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Multi-aggressor capacitive and inductive coupling noise modeling and mitigation

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ABSTRACT

Crosstalk noise in on-chip interconnect plays a major role in the performance of modern integrated circuits. Multi-aggressor capacitive and inductive coupling complicates both the modeling and mitigation of the noise. A novel method to model and analyze noise in RLC multi-line structures is proposed in this paper, exhibiting an error of up to 9% as compared to SPICE. This method is physically intuitive since it decomposes the noise produced by each of the aggressors into individual capacitive and inductive noise sources. The proposed model and related layout noise mitigation guidelines are applied to crosstalk noise reduction in multi-line structures.

1. Introduction

Global and semi-global interconnect do not scale with feature size due to increased design complexity, demand for greater integration, and technology constraints. As technology progresses, the effect of the interconnect on the performance of high speed and high density integrated circuits has greatly increased. With shorter transition times and the inability to scale the global wires, inductive effects exhibited in the upper metal layers cannot be neglected. Consequently, long range inductive coupling should be included with the already significant capacitive coupling in global interconnect lines since noise analysis and mitigation is not limited to only the nearest neighbors. Simultaneous capacitive and inductive coupling together with multiple aggressors are significant risks to the signal integrity of the global interconnects.

The primary interconnect structures in the upper metal layers are the clock and power/ground (P/G) distribution networks and wide data busses. The global clock network is usually highly shielded and affected by the self-inductance rather than mutual inductive effects, which greatly simplifies the analysis and optimization process. In P/G networks, the noise is caused by both the self-inductance and mutual inductance. These networks however generally exhibit uniform structures. Random data signals, unshielded clock signals, and wide data busses, as illustrated in Fig. 1, suffer from both self-inductance and mutual inductive coupling and can be affected by numerous aggressors due to the long range nature of inductive coupling. Simultaneous capacitive and inductive coupling and different switching patterns further complicate the modeling and analysis process.

Several authors have addressed modeling and behavioral analysis of noise in multi-line structures in the presence of inductance. In [1], a two line decoupling technique is extended by applying superposition of the fundamental modes to three lines and proposes this technique for N coupled lines. The model is rather general (no limitations on the line parameters) but is complex and requires adjustment for different bus sizes. The use of modal analysis to decouple multiple transmission line (TL) systems is described in [2,3]. These models are valid for identical lines with an identical driver and loads assuming ideal transmission lines and are computationally complex. A TL based model is used in [4], but assumes no capacitive coupling and low loss, which is also assumed in [5]. The TWA method [6] is extended to multi-coupled transmission lines in [7]. The concept of an effective switching factor for multi-line systems is presented in [8] and the differences between multi-line worst case noise patterns for RC and RLC lines are discussed in [9].

These models do not describe the individual noise components—the noise caused by each aggressor and the noise due to both

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capacitive and inductive coupling. Since methods to mitigate each noise source (inductive, capacitive, different aggressors) can be different and sometimes contradictory, identification of the most critical noise sources and the preferable mitigation method for a specific physical layout and switching pattern are necessary. The conditions and methods to model noise as a combination of the noise caused by each aggressor and noise source (capacitive and inductive), as illustrated in Fig. 2, are described in this paper based on the additivity properties of capacitive and inductive coupling as well as multi-line system behavior in the presence of multiple noise sources.

The paper is organized as follows. In Section 2, the additivity properties of inductive and capacitive noise for a two line coupled system with simultaneous inductive and capacitive coupling are examined. Conditions under which the additivity of the two coupling noise sources can be applied are formulated. The behavior of multi-line systems is examined in the presence of capacitive coupling, inductive coupling, and simultaneous capacitive and inductive coupling in Section 3. The conditions which represent the sum of the noise caused by each aggressor are also described. In Section 4, noise models of multi-line systems are described. In Section 5, layout-based noise mitigation guidelines are presented and together with the proposed models can be used to reduce noise in multi-line systems. The results are summarized in Section 6.

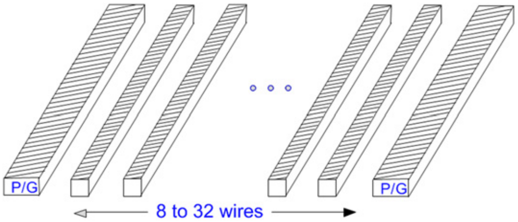

Fig. 1. Typical upper metal routing structure.

2. Additivity of capacitive and inductive coupling noise

Simultaneous capacitive and inductive coupling can occur between adjacent RLC lines. According to [10], capacitive and inductive coupling noise is additive under the low loss approximation, $R_{line} \gg (L_{self}-M)\omega$, where R_{line} and L_{self} are, respectively, the self-resistance and inductance of a line, M is the mutual inductance between the lines, and ω is the switching frequency, $\omega=2/t_r$, where t_r is the signal transition time. Note however that the low loss approximation cannot always be assumed in modern integrated circuits. Therefore, additivity of the two noise sources cannot be assumed in modern integrated circuits. By performing an analysis similar to [10], those regimes where additivity of capacitive and inductive coupling can be assumed, as illustrated in Fig. 3 for a two coupled line system, are established. The additivity property permits the noise components to be broken into noise sources. As a result, the dominant noise source can be identified and a suitable noise mitigation technique can be chosen. This distinction is important since noise reduction techniques for inductive and capacitive coupling are not only different, but often in conflict.

According to transmission line theory [18], coupled lines exhibit two modes of propagation with two different propagation constants and two different line impedances. The even mode represents the case of same direction switching and the odd mode represents opposite direction switching. Any signal in the system can be expressed as the sum of these modes. The characteristic impedance of the even and odd modes for two identical lines is presented in Eqs. (2.1) and (2.2) where R_{11}, C_{11}, and L_{11} are,

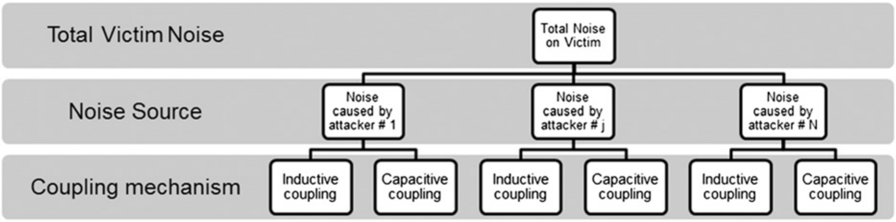

Fig. 2. Types of noise sources and mechanisms.

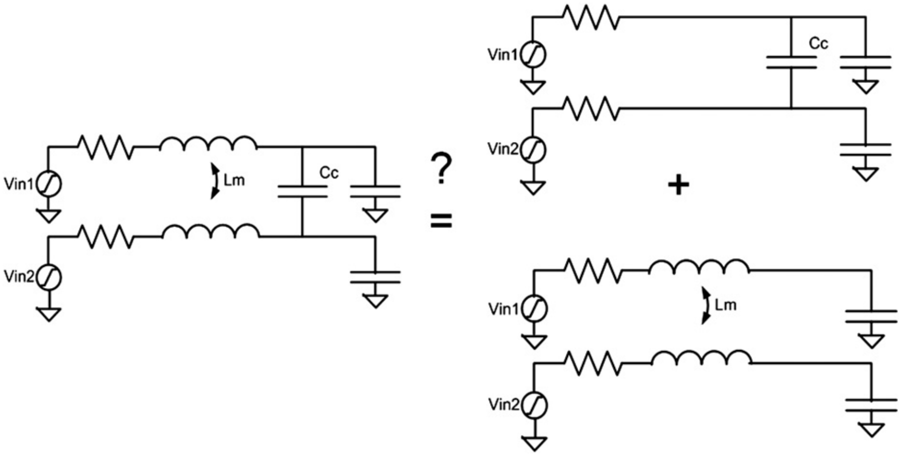

Fig. 3. Decoupling capacitive and inductive noise using additivity.