A Survey on the Effects of Capacitive and Inductive Couplings on Signal Transmission

Shayan Taheri
University of Central Florida, shayan.taheri@knights.ucf.edu

I. Introduction

Due to the ever reduction of process feature size for the purpose of including more devices in the design of integrated circuits (ICs), building and manufacturing IC packages moves toward denser and more complex structures. These structures can be used for circuits of different applications, such as nano-electronics, radio frequency, and digital computers. Specifically, the technology of very large scale integration (VLSI) that is used mostly for digital circuits is a driving force in this path.

Today's, high-performance VLSI processes provide the possibility of integrating more than several million transistors in a single IC package using deep sub-micron lithography. These circuits have more than several gigahertz bandwidth along with a lower noise margin due to lower power and higher speed operation. Looking at the dark side of this trend for the integrated circuits, is satisfaction of certain rigid electrical and mechanical requirements. These requirements are in relation with impedance and continuity of transmission line, signal delay, and cross-talk (cross-coupling) interferences. Lack of consideration of these requirements can degrade the performance and integrity of these circuits noticeably.

Substantial decrease in the spacing between adjacent metal lines in deep sub-micron technologies has made interconnection characterization, a very important requirement in IC design. It can affect both the signal delay and existing crosstalk between parallel wires in the same wiring plane and between planes. The capacitive and inductive interferences of crosstalk is highly troublesome at high speed operations. Thus, the reliability of the electrical communication is destroyed due to the action of crosstalk as a source of noise.

Crosstalk is a well-known phenomenon at all levels of electronic packaging and is an electromagnetic effect due to coupling capacitances and inductances between currents in electrical conductors. It causes undesired noise signal to be coupled from an active transmission line (aggressor) into a quiet transmission line (victim). Depending on its magnitude, the induced noise onto the victim line may influence the timing behavior of its signal by increasing the setup time. It can also cause failure by inducing false pulses or causing false signal levels, which may be propagated throughout the circuit. These effects can be even more problematic when dynamic elements are used in IC design. Due to the increase in system complexities and the availability of several layers of metal, the number of interactions between signals becomes large, which necessitates development of automated techniques for construction of layouts without crosstalk problems.

The rest of this survey is organized as follows. Section 2 describes the crosstalk phenomenon and its mechanism in detail. The existing solution techniques for overcoming the effects of crosstalk are discussed in Section 3. This survey is concluded in Section 4.

II. Crosstalk Phenomenon

Transmission line is a structure that can guide electrical energy from one point to another. In general, it is modeled as a two parallel conductor system, in which one of its end is connected to a source and the other one is connected to a load. The related interactions and operations to a transmission line are modeled as a Resistance - Inductance - Capacitance (RLC) network usually. The resistance part of network describes the losses and the other parts describe the lossless interactions and operations.

The structure of transmission lines is compatible with transverse electromagnetic (T.E.M.) waves and for a system with "N" transmission lines, there exists "N" possible modes for the characteristics and properties of these waves. The T.E.M. mode for a single line can be observed in Figure 1.

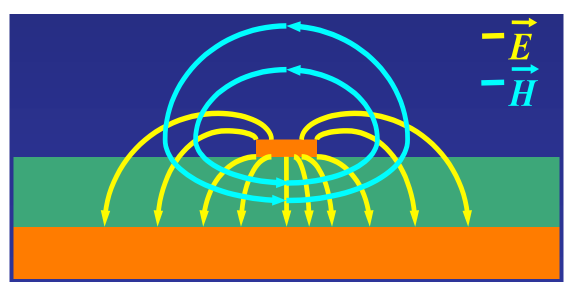
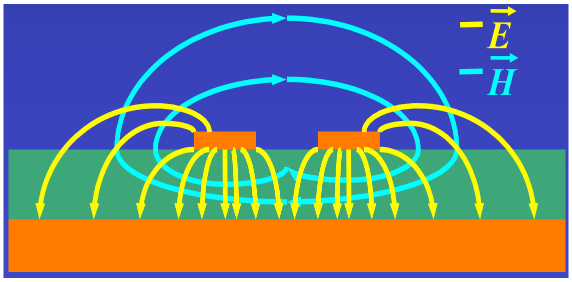


Figure 1. T.E.M. mode for a single line

For example, there are two possible modes for two adjacent lines that interact with each other through their electromagnetic fields: (a) Even Mode, in which both lines are driven in phase; and (b) Odd Mode, in which the lines are driven 180 degree out of phase. The interaction between the electrical field and magnetic field of these waves causes the emergence of crosstalk along with affecting the impedance, propagation velocity, and delay of the passive transmission line(s). Figure 2 shows the even and odd modes for two adjacent lines.



(a) Even Mode

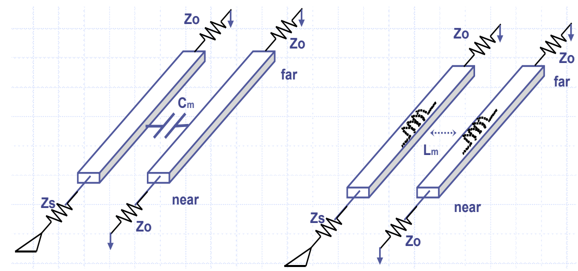
(b) Odd Modd

Figure 2. Modes of two adjacent lines

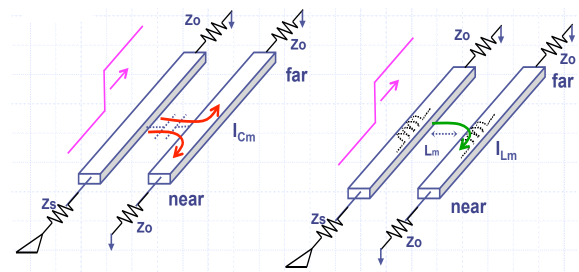
According to the definition of crosstalk phenomenon, a transmitted signal on a line or channel of a transmission system creates an undesired effect on another line or channel that is passive. This effect is caused by an undesired coupling, which is originated from the active line or channel.

Coupling between two transmission lines is introduced by their proximity to each other. It is defined as the transfer of energy from one medium to another medium, and its effects may be undesirable (e.g. crosstalk inside IC chips) or desirable (e.g. in directional couplers where the objective is to transfer power from one line to the other). There exist three types of coupling including, Conductive coupling (e.g. transfer of energy from a power source to an electrical load), Capacitive coupling (e.g. transfer of energy from an AC-biased circuit to a DC-biased circuit), Inductive coupling (e.g. transfer of energy between two circuits with different impedance by use of a transformer). The medium for conductive coupling can be wire, resistor, or etc as oppose to the capacitive coupling that is capacitor. In inductive coupling, the medium is a configuration of two conductors, in which a change in the passing current through one of the conductors induces a voltage across the ends of the other one.

Capacitive and inductive couplings can happen between on-chip and off-chip transmission lines. In capacitive coupling that is due to the interactions of electric fields, the applied voltage to an active line (a.k.a. aggressor line) causes the flow of an induced current on both directions of a passive line (a.k.a. victim line) through the mutual capacitance that is located between the lines. In inductive coupling that is due to the interactions of magnetic fields, the driving current that flows on the aggressor line induces a current in opposite direction on the victim line (according to the Lenz's law). In fact, the flowing current on the victim line is produced by the mutual inductance between the lines. Figure 3 visualizes the explained concepts.



(a) Mutual Capacitance and Inductance



(b) Crosstalk Mechanism

Figure 3. Crosstalk Mechanism and Its Elements

The equations for the crosstalk elements are represented according to Equations 1 and 2. In these equations, C_m is the mutual capacitance, L_m is the mutual inductance, I_{CM} is the transfused current on the victim line, and V_{LM} is the induced voltage across the victim line. The other terms are related to the aggressor line.

$$I_{CM} = C_m \cdot \frac{dV}{dt} \tag{1}$$

$$V_{LM} = L_m \cdot \frac{dI}{dt} \tag{2}$$

The detail of noise coupling mechanism is demonstrated in Figure 4. According to this figure, the current I_C flows through the mutual capacitance from the aggressor line to the victim line. Then, it splits into equal components traveling forward and backward on the victim line. Beside that, L_m induces the current I_L that travels backward on the victim line. So, the total backward and forward currents on the victim line are equal to $I_C + I_L$ and $I_C - I_L$ respectively. An illustration of the created noise signal by the flowing currents on the victim line can be seen in Figure 5.

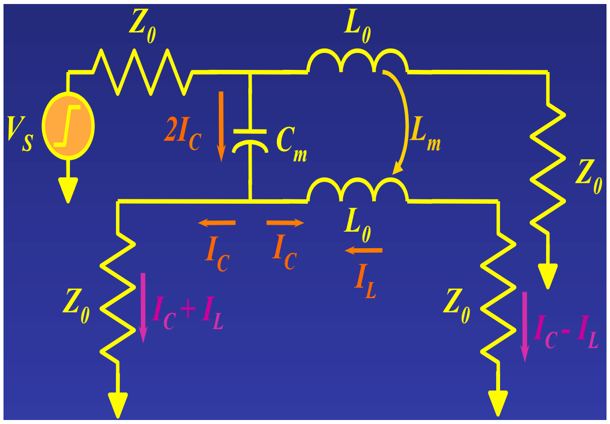


Figure 4. Detail of noise coupling mechanism

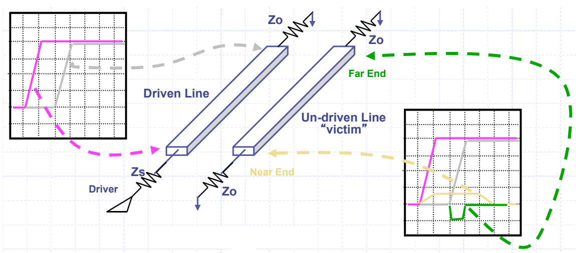


Figure 5. Created noise signal on the victim line

The characteristics and shape of the noise signal created by the flowing currents on the victim line are determined based on the termination configuration of this line. In general, the crosstalk effects can be described as: (a) changing the characteristics (i.e. impedance and peak voltage) of the aggressor line; and (b) the coupled noise signal onto the surrounding passive lines. The strength of these effects can be expressed in terms of the ratio of the mutual capacitance to the total capacitance along with the ratio of the mutual inductance to the self inductance of the transmission line.

III. Reducing Crosstalk Effects

In order to defeat the destructive and harmful effects of the crosstalk, various design and layout optimization techniques have been presented. In each of the presented techniques, certain aspects of the crosstalk were taken into account in order to develop a qualified model for transmission lines. These models can be used in IC CAD tools for automation of the optimization process. In the following, a number of the presented techniques are mentioned:

- Minimize physical distance between the components during placement.
- Group logic families according to functionality.
- Locate components away from I/O interconnects and other areas susceptible to data corruption and coupling.
- Avoid routing of traces parallel to each other.
- Reduced trace impedance and signal drive level.
- Partition or isolate high noise emitters onto different layers within stack up assignments.
- Provide termination on impedance-controlled traces, or traces rich in RF harmonic energy.
- Widen spacing between signal lines as much as routing restrictions allow.
- Design the transmission line so that the conductor is as close to the ground plane as possible. This couples the transmission line tightly to the ground plane and helps decouple it from adjacent signals.
- Use differential routing techniques where possible, especially for critical nets.
- Route signals on different layers orthogonal to each other, if there is significant coupling.
- Minimize parallel run lengths between signals. Route with short parallel sections and minimize long coupled sections between nets.
- Using striplines instead of microstrip for lines.
- Decreasing the thickness of metal layers.
- Using resistor packs instead of resistor networks.
- **Add Shields**: Routing "guard" traces between signal traces.

One of the effective and common ways to reduce crosstalk effects and improve signal integrity in VLSI digital circuits is Shielding. Shield is a wire that is connected directly to supply voltage or ground. In order to attenuate the coupled noise onto a victim line, the sides of line can be surrounded by either supply voltage- or ground- connected shields. Figure 6 shows an interconnect structure composed of two shielded signal lines. In insertion of shields around a victim line, certain parameters are taken into account. These parameters include the effects of the width and length of shield, separation between the shield and transmission line, and the numbers of connections for linking the shield to either supply voltage or ground.

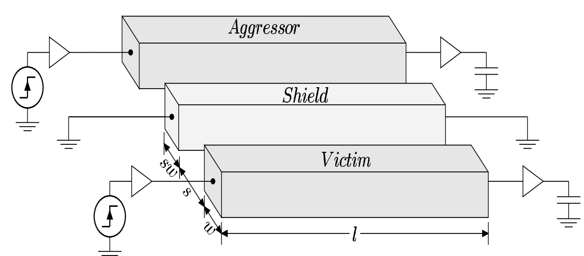


Figure 6. A shielded interconnect structure

Insertion of a shield line between two adjacent transmission lines causes elimination of the mutual capacitance. Instead, two new coupling capacitances are introduced between the signal lines and shield line. In this way, the switching activities of the neighboring lines are isolated efficiently. In case of inductive coupling, the mutual inductance between the signal lines is not eliminated but the originated noise from it is attenuated significantly. This attenuation is due to the provision of a closer and clearer defined current return path for both of the signal lines. According to the structure of shielded interconnect, the crosstalk effects are reduced by increase in the shield width and they are intensified by enhancement of the lines length. Beside the advantages of shielding technique, it brings a number of disadvantages such as, increase in power consumption, area, and interconnects routing complexity.

In order to develop a model for an interconnection structure with considering the crosstalk effects, certain facts about the capacitive and inductive couplings need to be taken into account:

❖ **Capacitive Coupling**

- Capacitive coupling exists between adjacent or crossing transmission lines virtually. So, its effects are localized according to interconnection configuration.
- This coupling has effects on both delay and signal integrity.
- If the location of crosstalk effects is determined, then the mutual capacitance can be pre-computed.
- The effects of this coupling are highly dependent on spacing between lines.
- The impact of capacitive coupling is determined based on the ratio of mutual capacitance to total capacitance. This ratio can be changed by wire sizing, adjusting the drivers of aggressor and victim lines, buffering, spacing, net ordering, and shielding.

❖ **Inductive Coupling**

- Inductance coupling effects are dependent upon technology scaling and increase in clock frequencies, These effects are on both delay and signal integrity.
- Shielding, buffering, using ground plane, differential signals, and signal line termination can minimize the effects of this coupling.
- The effects not sensitive to spacing, wire sizing, and net ordering.
- Inductive coupling exists between any two transmission lines as oppose to capacitive coupling that only exists between adjacent lines.

In order to obtain a comprehensive picture of the shielding technique, a model for on-chip interconnection is presented [5]. This model is a 2π RLC model based on symmetrical interconnect system in which a shield line has two ends that are connected to ground. A driving resistance is leveraged at the driver end and a load capacitance is incorporated at the load end. The distributed parameters are gained though lumped circuit structure. Also, it is assumed that the current only returns through the supply voltage and shield lines. This circuit for this interconnection model is shown in Figures 7 and 8.

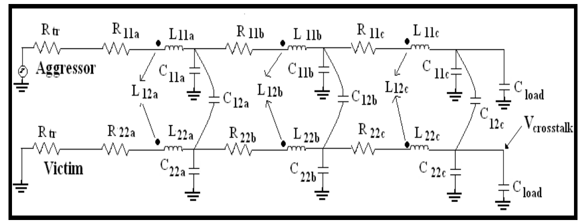


Figure 7. Interconnection model without shield

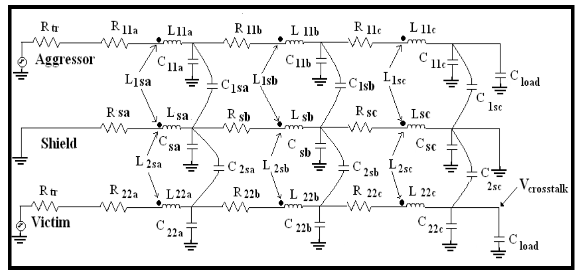
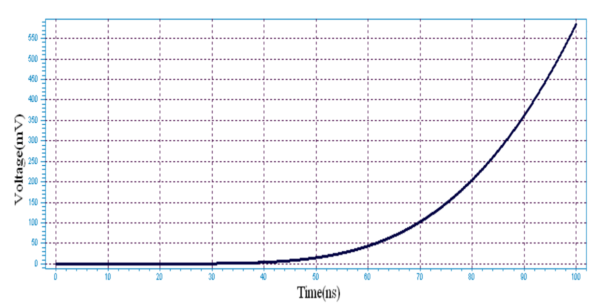


Figure 8. Interconnection model with shield

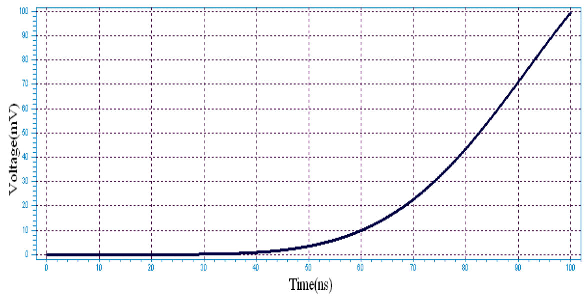
In this model, the value of oxide dielectric constant is 3.9, load capacitance is 76 fF, transistor gate resistance is 82.76 Ω, sheet resistance of metal line is 500 Ω, length of interconnect is 5 mm, metal thickness is 2 μm, track substrate height is 2 μm, separation of a track from the nearest neighbors is 2 μm (without shield) and 1 μm (with shield). Also, the values for line and mutual capacitances and inductances are used according to Table 1. Meanwhile, 90nm CMOS process technology is utilized in circuit simulation.

Parameter	Without Shield	With Shield
L_{Line}	83.24 μH	83.24 μH
L_m	8.21 μH	7.51 μH
C_{Line}	134.41 pF	134.41 pF
C_m	69.50 pF	27.47 pF

Table 1



(a) Noise signal without shield



(b) Noise signal with shield

Figure 9. Effect of shied insertion on noise signal

The top and bottom waveforms in Figure 9 show the extent of crosstalk noise voltage signal on the victim line in absence and presence of the ground shield respectively. As it can be perceived from the figure, a considerable reduction in the noise signal is observed.

The effect of shield insertion on propagation delay and rise time on aggressor and victim lines can be seen in Table 2. According to the results, the delay and transition time on victim lines correspond to their noise signal. By insertion of shield, the voltage level of noise signal along with the propagation delay and rise time of both aggressor and victim lines are reduced.

Parameter	Without Shield	With Shield
V_{Victim}	590 mV	100 mV
$Delay_{Aggressor}$	52.86 ns	51.97 ns
$Delay_{Victim}$	90.24 ns	31.8 ns
$t_{Rise-Aggressor}$	6.88 ns	5.96 ns
$t_{Rise-Victim}$	97.98 ns	27.5 ns

Table 2

IV. Conclusion

Crosstalk between signal lines of an on-chip bus is becoming a significant problem in deep sub-micron IC design. It can result in remarkable delay variations as well as signal integrity problems. This phenomenon is due to unintended electromagnetic couplings (capacitive and inductive couplings) between traces, wires, trace to wire, cable assemblies, and any other electrical components. In this survey, an overview of crosstalk phenomenon and its mechanism is presented in the beginning. The occurrence of crosstalk is originated from the interactions of transverse electromagnetic (T.E.M.) waveforms between the neighboring transmission lines. The interactions appear in form of capacitive and inductive couplings. These couplings cause creation of a signal noise on a passive transmission line (a.k.a. victim line).

Next, a number of techniques for reducing the effects of crosstalk are mentioned. Also, the structure of shielding technique is discussed in detail along with provision of a shielded interconnection model. The model is built on basis of the distributed RLC model. The simulation results show a decrease in level of the crosstalk noise voltage signal by insertion of shield between the aggressor and victim lines. However, the presented model cannot show the strength of the shielding technique completely since there exist other designed models that can eliminate the effects of crosstalk with high degree of accuracy.

V. References

[1] Vittal, Ashok, Lauren Hui Chen, Malgorzata Marek-Sadowska, Kai-Ping Wang, and Sherry Yang. "Crosstalk in VLSI interconnections." Computer-Aided Design of Integrated Circuits and Systems, IEEE Transactions on 18, no. 12 (1999): 1817-1824.

[2] Eo, Yungseon, William R. Eisenstadt, Ju Young Jeong, and Oh-Kyong Kwon. "A new on-chip interconnect crosstalk model and experimental verification for CMOS VLSI circuit design." Electron Devices, IEEE Transactions on 47, no. 1 (2000): 129-140.

[3] Cao, Yu, Xuejue Huang, Dennis Sylvester, Norman Chang, and Chenming Hu. "A new analytical delay and noise model for on-chip RLC interconnect." In International Electron Devices Meeting, pp. 823-826. IEEE; 1998, 2000.

[4] Hunagund, P. V., and A. B. Kalpana. "Crosstalk noise modeling for RC and RLC interconnects in deep submicron VLSI circuits." arXiv preprint arXiv:1004.4458 (2010).

[5] Mishra, Divya, Shailendra Mishra, Praggya Agnihotry, and B. K. Kaushik. "Effect of Distributed Shield Insertion on Crosstalk in Inductively Coupled VLSI Interconnects." arXiv preprint arXiv:1006.2820 (2010).

[6] Zhang, Qi-Jun, Stephen Lum, and Michel S. Nakhla. "Minimization of delay and crosstalk in high-speed VLSI interconnects." Microwave Theory and Techniques, IEEE Transactions on 40, no. 7 (1992): 1555-1563.

[7] Joardar, Kuntal. "A simple approach to modeling cross-talk in integrated circuits." Solid-State Circuits, IEEE Journal of 29, no. 10 (1994): 1212-1219.

[8] Venkatesan, Raguraman, Jeffrey Davis, and James D. Meindl. "Compact distributed RLC interconnect models-part IV: unified models for time delay, crosstalk, and repeater insertion." Electron Devices, IEEE Transactions on 50, no. 4 (2003): 1094-1102.

[9] Agarwal, Kanak, Dennis Sylvester, and David Blaauw. "Modeling and analysis of crosstalk noise in coupled RLC interconnects." Computer-Aided Design of Integrated Circuits and Systems, IEEE Transactions on 25, no. 5 (2006): 892-901.

[10] Wong, Shyh-Chyi, Gwo-Yann Lee, and Dye-Jyun Ma. "Modeling of interconnect capacitance, delay, and crosstalk in VLSI." Semiconductor Manufacturing, IEEE Transactions on 13, no. 1 (2000): 108-111.

[11] Zhang, Junmou, and Eby G. Friedman. "Crosstalk noise model for shielded interconnects in VLSI-based circuits." In Proc. IEEE Int. SOC Conf, pp. 243-244. 2003.

[12] Duan, Chunjie, Anup Tirumala, and Sunil P. Khatri. "Analysis and avoidance of cross-talk in on-chip buses." In Hot Interconnects 9, 2001., pp. 133-138. IEEE, 2001.

[13] Anish, D., G. Kranthi Kumar, and Rohita Jagdale. "Minimization of crosstalk in high speed PCB." In Proceedings of the 12th international

conference on Networking, VLSI and signal processing, pp. 104-107. World Scientific and Engineering Academy and Society (WSEAS), 2010.

[14] Stöhr, Tilmann, Markus Alt, Asmus Hetzel, and Jürgen Koehl. "Analysis, reduction and avoidance of crosstalk on VLSI chips." In Proceedings of the 1998 international symposium on Physical design, pp. 211-218. ACM, 1998.

[15] Chen, Pinhong, and Kurt Keutzer. "Towards true crosstalk noise analysis." In Proceedings of the 1999 IEEE/ACM international conference on Computer-aided design, pp. 132-138. IEEE Press, 1999.

[16] Hetzel, Asmus, Erich Klink, Juergen Koehl, Dieter Wendel, and Parsotam Trikam Patel. "Structure for reducing cross-talk in VLSI circuits and method of making same using filled channels to minimize cross-talk." U.S. Patent 6,218,631, issued April 17, 2001.

[17] "Basic Principles of Signal Integrity", https://www.altera.com/content/dam/altera-www/global/en_US/pdfs/literature/wp/wp_sgnlntgry.pdf

[18] Heck, Howard. "Module 5: Advanced Transmission Lines - Topic 3: Crosstalk", http://home.comcast.net/~howard.heck/5-3.ppt

[19] "Crosstalk - Overview and Modes", lappd.uchicago.edu/library/anodes/Anodes_Crosstalk_Overview.ppt