the LC model of a transmission line, we assumed that the ground (or return path) was a perfect conductor.
  - That allowed us to model the ground with a simple wire.
  - This is reasonable in a transmission line when the ground conductor is much larger than the signal conductor.

  Example PCB trace:
  - the signal sees an infinite-ground plane beneath it.

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• **Switching Noise**
  - When the signal travels through connectors or packages, the shape of the return path changes.
  - This typically results in a return path with the same geometry as the signal.
Crosstalk

- **Switching Noise**
  - This means we need to model the return path’s electrical properties.
  - The capacitance between the signal and ground is already present in our LC model.
  - However, we need to add an inductive component into the return path for an accurate model.

- **Switching Noise (Switching Noise)**
  - This geometry change in the conductors results in a highly inductive path that the current needs to flow through.
  - In addition, the capacitance typically is reduced due to the surface area of the connector/package being less than in the trace section of the link.

Crosstalk

- **Switching Noise (Ground Bounce)**
  - The return current that passes through the inductive interconnect causes a voltage to form following:
    \[ V_G = \frac{dI}{dt} \]  
  - This voltage changes the ground potential of the integrated circuit relative to the ground of the system which gives the name *Ground Bounce*.

Crosstalk

- **Switching Noise (Ground Bounce)**
  - This becomes a more critical problem when signals in packages and connectors share a common return pin.
  - It is cost effective to reduce the pin count of packages/connectors by sharing ground pins.
  - However, the Ground Bounce now becomes proportional to the number of signal lines using that return pin.
    \[ V_G = \frac{dI}{dt} \left( \frac{L_{ret}}{Z_0} \right) \]  
    \[ \left( \text{df} \right) \]  
    \[ \left( \text{of signals} \right) \]  
  - This can be related to voltage by using \( V_G = Z_0 I \)
    \[ V_G = \frac{0.8 V_{rise}}{L_{ret}} \]  
    \[ \left( \text{of signals} \right) \]  

- \( L_{ret} = 10 \text{nH} \)  
  - \( Z_0 = 50 \Omega \)  
  - \( V_{rise} = 8 \text{ns} \)

Crosstalk

- **Switching Noise (Ground Bounce)**
  - This becomes a more critical problem when signals in packages and connectors share a common return pin.
  - It is cost effective to reduce the pin count of packages/connectors by sharing ground pins.
  - However, the Ground Bounce now becomes proportional to the number of signal lines using that return pin.
  - \( V_{G_{max}} = \left( \frac{0.8 V_{rise}}{L_{ret}} \right) \left( \text{of signals} \right) \)
  - \( V_{G_{max}} = 0.2 \text{V} \)
  - A positive \( df \) causes current to flow back to the source. The inductor acts as a passive element in this case so the voltage induced causes the source ground to become negative.
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- Switching Noise (Mutual Inductance)
  - There is also mutual inductance that couples between the signal inductance and the return path inductance.
  - In this case, the inductor acts as a voltage source in the return path, which creates a voltage in the opposite polarity as the noise caused by the return current.
  - This actually has the result of decreasing the total inductive ground bounce noise and can be a good thing.
  - However, this is a secondary effect compared to the noise generated when multiple signals share a common return path.

\[
\begin{align*}
V_{in} &= L_r \cdot \frac{0.6 \cdot V_{p}}{Z_0} \\
V_{in} &= 2.5 \cdot \frac{0.8 \cdot 1 \, \text{V}}{50 \, \Omega} \approx 0.05 \, \text{V}
\end{align*}
\]

- Mutual inductive coupling causes the return inductor to act as a voltage source on the resultant voltage is opposite in polarity to the return noise. The total voltage in this case is: \(-0.2 + 0.05 = -0.15\, \text{V}\)