Incremental Delay Change due to Crosstalk Noise

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ABSTRACT

In this paper we present efficient closed-form formulas to estimate the incremental delay change induced by capacitive interconnect coupling. We also analyze temporal correlations among switching signals and develop criteria for timing window alignment. Our approximations are conservative and yet achieve acceptable accuracy. The formulas are simple enough to be used in the inner loops of static timing analysis.

1. INTRODUCTION

Scaling the feature sizes and lowering the level of power supply voltage has made digital designs vulnerable to noise. Noise sources are spread widely over the chip. Interconnect coupling noise (or crosstalk) becomes a performance-limiting factor and plays a pivotal role in the entire design flow affecting timing closure. Recently, the leading industrial static timing analysis tools, for example PrimeTime-SI [20], have included signal integrity measures related to crosstalk noise.

Substantial effort has been invested into developing accurate and efficient metrics for crosstalk-induced noise and delay [1][3][4][5][8][9][11][16][18][19]. Most of the research efforts for noise estimation have focused on developing formulas for the peak noise pulse amplitude (V_p). Less attention has been given to the peak noise occurring time and the rising and falling transition times because these parameters (other than V_p) don't present an obvious liaison to the timing measurement. On the other hand, various delay metrics have been proposed to include the interconnect coupling effects [1][4][18][10]. However, in static timing analysis, timing windows of each stage need to be adjusted iteratively [2][17], causing repetitive computations of crosstalk-induced delay for each stage. In other words, the current static timing analysis methods suffer from extra CPU time spent on delay computation. Therefore, a simple delay metric which can re-use nominal delay and noise values in the iteration procedure is desirable. *Incremental delay change* is one such metric.

Interconnect coupling-induced delay is caused by the crosstalk noise, therefore, it will be influenced by the noise waveform's features, like peak amplitude, peak noise occurring time, and the rising and falling transition times. Reference [10] points out the relationship between the worst-case coupling-induced delay and the two crosstalk-noise parameters: V_p and T_p. This observation has been used in [15] to find the worst aggressor alignment conditions. Due to the constraints imposed by the actual timing windows, the conditions causing the expected worst-case delay may not always be satisfiable. Therefore, a simple delay-noise relationship considering arbitrary input arrival time are of practical interest. Especially useful would be a simple closed-form metric which captures the *incremental change of delay* caused by the presence of crosstalk noise for arbitrary input arrival times.

A timing window of a signal is the difference between its latest and earliest arrival times. The *overlapping-timing-windows* have been widely used as a condition indicating that the victim's delay can be affected by a particular aggressors' switching. The underlying assumption is that the victim and aggressor should have the same arrival times at the inputs of a logic stage for the mutual influence to occur. This condition is valid only in special cases and does not apply to a wide class of interconnect coupling structures occurring in deep submicron circuits. It no longer serves as a valid constraint for design optimization. However, it is being used due to its simplicity and due to absence of simple closed-form metrics which would capture more realistic conditions for temporal correlation.

In this paper, we examine the incremental delay change caused by crosstalk noise and present simple metrics to account for the change. Based on our new delay metric, we propose a set of new temporal correlation criteria for the alignment of timing windows.

The rest of the paper is organized as follows. Section 2 gives our new incremental delay metric. Section 3 presents our new temporal correlation, followed by a validation of our delay model in section 4. Concluding remarks are given in section 5.

2. INCREMENTAL CHANGE OF DELAY DUE TO CROSSTALK NOISE

In this section, we assume that the following are known: the structure of the coupling circuit, characteristics of the active device, the interconnect and the technology parameters, as well as the parameters for the input signals such as the arrival and transition times. The objective is to obtain the parameters of the output waveform at the victim's receiver node. Considering arbitrary input arrival times, we have developed simple closed-form metrics for the incremental change of delay due to crosstalk noise.

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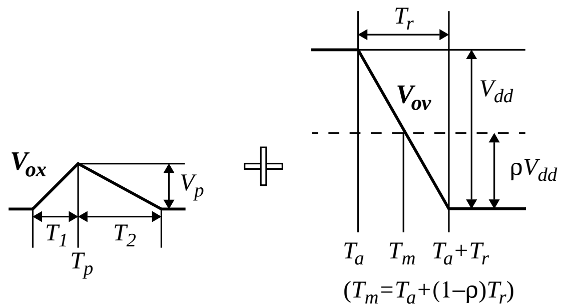


(a) noise produced by switching aggressors on a quiet victim

(b) signal transition at the victim's receiver node when aggressors are quiet

Figure 1. Notations for determination of incremental delay change and temporal correlation between V_{ox} and V_{ov}

Figure 1 introduces the notation. We apply the principle of superposition to compute the delay change in the presence of crosstalk noise. Piecewise-linear simplification is applied to the noise waveform V_{ox}, and to the original signal transition V_{ov} on the victim's receiver node. V_{ox} is produced by switching aggressors on a quiet victim, and V_{ov} is produced when the victim net is making a transition from high to low and aggressors are quiet. These are the parameters for V_{ox}: V_p is the peak noise amplitude, T_p is the peak noise occurring time, T_1 and T_2 are the rising and falling transition times. For V_{ov}, T_a denotes the arrival time of the waveform, and T_r is the transition time. The delay is usually measured when the voltage reaches certain ρV_{dd}, where 50% is a typical value for ρ. T_m is the time when V_{ov}'s voltage reaches ρV_{dd}. The parameters for waveforms V_{ov} and V_{ox} can be computed using an approach described in [3][4][5][18]. Therefore, we consider the following parameters as nominal values which can be re-used: V_p, T_p, T_1, T_2, T_a, and T_r. Other parameters can be derived from these values.

Figure 2 illustrates the conditions when the crosstalk noise V_{ox} affects the signal delay of V_{ov}. We show a delay increase as an example, but other cases can be analyzed in a similar way.

ΔT_d represents the incremental change of delay in the presence of crosstalk noise. According to figure 2 (a) and (b), we have

$$\Delta T_d = 0$$

when

$$T_p \le T_m - T_2 \text{ (noise occurs too early)} \tag{1}$$

or

$$T_p \ge T_m + T_1 \text{ (noise occurs too late)} \tag{2}$$

From equations (1) and (2), we can determine when the noise waveform V_{ox} affects the delay of V_{ov}.

$$T_m - T_2 < T_p < T_m + T_1 \tag{3}$$

However, under specific circumstances, V_{ox} can still affect the delay of V_{ov} even when equation (3) is not satisfied. This is illustrated in figure 2 (c2), with the maximum change of delay occurring when

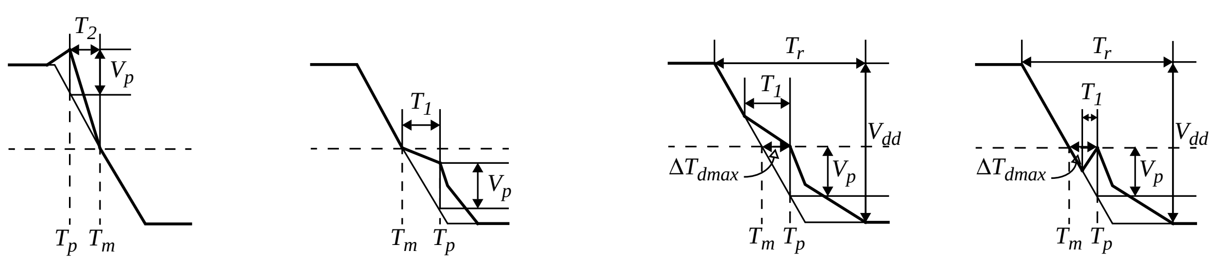
$$T_p = T_m + T_r \cdot \frac{V_p}{V_{dd}} \text{ and } T_1 < T_r \cdot \frac{V_p}{V_{dd}} \tag{4}$$

Figure 2 (c) gives the condition when ΔT_d is maximized. No matter $T_1 \ge T_r \cdot \frac{V_p}{V_{dd}}$ or $T_1 < T_r \cdot \frac{V_p}{V_{dd}}$, we have a maximized delay change

$$\Delta T_d = \Delta T_{dmax} = T_r \cdot \frac{V_p}{V_{dd}} \tag{5}$$

when

$$T_p = T_m + T_r \cdot \frac{V_p}{V_{dd}} \tag{6}$$



(c1) $T_1 \ge T_r \cdot V_p / V_{dd}$

(c2) $T_1 < T_r \cdot V_p / V_{dd}$

(a) Noise occurs too early
$\Delta T_d = 0$ when $T_p \le T_m - T_2$

(b) Noise occurs too late
$\Delta T_d = 0$ when $T_p \ge T_m + T_1$

(c) Noise induced delay change is maximized
$\Delta T_d = \Delta T_{dmax} = T_r \cdot \frac{V_p}{V_{dd}}$ when $T_p = T_m + T_r \cdot \frac{V_p}{V_{dd}}$

Figure 2. Temporal correlation between V_{ox} and V_{ov} from figure 1

Figure 3 illustrates the approach to compute the corresponding delay change under different temporal correlations. The solid thin lines represent the original shape for the falling transition V_{ov}. The solid thick lines represent the combined waveform of V_{ox} and V_{ov} for given temporal correlations. The dotted horizontal lines represent voltage level ρV_{dd}. The intersection point (t_z, V_z) between the solid thick line and the dotted horizontal line indicates the new delay in the presence of crosstalk noise. The delay change is determined by the time difference between T_m and t_z. Namely,

$$\Delta T_d = t_z - T_m \tag{7}$$

where

$$T_m = T_a + (1 - \rho) \cdot T_r \tag{8}$$

Based on our piecewise-linear approximation of the waveform, (t_z, V_z) is the intersection point between the dotted horizontal line and the solid thick straight line whose two endpoints are (t_x, V_x) and (t_y, V_y). Hence,

$$t_z = t_y + (t_x - t_y) \cdot \frac{v_z - v_y}{v_x - v_y} \tag{9}$$

where

$$v_z = \rho \cdot V_{dd} \tag{10}$$

Consider the time T_p as a central point of the combined waveform, indicated by the solid thick curves. The dotted horizontal line intersects the right edge of the solid thick curve when

$$T_m - T_2 < T_p < T_m + T_r \cdot \frac{V_p}{V_{dd}} \text{ (figure 3 (a))} \tag{11}$$

Different cases exist for particular parameter-combinations, as shown in figure 3 (a1)-(a4).

Similarly, the dotted horizontal line intersects with the left edge of the solid thick curve when

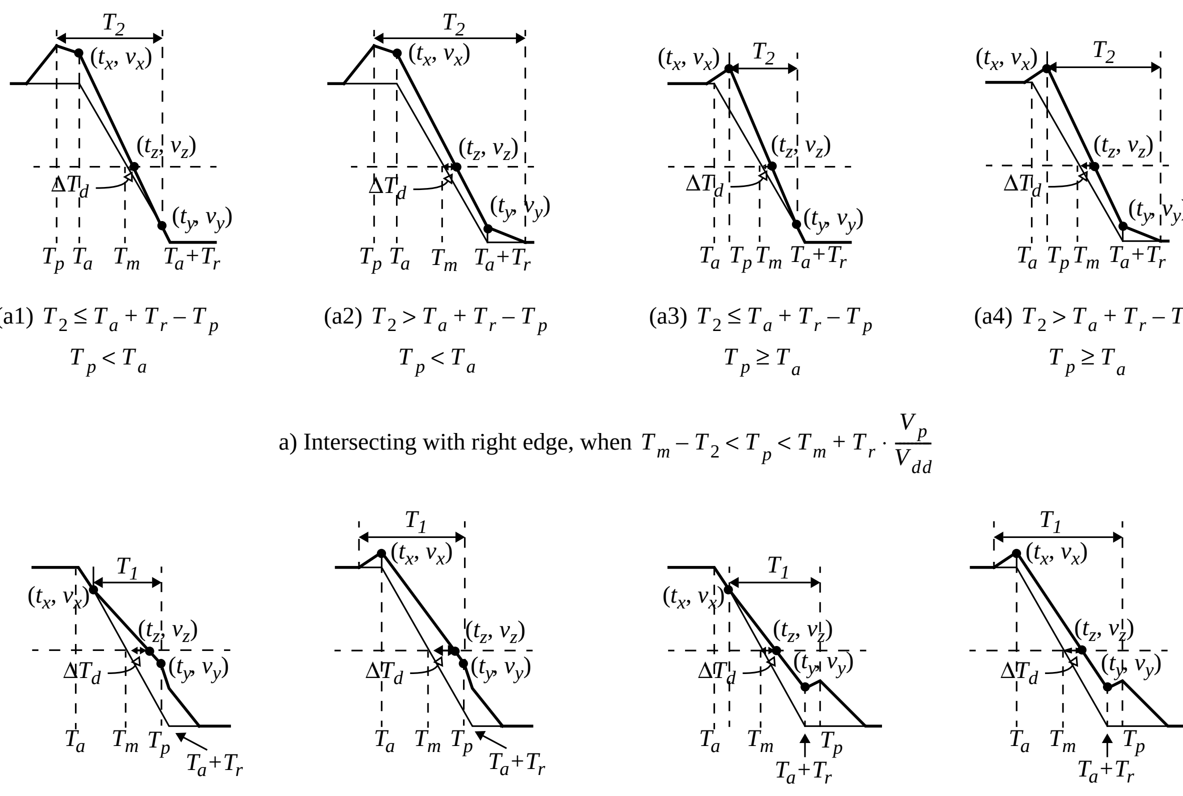
$$T_m + T_r \cdot \frac{V_p}{V_{dd}} < T_p < T_m + T_1 \text{ and } T_r \cdot \frac{V_p}{V_{dd}} < T_1 \tag{12}$$

(figure 3 (b))

Several cases exist for different parameter-combinations, as shown in figure 3 (b1)-(b4)

There is no intersection with the left edge if

$$T_r \cdot V_p / V_{dd} \geq T_1 \tag{13}$$



(a1) $T_2 \leq T_a + T_r - T_p$, $T_p < T_a$

(a2) $T_2 > T_a + T_r - T_p$, $T_p < T_a$

(a3) $T_2 \leq T_a + T_r - T_p$, $T_p \geq T_a$

(a4) $T_2 > T_a + T_r - T_p$, $T_p \geq T_a$

a) Intersecting with right edge, when $T_m - T_2 < T_p < T_m + T_r \cdot \frac{V_p}{V_{dd}}$

(b1) $T_1 \leq T_p - T_a$, $T_p \leq T_a + T_r$

(b2) $T_1 > T_p - T_a$, $T_p \leq T_a + T_r$

(b3) $T_1 \leq T_p - T_a$, $T_p > T_a + T_r$

(b4) $T_1 > T_p - T_a$, $T_p > T_a + T_r$

b) Intersecting with left edge, when $T_m + T_r \cdot \frac{V_p}{V_{dd}} < T_p < T_m + T_1$ and $T_r \cdot \frac{V_p}{V_{dd}} < T_1$

Figure 3. Computing incremental delay change with different temporal correlations

For particular cases, the values for the two endpoints (t_x, V_x) and (t_y, V_y) differ; hence we get different values for the delay change ΔT_d.

- For figure 3(a1)

$$t_x = T_p, \; v_x = V_p + \frac{V_{dd} \cdot (T_a + T_r - T_p)}{T_r}$$

$$t_y = T_p + T_2, \; v_y = \frac{V_{dd} \cdot (T_a + T_r - T_p - T_2)}{T_r}$$

- For figure 3(a2)

$$t_x = T_p, \; v_x = V_p + \frac{V_{dd} \cdot (T_a + T_r - T_p)}{T_r}$$

$$t_y = T_a + T_r, \; v_y = \frac{V_{dd} \cdot (T_p + T_2 - T_a - T_r)}{T_2}$$

- For figure 3(a3)

$$t_x = T_a, \; v_x = V_{dd} + \frac{V_p \cdot (T_p + T_2 - T_a)}{T_2}$$

$$t_y = T_p + T_2, \; v_y = \frac{V_{dd} \cdot (T_a + T_r - T_p - T_2)}{T_r}$$

- For figure 3(a4)

$$t_x = T_a, \; v_x = V_{dd} + \frac{V_p \cdot (T_p + T_2 - T_a)}{T_2}$$

$$t_y = T_a + T_r, \; v_y = \frac{V_{dd} \cdot (T_p + T_2 - T_a - T_r)}{T_2}$$

- For figure 3(b1)

$$t_x = T_p - T_1, \; v_x = \frac{V_{dd} \cdot (T_a + T_r - T_p + T_1)}{T_r}$$

$$t_y = T_p, \; v_y = V_p + \frac{V_{dd} \cdot (T_a + T_r - T_p)}{T_r}$$

- For figure 3(b2)

$$t_x = T_a, \; v_x = V_{dd} + \frac{V_p \cdot (T_a - T_p + T_1)}{T_1}$$

$$t_y = T_p, \; v_y = V_p + \frac{V_{dd} \cdot (T_a + T_r - T_p)}{T_r}$$

- For figure 3(b3)

$$t_x = T_p - T_1, \; v_x = \frac{V_{dd} \cdot (T_a + T_r - T_p + T_1)}{T_r}$$

$$t_y = T_a + T_r, \; v_y = \frac{V_p \cdot (T_a + T_r - T_p + T_1)}{T_1}$$

- For figure 3(b4)

$$t_x = T_a, \; v_x = V_{dd} + \frac{V_p \cdot (T_a - T_p + T_1)}{T_1}$$

$$t_y = T_a + T_r, \; v_y = \frac{V_p \cdot (T_a + T_r - T_p + T_1)}{T_1}$$

Substituting the corresponding values of (t_x, V_x) and (t_y, V_y) into equation (9), then substituting the equations (8) and (9) into (7), we obtain the desired incremental delay change (ΔT_d) due to crosstalk noise.

3. The new temporal correlation

In this section, we will focus on temporal correlation conditions between the victim and aggressor signal arrival times. Those conditions are different from that of the commonly used overlapping-timing-window method.

Figure 4 shows the timing windows for each input signal. We want to observe aggressors one at a time and determine for each of them whether its switching affects the victim's signal delay. We will develop screening rules allowing us to ignore aggressors temporally unrelated to the victim's transition. Our reasoning is based on conditions illustrated in figure 2.

In the traditional methods [7][14] it is assumed that the aggressor affects the victim if these two signals have the same arrival time ($t_A = t_V$). In other words, overlapping of the timing windows is checked, which is equivalent to

$$\exists(t_A = t_V) \text{ if } t_{VR} > t_{AL} \wedge t_{VL} < t_{AR} \qquad (14)$$

where

$$t_A \in (t_{AL}, t_{AR}), \; t_V \in (t_{VL}, t_{VR})$$

According to the analysis in the previous section, we know that equation (14) is not a sufficient condition to guarantee that the interference between the victim and the aggressor will occur. Therefore, we have the following theorems:

Theorem 1: A particular aggressor can be ignored if its corresponding noise waveform at the victim's receiver node does not satisfy the following temporal relation:

$$T_m - T_2^{(j)} < T_p^{(j)} < Min\left(T_m + T_1^{(j)}, T_m + T_r \cdot \frac{V_p}{V_{dd}}\right) \qquad (15)$$

where $T_p^{(j)}$, $T_1^{(j)}$, $T_2^{(j)}$ and $V_p^{(j)}$ are parameters of the noise waveform produced at the victim's receiver node when the corresponding jth aggressor is switching and all the other aggressors are quiet. T_m is given by equation (8).

Proof: The proof is a direct consequence of figure 2.

Now assume for the victim's receiver node that $T_{p0}^{(j)}$ is the peak noise occurring time and T_{a0} is the falling transition's

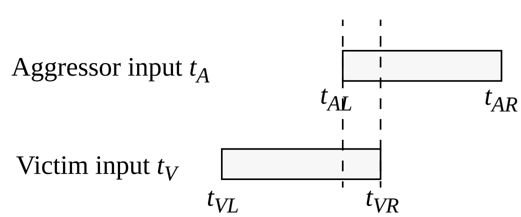


Figure 4. Timing windows for input signals

arrival time. We assume that each driver input's arrival time is 0. The timing windows for V_{ox}'s peak noise occurring time and V_{ov}'s arrival time (figure 1) are given by

$$T_p^{(j)} \in (t_{AL} + T_{p0}^{(j)}, t_{AR} + T_{p0}^{(j)}) \quad (16)$$

$$T_a \in (t_{VL} + T_{a0}, t_{VR} + T_{a0}) \quad (17)$$

Instead of checking the overlap-of-timing-windows, we check the skewed-overlap of timing-windows. Modifications of equation (14) are summarized in the following theorem:

Theorem 2: A necessary condition for the aggressor to affect the victim's delay is that their input signals' timing windows satisfy at least one of the following 4 conditions:

$$\begin{array}{c} (t_{VL} + t_{a0}) + (1-\rho)T_r - T_2^{(j)} < t_{AL}^{(j)} + t_{p0}^{(j)} \\ t_{AL}^{(j)} + t_{p0}^{(j)} < Max\left(t_{VL} + t_{a0} + T_1^{(j)}, t_{VL} + t_{a0} + T_r \cdot \frac{V_p^{(j)}}{V_{dd}}\right) \end{array} \quad (18)$$

$$\begin{array}{c} (t_{VR} + t_{a0}) + (1-\rho)T_r - T_2^{(j)} < t_{AL}^{(j)} + t_{p0}^{(j)} \\ t_{AL}^{(j)} + t_{p0}^{(j)} < Max\left(t_{VR} + t_{a0} + T_1^{(j)}, t_{VR} + t_{a0} + T_r \cdot \frac{V_p^{(j)}}{V_{dd}}\right) \end{array} \quad (19)$$

$$\begin{array}{c} (t_{VL} + t_{a0}) + (1-\rho)T_r - T_2^{(j)} < t_{AR}^{(j)} + t_{p0}^{(j)} \\ t_{AR}^{(j)} + t_{p0}^{(j)} < Max\left(t_{VL} + t_{a0} + T_1^{(j)}, t_{VL} + t_{a0} + T_r \cdot \frac{V_p^{(j)}}{V_{dd}}\right) \end{array} \quad (20)$$

$$\begin{array}{c} (t_{VR} + t_{a0}) + (1-\rho)T_r - T_2^{(j)} < t_{AR}^{(j)} + t_{p0}^{(j)} \\ t_{AR}^{(j)} + t_{p0}^{(j)} < Max\left(t_{VR} + t_{a0} + T_1^{(j)}, t_{VR} + t_{a0} + T_r \cdot \frac{V_p^{(j)}}{V_{dd}}\right) \end{array} \quad (21)$$

Proof: There are four combinations for the boundary value of timing windows:

$$(t_{AL} + T_{p0}^{(j)}, t_{VL} + T_{a0}), \ (t_{AL} + T_{p0}^{(j)}, t_{VR} + T_{a0}),$$

$$(t_{AR} + T_{p0}^{(j)}, t_{VL} + T_{a0}), \text{ and } (t_{AR} + T_{p0}^{(j)}, t_{VR} + T_{a0}).$$

Substituting each combination into equation (15), we get the above four expressions.

4. MODEL VALIDATION

We have verified our new delay metric in 0.25μm technology for a variety of coupling circuits, including two-pin nets and RC trees, described in figure 5. For each type of coupling circuit (a1, a2, b1, and b2), we select 10 different combinations of parameters (driver sizes, coupling lengths, transition times, arrival times, etc.), and compute the incremental delay change for each case. We first obtain the parameters for V_{ox} when the victim net is quiet and aggressor net is switching, then the parameters for V_{ov} when the victim is switching and the aggressor is quiet. Next use the conditions given in figure 3 to select suitable expressions to compute the corresponding values of (t_x, V_x) and (t_y, V_y). After a few substitutions, we can use equation (7) to obtain the desired incremental delay change (ΔT_d) due to crosstalk noise. Table 1 shows a sample case for each coupling circuit given in figure 5, and the corresponding ΔT_d obtained through both HSpice simulation and our calculations. The error percentage of our method compared to simulation result for each sample case is given in the column labeled "Error (%)". The average error percentage over 10 cases for each circuit (a1, a2, b1, b2) is given in the column labeled "Average error (%)". The good accuracy of our method supports our claims that the temporal correlation given in figure 2 is correct and that the incremental delay change computed based on the temporal correlation is accurate.

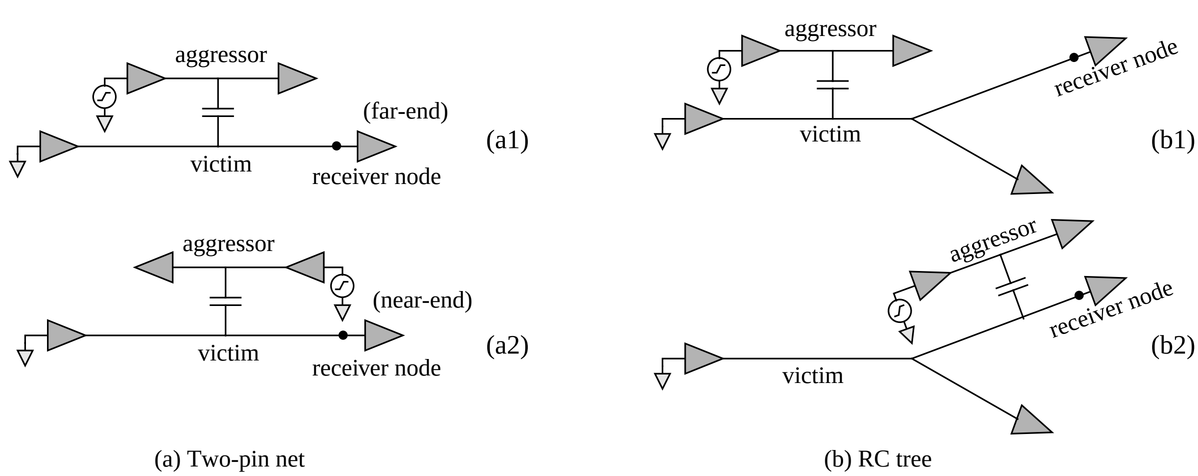


Figure 5. Coupling circuit structure for experiments

Table 1: Error percentage for our new delay metrics

Parameters	Normans noise: V_{ox}				Normans delay: V_{ov}		Change of delay: ΔT_d (ps)		Error (%)	Average error (%)
	V_p (volt)	T_p (ps)	T_1 (ps)	T_2 (ps)	T_a (ps)	T_r (ps)	Simulation	Our method		
Circuit (a1)	0.65	151	118	142	69	196	44	48	9%	11%
Circuit (a2)	0.85	220	114	146	48	206	59	66	12%	13%
Circuit (b1)	0.72	110	147	107	77	181	14	16	14%	17%
Circuit (b2)	1.08	290	97	131	83	275	122	133	9%	14%

5. CONCLUSION

In this paper, we have proposed new metrics for the incremental delay change due to crosstalk noise. These metrics allow us to capture the temporal correlations of the victim and aggressors' switching expressed by timing windows alignment. Based on the analysis of the timing metrics we have developed simple closed-form criteria for the aggressor-screening. Our work can significantly save iterative delay computation effort, and it provides more accurate metrics for timing window alignment in static timing analysis.

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