Short Papers

Considering Crosstalk Effects in Statistical Timing Analysis

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***Abstract*—The impact of crosstalk effects on timing performance is increasing as the device geometries are shrinking. As a consequence, crosstalk effects need to be considered in statistical timing analysis for higher accuracy. In this letter, the statistical interconnect delay due to crosstalk effects is calculated based on a piecewise linear delay change curve model (PLDM), which enables fast closed-form analytical delay evaluation. The PLDM-based method is independent of the delay change characteristics and is able to handle both Gaussian and non-Gaussian input skew distributions. The proposed method can be integrated into a statistical timing analyzer with runtime proportional to the number of samples for PLDM characterization. Experimental results demonstrate that the proposed method can estimate the delay mean and standard deviation for coupled RC interconnects at PTM 65-nm technology with errors better than −0.07% and −1.23%, respectively, with only 20 samples for PLDM characterization. In addition, the proposed method typically achieves two to three orders of magnitude speedup compared to Monte Carlo simulations.**

***Index Terms*—Crosstalk effect, input skew, interconnect delay, process variation, statistical timing analysis.**

I. Introduction

Due to imperfections in fabrication processes, e.g., photolithography and etching, when the device geometries are scaled down, random process variations result in statistical arrival time and delay distributions. Also, the impact of crosstalk effects on delay increases with each new technology generation. As the spacing between wires continues to shrink, the coupling capacitance starts to dominate the ground capacitance. If the victim and aggressor inputs switch in the same direction, coupling effects can speed up the victim transition and reduce the interconnect delay. On the other hand, if victim and aggressor inputs switch in opposite directions, victim transitions slow down, and thus victim delay increases. Crosstalk effects may increase path delay by up to 30%, making it the biggest variation component within a die [2]. According to our experimental results in [6], not considering crosstalk effects for a pair of 500 μm coupled intermediate interconnects causes up to 139% delay mean error and 83% delay standard deviation error. Therefore, to estimate interconnect delay distributions accurately, considering crosstalk effects is an absolute necessity for statistical timing analysis.

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The interconnect delay distribution in the presence of crosstalk effects depends on several factors, such as aggressor and victim slew rates, driver strength, and input skew, which is defined as the aggressor–victim input arrival time difference. In addition, an aggressor can couple delay noise to a victim only when the aggressor transition is temporally close to the victim transition. When the input skew varies in close proximity to zero, the victim delay changes as a function of input skew, which is called delay change curve (DCC). Consequently, the input skew becomes a significant variation source and should be taken into account for statistical interconnect delay calculation [3]–[5], [8].

In order to consider input skew variations for statistical interconnect delay calculation, triangular distribution is assumed for arrival time in [11]. In addition, the victim delay with respect to input skew is modeled in a quadratic DCC model in [5] and a piecewise quadratic DCC model in [3] and [4]. Based on the quadratic DCC model, the method in [5] uses thousands of Monte Carlo (MC) samples, which limits the efficiency for statistical timing analysis. The method proposed in [3] and [4] models the original DCC as a bathtub-shaped model and requires a Gaussian-distributed input skew distribution. However, due to the process variations in previous stages, input skew may be non-Gaussian distributed.

In this letter, we present a piecewise linear DCC model (PLDM) for the dependence of victim delay on input skew, and a PLDM-based statistical delay calculation method. The proposed method has the following features.

1) There is no assumption for the original DCC shape.
2) It can handle both Gaussian and non-Gaussian input skew variations and process variations.
3) Delay is calculated analytically based on closed-form expressions.
4) A worst/best-case delay calculation technique from statistical input skew windows is presented to apply the PLDM-based method in statistical static timing analysis (SSTA) engines.

Compared to our published work [6], the method proposed in this letter is more general, without any limitation to the DCC shape, and more accurate in many practical circumstances.

II. Problem Formulation

Due to the process variations, stage delay becomes a statistical quantity, and hence victims and aggressors have statistical input arrival time distributions (Fig. 1). Since input skew is the aggressor–victim arrival time difference, the input skew of a pair of coupled wires becomes statistical, leading to interconnect delay variations. In addition, due to the process variations in the interconnect under analysis, the resistance (R_w), ground capacitances (C_g), and coupling capacitance (C_c) of the interconnect model shown in Fig. 1 also become statistical, causing interconnect delay variabilities. As a consequence, we need to calculate the delay of a coupled interconnect system in the

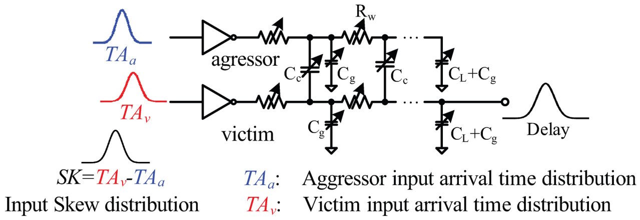

Fig. 1. Crosstalk-aware interconnect delay calculation.

presence of both input skew variations and process variations. According to [3], [4], and [8], the wire process variations (PVs) and input skew (SK) variations can be considered independent without significant loss of accuracy. Therefore, efficiency can be improved for delay calculation with

$$\mu_D = \mu_{D_{sk}} + \mu_{D_{pv}} - D_0 \tag{1}$$

$$\sigma_D^2 = \sigma_{D_{sk}}^2 + \sigma_{D_{pv}}^2 \tag{2}$$

where μ_D and σ_D^2 are the mean and variance of the interconnect delay, $\mu_{D_{sk}}$ and $\sigma_{D_{sk}}^2$ are the mean and variance of the SK-induced interconnect delay with all process variations in the interconnects set to their nominal values, $\mu_{D_{pv}}$ and $\sigma_{D_{pv}}^2$ are the mean and variance of the PV-induced interconnect delay with victim–aggressor input arrival times set to their nominal values, and D_0 is the nominal delay value.

For higher efficiency, linear driver models are typically constructed and used for interconnect delay calculation in timing analysis methods [3]–[5], [8], [14]. The application of linear driver models allows the principle of linear superposition. Thus, it is straight-forward to extend a delay calculation method for a single victim–aggressor pair to estimate the delay variations caused by multiple aggressors using linear superposition. Additionally, the efficiency can also be improved by considering only the aggressors that contribute significantly to crosstalk noise and ignoring the rest.

Based on the superposition formulated in (1) and (2), the following methods are required to consider crosstalk effects for interconnect delay calculation: 1) PV-induced interconnect delay calculation ($\mu_{D_{pv}}$ and $\sigma_{D_{pv}}^2$) and 2) SK-induced interconnect delay calculation ($\mu_{D_{sk}}$ and $\sigma_{D_{sk}}^2$). Many PV-induced interconnect delay calculation methods have been proposed in statistical timing analysis methods [9], [10], [12], [14]–[16]. The closed-form computation in [14] and [15] and the asymptotic waveform evaluation-based method in [16] can also be used for PV-induced delay calculation. In contrast, SK-induced interconnect delay calculation is still challenging. The difficulty lies in the consideration of input skew variations for delay calculation.

III. PLDM-Based Interconnect Delay Calculation

A. *Piecewise Linear DCC Model (PLDM)*

The victim delay change curve with respect to input skew value (s) calculated in Spice-like engines ($D_{sk}(s)$) can have different shapes. For instance, the original $D_{sk}(s)$ of a pair of coupled 200-μm intermediate wires has different shapes as shown in Fig. 2:

1) WI, when $R_d = 50\ \Omega$ and $T_r = 20$ ps;
2) WII, when $R_d = 50\ \Omega$ and $T_r = 50$ ps;

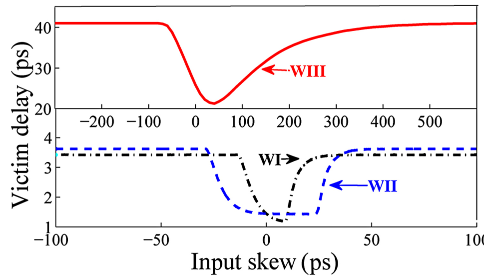

Fig. 2. DCC shapes of coupled intermediate wires in 65-nm PTM [1] technology when both victim and aggressor inputs switch in the same direction.

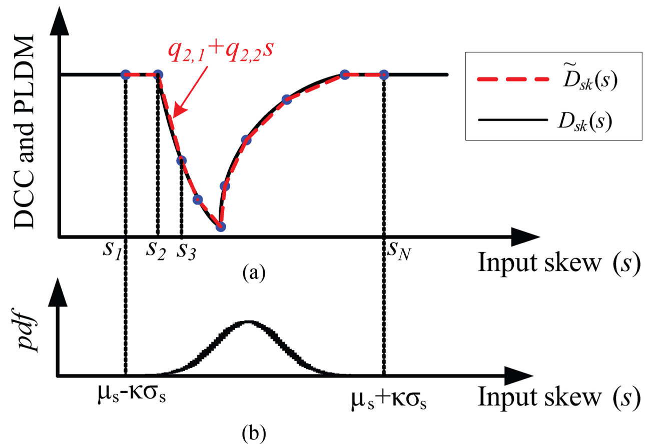

Fig. 3. (a) PLDM model for SK-induced interconnect delay calculation. (b) Truncated single input skew distribution where $\kappa \approx$ 4–6.

3) WIII, when $R_d = 1500\ \Omega$ and $T_r = 50$ ps, where R_d denotes driver resistance and T_r is input transition time.

Therefore, it is not accurate enough to model $D_{sk}(s)$ as a specific shape, such as the bathtub-shape used in [3] and [4] or the quadratic shape used in [5].

In order to account for arbitrary $D_{sk}(s)$ shapes, we model it as a multisegment PLDM, denoted as $\tilde{D}_{sk}(s)$ as shown in Fig. 3(a). The input skew distribution is truncated within $[\mu_s - \kappa\sigma_s, \mu_s + \kappa\sigma_s]$ as shown in Fig. 3(b), where σ_s denotes the standard deviation of input skew and κ is a constant. We choose $\kappa \approx$ 4–6 so that we can define the *pdf* of the input skew as zero ($f_s(s) = 0$) when $s \le \mu_s - \kappa\sigma_s$ and $s \ge \mu_s + \kappa\sigma_s$. Within the range $[\mu_s - \kappa\sigma_s, \mu_s + \kappa\sigma_s]$, N input skew samples are selected to obtain a $N-1$ segment PLDM with N crossing points. The N crossing points are denoted as $\mu_s - \kappa\sigma_s = s_1 < s_2 < \cdots < s_{N-1} < s_N = \mu_s + \kappa\sigma_s$. Within each segment $[s_i, s_{i+1}]$ where $i = 1 : N-1$, the victim delay is modeled as a straight line $\tilde{D}_{sk}(s) = q_{i,1} + q_{i,2}s$ ($s \in [s_i, s_{i+1}]$), where $q_{i,1}$ and $q_{i,2}$ are the coefficients of the ith PLDM segment. $\tilde{D}_{sk}(s)$ ($s \in [s_i, s_{i+1}]$) is obtained based on two consecutive crossing points $(s_i, D_{sk}(s_i))$ and $(s_{i+1}, D_{sk}(s_{i+1}))$. Hence, the PLDM consists of piecewise linear lines between every two consecutive samples, as shown in Fig. 3(a).

B. *PLDM-Based Calculation Method and Algorithm*

In most SSTA methods, the arrival time and delay are modeled using linear or quadratic delay models. Since input skew is defined by the difference between aggressor arrival time and victim arrival time, input skew can then also be expressed as a linear or quadratic function of the process variations in statistical timing analysis. Thus, the input skew may be non-Gaussian distributed if the process variation distributions are not Gaussian. Therefore, given the probability density function (pdf) or cumulative density function (cdf) of an input skew distribution, an SK-induced interconnect delay calculation method without any Gaussian assumption for the input skew distribution is desired.

Based on the characterized PLDM model, the mean and standard deviation of the interconnect delay caused by an input skew distribution can be calculated as

$$\begin{aligned} \mu_{D_{sk}} &= E\{D_{sk}(s)\} \approx E\{\tilde{D}_{sk}(s)\} = \int_{-\infty}^{+\infty} \tilde{D}_{sk}(s) f_s(s) ds \\ &= \sum_{i=1}^{N-1} \int_{s_i}^{s_{i+1}} (q_{i,1} + q_{i,2}s) f_s(s) ds \\ &= \sum_{i=1}^{N-1} \left(q_{i,1}(F_s(s_{i+1}) - F_s(s_i)) + q_{i,2} G(s_i, s_{i+1}, f_s) \right) \end{aligned} \quad (3)$$

$$\begin{aligned} \sigma^2_{D_{sk}} &= E\{D^2_{sk}(s)\} - (E\{D_{sk}(s)\})^2 \approx \varrho^2_{D_{sk}} - \mu^2_{D_{sk}} \\ &= \sum_{i=1}^{N-1} \int_{s_i}^{s_{i+1}} (q_{i,1} + q_{i,2}s)^2 f_s(s) ds - \mu^2_{D_{sk}} \\ &= \sum_{i=1}^{N-1} (q^2_{i,1}(F_s(s_{i+1}) - F_s(s_i)) + q^2_{i,2} H(s_i, s_{i+1}, f_s) \\ &\quad + 2q_{i,1}q_{i,2} G(s_i, s_{i+1}, f_s)) - \mu^2_{D_{sk}} \end{aligned} \quad (4)$$

where $\varrho^2_{D_{sk}} = E\{\tilde{D}^2_{sk}(s)\}$, $F_s(\cdot)$ and $f_s(\cdot)$ are the *cdf* and *pdf* of the input skew variation, respectively. $G(s_i, s_{i+1}, f_s) = \int_{s_i}^{s_{i+1}} s f_s(s) ds$ and $H(s_i, s_{i+1}, f_s) = \int_{s_i}^{s_{i+1}} s^2 f_s(s) ds$. Given the *pdf* or *cdf* of the input skew distribution, such as a Gaussian or an uniform distribution, μ_{sk} and σ^2_{sk} can be computed analytically in closed form. In the case of a Gaussian distribution, the following closed-form expressions are substituted into (3) and (4):

$$G(s_i, s_{i+1}, f_s) = \frac{\sigma_s}{\sqrt{2\pi}} \left(e^{-z_0^2/2} - e^{-z_1^2/2} \right) + \mu \left(\Phi(z_1) - \Phi(z_0) \right) \quad (5)$$

$$\begin{aligned} H(s_i, s_{i+1}, f_s) &= \frac{\sigma^2_s}{\sqrt{2\pi}} \left(z_0 e^{-z_0^2/2} - z_1 e^{-z_1^2/2} \right) \\ &+ (\mu^2_s + \sigma^2_s)(\Phi(z_1) - \Phi(z_0)) + \frac{2\mu_s \sigma_s}{\sqrt{2\pi}} \left(e^{-z_0^2/2} - e^{-z_1^2/2} \right) \end{aligned} \quad (6)$$

where $z_0 = (s_i - \mu_s)/\sigma_s$, $z_1 = (s_{i+1} - \mu_s)/\sigma_s$, and $\Phi(z_0) = \frac{1}{2}\left[1 + erf\left(\frac{z_0}{\sqrt{2}}\right)\right]$ is the cdf of the standard normal distribution. Based on the theory introduced above, we calculate the crosstalk-aware interconnect delay by using Algorithm 1.

IV. Delay Calculation From Input Skew Window

In SSTA, the maximum (latest) and the minimum (earliest) of the arrival time distributions are calculated and propagated. Therefore, the victim (aggressor) has an earliest input arrival time distribution and a latest input arrival time distribution. As a consequence, the input skew window has minimum and maximum input skew distributions, which are denoted as SK_e and SK_l, respectively as shown in Fig. 4. Hence, in order to apply the proposed interconnect delay calculation method for SSTA engines, a worst/best-case delay calculation from input skew is required.

Algorithm 1 PLDM-based SK-induced interconnect delay calculation

Input: N crossing points in PLDM model $s_1 \sim s_N$.
Input: Coefficients of the PLDM line in each segment $q_{i,1}$ and $q_{i,2}$ $(i = 1 : N-1)$.
Output: Mean and standard deviation of SK-induced interconnect delay: $\mu_{D_{sk}}$ and $\sigma_{D_{sk}}$.
Initialization $\mu_{D_{sk}} = 0$, $\varrho^2_{D_{sk}} = 0$
for $i = 1 : N-1$ **do**
$\mu_{D_{sk}} = \mu_{D_{sk}} + q_{i,1}(F_s(s_{i+1}) - F_s(s_i))$
$+ q_{i,2} G(s_i, s_{i+1}, f_s)$
$\varrho^2_{D_{sk}} = \varrho^2_{D_{sk}} + q^2_{i,1}(F_s(s_{i+1}) - F_s(s_i))$
$+ 2q_{i,1}q_{i,2} G(s_i, s_{i+1}, f_s) + q^2_{i,2} H(s_i, s_{i+1}, f_s)$
end for
$\sigma^2_{D_{sk}} = \varrho^2_{D_{sk}} - \mu^2_{D_{sk}}$

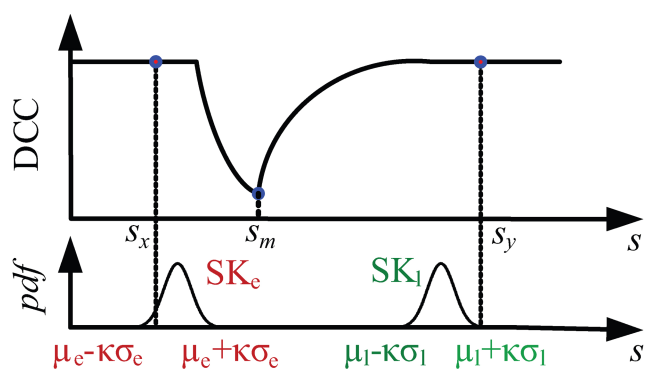

Fig. 4. Interconnect delay calculation from an input skew window.

According to [8], for worst-case interconnect delay calculation, SK_e and SK_l distributions shown in Fig. 4 can be computed based on the latest arrival time distribution of victim, and the latest and earliest arrival time distributions of aggressor. SK_e and SK_l are truncated to $[\mu_e - \kappa\sigma_e, \mu_e + \kappa\sigma_e]$ and $[\mu_l - \kappa\sigma_l, \mu_l + \kappa\sigma_l]$, respectively, where $\kappa \geq 4$. SK_e and SK_l form the input skew window.

After obtaining the input skew window, we need to calculate the effective input skew distribution for the worst/best-case SK-induced interconnect delay calculation. As illustrated in Fig. 4, for an arbitrary $D_{sk}(s)$, $[-\infty, s_x]$, and $[s_y, +\infty]$ are the input skew ranges, where the aggressor does not couple noise to the victim. s_m denotes the point where $D_{sk}(s_m)$ is the minimum delay value (or the maximum value when victim–aggressor switch in opposite directions). μ_e and μ_l are the mean value of the SK_e and SK_l distributions, respectively.

To be able to extract the effective input skew distribution from the input skew window, according to [8] and [6] we need to distinguish the following situations (illustrated in Fig. 4).

1) $\mu_l + \kappa\sigma_l < s_x$ or $\mu_e - \kappa\sigma_e > s_y$. Victim delay is not impacted by the crosstalk noise coupled from the aggressor.
2) $\mu_l < s_m$. $D_{sk}(s)$ is a decreasing curve (or an increasing curve if the victim–aggressor pair switch in opposite directions), thus, SK_l is the effective input skew distribution for the best/worst-case delay calculation.

3) $\mu_e > s_m$. $D_{sk}(s)$ is an increasing curve (or a decreasing curve if the victim–aggressor pair switch in opposite directions), thus, SK_e is the effective input skew distribution for the best/worst-case delay calculation.
4) $\mu_e < s_m$ and $\mu_l > s_m$. In the input skew window, any input skew distribution is possible. Hence, $D_{sk}(s_m)$ is the best-case delay (or the worst-case delay if the victim–aggressor pair switch in opposite directions). By using the effective input skew distribution, the PLDM-based delay calculation method presented in Section III can be used to calculate the worst/best-case delay.

V. Complexity Analysis

The characterization of the proposed PLDM model has a complexity of $O(N)$, where N is the number of input skew samples for PLDM characterization. For each input skew sample, the victim delay is simulated by either Spice-like engines or model order reduction-based interconnect delay calculation techniques. Based on the PLDM, the calculation of interconnect delay distribution takes $O(N-1)$ time by using Algorithm 1. However, based on the closed-form expressions, the calculation time is negligible compared to the N simulations required for the PLDM characterization. As a consequence, the PLDM characterization runtime dominates the runtime of the PLDM-based interconnect delay calculation method, which has $O(N)$ complexity.

Therefore, the value of N should be chosen based on an accuracy–efficiency tradeoff, which depends on the range $[\mu_s - \kappa\sigma_s, \mu_s + \kappa\sigma_s]$. As shown in Section VI, $N \approx 20$ is sufficient to obtain a PLDM model for accurate delay calculation. The samples are uniformly taken within the time range $[\mu_s - \kappa\sigma_s, \mu + \kappa\sigma_s]$ since the PLDM shape is unknown before sampling. As illustrated in Fig. 4, an aggressor couples delay noise to a victim wire within the input skew range $[s_x, s_y]$. Therefore, nonuniform sampling can be applied if: 1) $\mu_s + \kappa\sigma_s > s_y$ and $\mu_s - \kappa\sigma_s < s_y$, and 2) $\mu_s - \kappa\sigma_s < s_x$ and $\mu_s + \kappa\sigma_s > s_x$. Only two to three samples are necessary within the range $[s_y, \mu_s + \kappa\sigma_s]$ for case 1 and $[\mu_s - \kappa\sigma_s, s_x]$ for case 2. If N_{MC} MC trials are required for sufficient confidence in MC simulations, our method achieves N_{MC}/N times speed-up, which is typically two or three orders of magnitude faster.

VI. Experimental Results

We verified the proposed method on a couple of 200-μm intermediate wires using the PTM 65-nm technology [1]. Based on a $\pi 3$ model for the wires, the simulated DCC is illustrated in Fig. 5. The relative errors of delay mean (μ_D) and standard deviation (σ_D) calculated by using the five-segment bathtub-shape model [3], [4], [6] and by using the proposed PLDM (with only 20 samples) are listed in Table I. The victim–aggressor input arrival time variation is extracted from an INV_X4 gate with transistor length variation $3\sigma_L = 30\%\mu_L$, resulting in an input skew with variability $3\sigma_s = 20$ ps. The mean value of the input skew distribution (μ_s) is varied to verify the proposed method under different crosstalk strengths. Since MC simulation results do not converge using 5K MC trials, in the end, all relative errors are compared to 50K Spectre MC simulations.

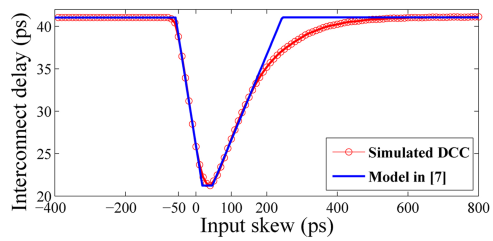

Fig. 5. Simulated DCC with respect to input skew.

TABLE I
μ_D AND σ_D ERRORS FROM DIFFERENT APPROACHES

Methods	5-segment bathtub-shaped model		PLDM-based method	
μ_s (ps)	μ_D error (%)	σ_D error (%)	μ_D error (%)	σ_D error (%)
-30	0.35	0.76	-0.01	-0.20
-10	-0.10	1.26	-0.01	-0.14
0	0.14	-9.02	-0.02	-0.09
100	0.40	7.16	0.01	-0.49
200	-4.13	-83.76	0.00	-1.21

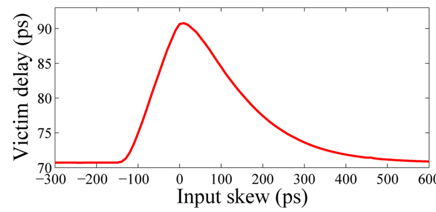

Fig. 6. Simulated delay change curve with respect to input skew.

According to Fig. 5, the proposed five-segment bathtub-shape model in [3], [4], and [6] is accurate when the original DCC is close to a bathtub shape but is erroneous if the DCC differs from that. For instance, it is clear from Fig. 5 that the five-segment bathtub-shape model cannot capture the delay well when the input skew is within [0, 100] ps and [180 ps, 400 ps]. As a consequence, when the input skew distribution is inside these ranges (e.g., $\mu_s = 200$ ps), the methods in [3], [4], and [6] result in larger errors, as shown in Table I.[1] In contrast, the PLDM-based method proposed in this letter is able to capture any realistic DCC shape, and thus, it can estimate the delay μ_D and σ_D with high accuracy.

The PLDM-based method in Algorithm 1 is independent of the $D_{sk}(s)$ shape, and thus, is a general delay calculation method. We also verified this method on a pair of coupled wires extracted from PTM 65-nm global wires with 500 resistors and 750 ground and coupling capacitors. Aggressor and victim inputs switch in opposite directions. According to the simulated DCC of this system shown in Fig. 6, the crosstalk effects increase interconnect delay.

As pointed out in Section V, the PLDM-based interconnect delay calculation method has a complexity of $O(N)$, where N denotes the number of samples. Additionally, the accuracy of the proposed method is influenced by N. In order to verify the N value required by large input skew variabilities for the PLDM characterization, $3\sigma_s = 120$ ps and $\kappa = 4$ are chosen for sample selection and delay calculation. Based on these settings, the characterization is performed within

[1] It is mentioned in [3], [4], and [6] that more segments can be used for higher accuracy. However, it requires a large sample number to obtain the whole simulated DCC, and there is no general method for an optimum model.

TABLE II
STATISTICAL INTERCONNECT DELAY CALCULATION ACCURACY WITH DIFFERENT SAMPLE NUMBERS N AND INPUT SKEW DISTRIBUTIONS μ_s

μ_s (ps)	-100	-50	0	50	100	200
N	Relative Error of Delay Standard Deviation σ_D					
10	-1.74%	-2.79%	-2.51%	-3.96%	-1.21%	0.29%
20	-0.49%	-0.48%	-0.47%	-1.23%	-0.44%	0.22%
30	-0.16%	-0.12%	-0.25%	0.23%	0.12%	0.21%
50	0.02%	0.01%	0.16%	0.09%	0.03%	0.24%

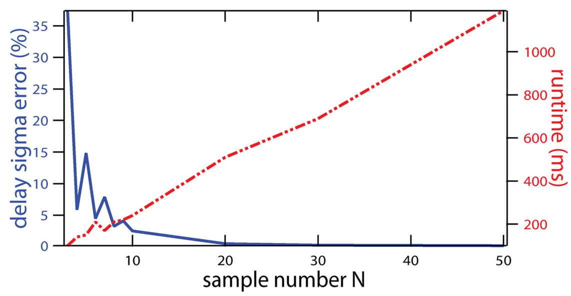

Fig. 7. Delay σ errors and runtime with respect to sample number N.

$[\mu_s - 4\sigma_s, \mu_s + 4\sigma_s]$. We use different N values to verify the relationship between N and accuracy.

The delay standard deviation (σ_D) from the PLDM-based calculation method are compared to 50 K Spectre MC simulations, with different N and μ_s as shown in Table II. The delay mean errors are all within 0.2%. The N input skew samples are uniformly selected from $[\mu_s - 4\sigma_s, \mu_s + 4\sigma_s]$. Besides these experiments, we also verified the proposed method in many other experiments with different σ_s, μ_s and coupled interconnect structures. From the experimental results, we have the following two observations: 1) the proposed PLDM-based method has much better accuracy when using $N = 20$ than choosing $N \leq 10$, and 2) the accuracy is not improved significantly when using $N > 20$. Therefore, $N = 20$ is sufficient for μ_D and σ_D calculation with high accuracy. By using $N = 20$, the proposed method achieves maximum μ_D error of $|-0.07\%|$ and maximum σ_D error of $|-1.23\%|$ with three orders of magnitude speedup compared to 50 K Monte Carlo simulations.

The delay standard deviation relative error magnitude and runtime with respect to the sample number N when $\mu_s = 0$ are shown in Fig. 7. The DCC curve is characterized by using transient analysis in spectre. We can see that the absolute value of the delay σ_D errors decreases with N while the runtime increases almost linearly with N. Additionally, Fig. 7 illustrates that the even number of N offers better accuracy than their successive odd numbers. When even N is used, μ_s is taken as one sample, and thus, provides better accuracy. It is noted that the runtime can be significantly reduced by using simpler models (e.g., model order reduction techniques) and faster interconnect delay calculation methods for characterization.

VII. CONCLUSION

Crosstalk-aware statistical interconnect delay calculation is significant for accurate statistical timing analysis tools. In this letter, statistical interconnect delay variations caused by input skew are studied since the input skew variation is a significant variation source due to crosstalk effects. We model the victim delay as a PLDM. Based on the PLDM model, the mean and variance of interconnect delay can be calculated based on closed-form expressions, which can handle both Gaussian and non-Gaussian input skew distributions. A PLDM-based worst/best-case interconnect delay calculation method from input skew window is also presented, so the proposed method can be integrated into SSTA engines. The proposed method has complexity of $O(N)$, where N is the sample number for PLDM characterization. Experimental results show that $N = 20$ is sufficient for high accuracy and the proposed method can estimate the delay mean and delay standard deviation with errors of $\leq |-0.07\%|$ and $\leq |-1.23\%|$, respectively for coupled RC interconnects in PTM 65-nm technology.

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