A Novel High-Frequency Simulation Methodology for IBIS Models Utilizing Verilog-AMS Dynamic Parameter Compensation

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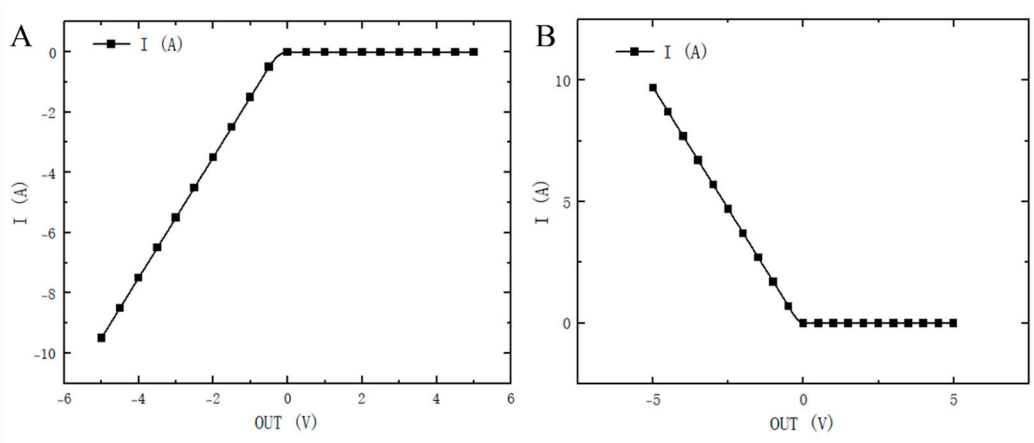


Figure S1. (A) Result of Sweeping [Pulldown]; (B) Result of Sweeping [Pullup]

1. Empirical Parameter Adjustment Based on Single Pulse

Here, $n_A T_0$, $n_B T_0$, $n_C T_0$, $n_D T_0$, $n_E T_0$, $n_F T_0$, $n_G T_0$, $n_H T_0$ represent the critical values of pulse width corresponding to the need to start adjusting x or y independently in the eight scenarios, respectively; $m_A T_0$, $m_B T_0$, $m_C T_0$, $m_D T_0$, $m_E T_0$, $m_F T_0$, $m_G T_0$, $m_H T_0$ represent the critical values of pulse width corresponding to the need to start adjusting x and y simultaneously in the eight scenarios, respectively. n_A~n_H and m_A~m_H are all positive integers.

Table S1. Empirical Table for α_1 with Single Pulse Input

$W_{IBIS} > W_{SPICE}$, $\frac{\delta V}{\delta x} > 0$; $W_{IBIS} < W_{SPICE}$, $\frac{\delta V}{\delta x} < 0$	
PW	α_1
$(n_1+1)T_0$	1
$n_1 T_0$	α_{1,n_1}
$(n_1-1)T_0$	α_{1,n_1-1}
…	…
$2T_0$	α_{12}
T_0	α_{11}

This table presents the empirical mapping relationship of the multiplicative correction coefficient α_1 for the pull-up factor kpu varying with pulse width PW. PW is expressed as an integer multiple of the base time unit T_0. When PW is greater than or equal to $(n_1+1)T_0$, $\alpha_1 = 1$ (no correction needed); when PW = $n_1 T_0$,

takes the value $\alpha_{1,n1}$; as PW decreases, α_1 gradually deviates from 1. The minimum α_{11} at the end of the table corresponds to T_0, indicating that the narrower the pulse width, the larger the magnitude of reduction required for k_{pu}. This table structure forms the basis for constructing the lookup table matrix. In practical applications, specific numerical values need to be filled in through iterative simulation. "n_1" in the table is the critical pulse width index, determined by the device characteristics.

Table S2. Empirical Table for α_2 with Single Pulse Input

$W_{IBIS} > W_{SPICE}, \frac{\delta V}{\delta y} > 0; W_{IBIS} < W_{SPICE}, \frac{\delta V}{\delta y} < 0$	
PW	α_2
$(n_2 + 1)T_0$	1
$n_2 T_0$	α_{2,n_2}
$(n_2 - 1)T_0$	α_{2,n_2-1}
…	…
$2T_0$	α_{22}
T_0	α_{21}

This table defines the variation of the multiplicative correction coefficient α_2 for the pull-down factor k_{pd} with pulse width PW. When PW is large, $\alpha_2 = 1$. As PW decreases, α_2 may be less than 1 (decreasing k_{pd}) or greater than 1 (increasing k_{pd}), depending on the monotonicity direction and the waveform comparison result $\alpha_{2,n2}$, $\alpha_{2,n2\text{-}1}$, et al., are parameters to be calibrated. This table, together with Table S1, constitutes the multiplicative adjustment matrix used in combined strategies such as "$x \rightarrow \alpha_1 x, y \rightarrow \alpha_2 y$ " or " $x \rightarrow \alpha_1 x, y \rightarrow y + \beta_2$ ".

Table S3. Empirical Table for β_1 with Single Pulse Input

$W_{IBIS} > W_{SPICE}, \frac{\delta V}{\delta x} < 0; W_{IBIS} < W_{SPICE}, \frac{\delta V}{\delta x} > 0$	
PW	β_1
$(n_3 + 1)T_0$	0

n_3T_0	β_{1,n_3}
$(n_3-1)T_0$	β_{1,n_3-1}
…	...
$2T_0$	β_{12}
T_0	β_{11}

This table presents the variation of the additive correction offset β_1 for the pull-up factor k_{pu} with pulse width PW. When PW is greater than the critical value $(n_3+1)T_0$, $\beta_1 = 0$ (no additive adjustment needed); when PW = n_3T_0, β_1 takes the value $\beta_{1,n3}$; as PW further decreases, β_1 increases. Additive adjustment is suitable for scenarios where the original IBIS waveform is lower than SPICE and monotonicity analysis indicates a need to increase k_{pu}. The value of β_1 is typically positive, its physical significance being compensation for the pull-up drive strength lost due to high-frequency effects. The β_{11} in the table corresponds to the narrowest pulse width T_0 and has the largest numerical value.

Table S4. Empirical Table for β_2 with Single Pulse Input

$W_{IBIS} > W_{SPICE}, \frac{\delta V}{\delta y} < 0$; $W_{IBIS} < W_{SPICE}, \frac{\delta V}{\delta y} > 0$	
PW	β_2
$(n_4+1)T_0$	0
n_4T_0	β_{2,n_4}
$(n_4-1)T_0$	β_{2,n_4-1}
…	...
$2T_0$	β_{22}
T_0	β_{21}

This table defines the variation of the additive correction offset β_2 for the pull-down factor k_{pd} with pulse width PW. When PW is greater than $(n_4+1)T_0$, $\beta_2 = 0$; when PW = n_4T_0, it takes the value $\beta_{2,n4}$; the narrower the pulse width, the larger β_2 becomes. Additive adjustment is applicable to scenarios where k_{pd} needs to be increased to pull down the output level (e.g., when W_{IBIS} is higher than SPICE). β_2 is usually positive, representing the addition of a positive offset to the

original k_{pd} value. The four empirical tables (α_1, α_2, β_1, β_2) together constitute the complete parameter space for single-pulse compensation.

Table S5. Dual-Parameter Adjustment for Scenario One

$W_{IBIS} > W_{SPICE}$, $\frac{\delta V}{\delta x} > 0$, $\frac{\delta V}{\delta y} > 0$, $0 < m_A < n_A$			
PW	x		y
$(n_A + 1)T_0$	$x \to x$	or	$y \to y$
$n_A T_0$	$x \to \alpha_1 n_A x$	or	$y \to \alpha_2 n_A y$
...	...	...	...
$(m_A + 1)T_0$ 0	$x \to \alpha_1 m_{A+1} x$	and	$y \to \alpha_2 m_{A+1} y$
$m_A T_0$	$x \to \alpha_1 m_A x$	and	$y \to \alpha_2 m_A y$
...	...	...	...
T_0	$x \to \alpha_{11} x$	and	$y \to \alpha_{21} y$

This table corresponds to the first of the eight dual-parameter co-regulation scenarios. The table is arranged in descending order of pulse width PW and provides the joint correction rules for k_{pu} and k_{pd}. When PW is greater than or equal to $(n_A+1)T_0$ no adjustment is needed ($x \to x$, $y \to y$). When PW is between $(m_A+1)T_0$ and $n_A T_0$, the "or" logic is adopted, meaning either x or y can be adjusted independently. When PW is less than or equal to $m_A T_0$, both x and y must be adjusted simultaneously ("and" logic). $\alpha_1 n_A$, $\alpha_2 n_A$, et al., are coefficients to be calibrated. The necessity for dual-parameter adjustment stems from the inability of a single factor to compensate for strong nonlinear distortion under narrow pulse conditions.

Table S6. Dual-Parameter Adjustment for Scenario Two

$W_{IBIS} < W_{SPICE}$, $\frac{\delta V}{\delta x} > 0$, $\frac{\delta V}{\delta y} > 0$, $0 < m_B < n_B$			
PW	x		y
$(n_B + 1)T_0$	$x \to x$	or	$y \to y$
$n_B T_0$	$x \to x + \beta_1 n_B$	or	$y \to y + \beta_2 n_B$

...	...	...	...
$(m_B + 1)T_0$	$x \to x + \beta_1 m_{B+1}$	and	$y \to y + \beta_2 m_{B+1}$
$m_B T_0$	$x \to x + \beta_1 m_B$	and	$y \to y + \beta_2 m_B$
...	...	...	...
T_0	$x \to x + \beta_{11}$	and	$y \to y + \beta_{21}$

This table represents the second dual-parameter co-regulation mode. The difference from Scenario One lies in the type of adjustment operation: Scenario Two uses additive adjustment ($x \to x+\beta_1$, $y \to y+\beta_2$) instead of multiplicative adjustment. When the pulse width is wide, only unilateral additive adjustment is needed; when the pulse width is extremely narrow, additive offsets must be applied simultaneously to both k_{pu} and k_{pd}. The values of β_1 and β_2 are provided by Tables S3 and S4. This mode is suitable for situations where the amplitude deviation directions of the original waveforms are consistent and both pull-up and pull-down drive strengths need to be increased simultaneously.

Table S7. Dual-Parameter Adjustment for Scenario Three

$W_{IBIS} > W_{SPICE}$, $\frac{\delta V}{\delta x} > 0$, $\frac{\delta V}{\delta y} < 0$, $0 < m_C < n_C$

PW	x		y
$(n_C + 1)T_0$	$x \to x$	or	$y \to y$
$n_C T_0$	$x \to \alpha_1 n_c x$	or	$y \to y + \beta_2 n_C$
...	...	...	...
$(m_C + 1)T_0$	$x \to \alpha_1 m_{c+1} x$	and	$y \to y + \beta_2 m_{C+1}$
$m_C T_0$	$x \to \alpha_1 m_C x$	and	$y \to y + \beta_2 m_C$
...	...	...	...
T_0	$x \to \alpha_{11} x$	and	$y \to y + \beta_{21}$

Scenario Three employs a combination of "multiplicative adjustment for x" and "additive adjustment for y". When PW is in the middle interval, one can choose to either independently decrease k_{pu} (multiplicative) or independently increase k_{pd} (additive); when PW is below the critical value ($m_c T_0$, both decreasing k_{pu} (multiplicative) and increasing k_{pd} (additive) must be performed simultaneously. This hybrid strategy is common when a device exhibits

asymmetric distortion with excessively strong pull-up and insufficient pull-down under narrow pulse conditions. The $\alpha_1 n_c$ and $\beta_2 n_c$ in the table need to be calibrated through iterative simulation.

Table S8. Dual-Parameter Adjustment for Scenario Four

$W_{IBIS} < W_{SPICE}$, $\frac{\delta V}{\delta x} > 0$, $\frac{\delta V}{\delta y} < 0$, $0 < m_D < n_D$			
PW	x		y
$(n_D + 1)T_0$	$x \to x$	or	$y \to y$
$n_D T_0$	$x \to x + \beta_1 n_D$	or	$y \to \alpha_2 n_D y$
...	...	...	...
$(m_D + 1)T_0$	$x \to x + \beta_1 m_{D+1}$	and	$y \to \alpha_2 m_{D+1} y$
$m_D T_0$	$x \to x + \beta_1 m_D$	and	$y \to \alpha_2 m_D y$
...	...	...	...
T_0	$x \to x + \beta_{11}$	and	$y \to \alpha_{21} y$

Scenario Four adopts a combination of "additive adjustment for x" and "multiplicative adjustment for y". That is, correcting the waveform by increasing k_{pu} (additive) while simultaneously decreasing k_{pd} (multiplicative). This mode is suitable for scenarios where the overall IBIS waveform is low, but the pull-down is excessively strong, leading to an overly steep falling edge. The table indicates the transition thresholds from unilateral adjustment ("or") to bilateral simultaneous adjustment ("and") across different pulse width intervals. n_D and m_D are positive integers, their specific values determined by the transient response characteristics of the device.

Table S9. Dual-Parameter Adjustment for Scenario Five

$W_{IBIS} > W_{SPICE}$, $\frac{\delta V}{\delta x} < 0$, $\frac{\delta V}{\delta y} > 0$, $0 < m_E < n_E$			
PW	x		y
$(n_E + 1)T_0$	$x \to x$	or	$y \to y$
$n_E T_0$	$x \to x + \beta_1 n_E$	or	$y \to \alpha_2 n_E y$
...	...	...	...

$(m_E + 1)T_0$	$x \to x + \beta_1 m_{E+1}$	and	$y \to \alpha_2 m_{E+1} y$
$m_E T_0$	$x \to x + \beta_1 m_E$	and	$y \to \alpha_2 m_E y$
...	...	...	...
T_0	$x \to x + \beta_{11}$	and	$y \to \alpha_{21} y$

Scenario Five employs a combination of "additive adjustment for x" and "multiplicative adjustment for y" but with opposite directions: $x \to x+\beta_1$ (increase k_{pu}), $y \to \alpha_2 y$ (decrease k_{pd}). This adjustment simultaneously enhances pull-up capability and weakens pull-down capability, suitable for dual defects of insufficient rising edge and overshooting falling edge of the waveform. The table structure is similar to previous ones; as the pulse width narrows, the adjustment shifts from unilateral to bilateral. This mode is manifested in some pulse width intervals of Device 2 (PW1 = 100-140 ps).

Table S10. Dual-Parameter Adjustment for Scenario Six

$W_{IBIS} < W_{SPICE}$, $\frac{\delta V}{\delta x} < 0$, $\frac{\delta V}{\delta y} > 0$, $0 < m_F < n_F$			
PW	x		y
$(n_F + 1)T_0$	$x \to x$	or	$y \to y$
$n_F T_0$	$x \to \alpha_1 n_F x$	or	$y \to y + \beta_2 n_F$
...	...	...	...
$(m_F + 1)T_0$	$x \to \alpha_1 m_{F+1} x$	and	$y \to y + \beta_2 m_{F+1}$
$m_F T_0$	$x \to \alpha_1 m_F x$	and	$y \to y + \beta_2 m_F$
...	...	...	...
T_0	$x \to \alpha_{11} x$	and	$y \to y + \beta_{21}$

Scenario Six utilizes "multiplicative adjustment for x" and "additive adjustment for y" in the directions $x \to \alpha_1 x$ (decrease k_{pu}) and $y \to y+\beta_2$ (increase k_{pd}). This corresponds to reducing pull-up strength while enhancing pull-down strength, used to correct issues of waveform top overshoot and bottom sag. The table provides critical pulse widths n_F and m_F; when PW is below $m_F T_0$, both adjustments must be performed simultaneously. This mode is actually applied in the PW1 = 100-150 ps interval for Device 1.

Table S11. Dual-Parameter Adjustment for Scenario Seven

$W_{IBIS} > W_{SPICE}$, $\frac{\delta V}{\delta x} < 0$, $\frac{\delta V}{\delta y} < 0$, $0 < m_G < n_G$			
PW	x		y
$(n_G + 1)T_0$	$x \to x$	or	$y \to y$
$n_G T_0$	$x \to x + \beta_1 n_G$	or	$y \to y + \beta_2 n_G$
...	...	...	...
$(m_G + 1)T_0$	$x \to x + \beta_1 m_{G+1}$	and	$y \to y + \beta_2 m_{G+1}$
$m_G T_0$	$x \to x + \beta_1 m_G$	and	$y \to y + \beta_2 m_G$
...	...	...	...
T_0	$x \to x + \beta_{11}$	and	$y \to y + \beta_{21}$

Scenario Seven employs full additive adjustment, i.e., $x \to x+\beta_1$, $y \to y+\beta_2$, with both additive offsets being positive. This adjustment simultaneously enhances both pull-up and pull-down drive capabilities, suitable for situations where the overall waveform swing is insufficient (high level not high enough, low level not low enough). Since simultaneously enhancing both pull-up and pull-down may increase contention current, the ratio of β_1 to β_2 must be carefully calibrated. The table similarly distinguishes between unilateral adjustment intervals and bilateral adjustment intervals.

Table S12. Dual-Parameter Adjustment for Scenario Eight

$W_{IBIS} < W_{SPICE}$, $\frac{\delta V}{\delta x} < 0$, $\frac{\delta V}{\delta y} < 0$, $0 < m_H < n_H$			
PW	x		y
$(n_H + 1)T_0$	$x \to x$	or	$y \to y$
$n_G T_0$	$x \to \alpha_1 n_H x$	or	$y \to \alpha_2 n_H y$
...	...	...	...
$(m_H + 1)T_0$	$x \to \alpha_1 m_{H+1} x$	and	$y \to \alpha_2 m_{H+1} y$
$m_H T_0$	$x \to \alpha_1 m_H$ x	and	$y \to \alpha_2 m_H y$
...	...	...	...

T_0	$x \to \alpha_{11} x$	and	$y \to \alpha_{21} y$

Scenario Eight employs full multiplicative adjustment, i.e., $x \to \alpha_1 x$, $y \to \alpha_2 y$, with both α_1 and α_2 less than 1. This adjustment simultaneously weakens both pull-up and pull-down capabilities, suitable for situations where the overall waveform swing is excessive (severe overshoot). This mode is adopted in the PW1=50-100 ps interval for Device 3, for example, at PW1=90 ps, $x \to \times 0.95$, $y \to \times 0.9$. The table indicates the pulse width thresholds n_H and m_H for transitioning from unilateral to bilateral multiplicative adjustment.

2. Single-Pulse Calibration Experiments and Result

Table S13. Empirically Calibrated Adjustment Coefficients for Device 1 (TPS53317) under PW1 Waveform Excitation.

PW1	x		y
150 ps	× 1	or	+0
140 ps	× 0.75	or	+0.075
130 ps	× 0.65	or	+0.15
120 ps	× 0.5	or	+0.3
110 ps	× 0.375	or	+0.6
100 ps	× 0.7	or	+0.6
90 ps	× 0.6	and	+0.6
80 ps	× 0.55	and	+0.6
70 ps	× 0.5	and	+0.6
60 ps	× 0.45	and	+0.6
50 ps	× 0.4	and	+0.6
40 ps	× 0.35	and	+0.6
30 ps	× 0.3	and	+0.6
20 ps	× 0.2	and	+0.6
10 ps	× 0.1	and	+0.6

Table S14. Empirically Calibrated Adjustment Coefficients for Device 1 (TPS53317) under PW2 Waveform Excitation.

PW2	x		y
160 ps	+0	or	× 1
150 ps	+0.1	or	× 0.85
140 ps	+0.225	or	× 0.7
130 ps	+0.45	or	× 0.55
120 ps	+0.95	or	× 0.375
110 ps	+1.9	or	× 0.25
100 ps	+2	and	× 0.25
90 ps	+3	and	× 0.25
80 ps	+3.25	and	× 0.25
70 ps	+3.75	and	× 0.25
60 ps	+4.25	and	× 0.25
50 ps	+5.925	and	× 0.25
40 ps	+6.25	and	× 0.25
30 ps	+7.25	and	× 0.25
20 ps	+8.25	and	× 0.25
10 ps	+9.25	and	× 0.25

Table S15. Empirically Calibrated Adjustment Coefficients for Device 2 (BUF20800-Q1) under PW1 Waveform Excitation.

PW1	x		y
140 ps	+0	or	+0
130 ps	+0.15	or	+0.2
120 ps	+0.3	or	+0.25
110 ps	+0.4	or	+0.35
100 ps	+0.45	or	+0.4
90 ps	+0.5	and	+0.45
80 ps	+0.6	and	+0.55
70 ps	+0.65	and	+0.6
60 ps	+0.8	and	+0.65
50 ps	+0.9	and	+0.75

40 ps	+1.1	and	+0.95
30 ps	+1.2	and	+1
20 ps	+1.4	and	+1.2
10 ps	+1.6	and	+1.45

Table S16. Empirically Calibrated Adjustment Coefficients for Device 2 (BUF20800-Q1) under PW2 Waveform Excitation

PW2	x		y
120ps	+0	or	+0
110ps	+0.3	or	+0.45
100ps	+0.4	or	+0.6
90ps	+0.55	or	+0.7
80ps	+0.65	or	+0.95
70ps	+0.8	and	+1.25
60ps	+1.05	and	+1.3
50ps	+1.35	and	+1.55
40ps	+1.55	and	+1.7
30ps	+1.65	and	+1.95
20ps	+1.8	and	+2.25
10ps	+2	and	+2.5

Table S17. Empirically Calibrated Adjustment Coefficients for Device 3 (TPS22986) under PW1 Waveform Excitation

PW1	x		y
100 ps	×1	or	×1
90 ps	×0.95	or	×0.9
80 ps	×0.9	or	×0.8
70 ps	×0.8	or	×0.75
60 ps	×0.7	or	×0.7
50 ps	×0.65	or	×0.6
40 ps	×0.5	and	×0.55
30 ps	×0.3	and	×0.45
20 ps	×0.25	and	×0.3

10 ps	×0.2	and	×0.25

Table S18. Empirically Calibrated Adjustment Coefficients for Device 3 (TPS22986) under PW2 Waveform Excitation

PW2	x		y
80 ps	×1	or	×1
70 ps	×0.8	or	×0.9
60 ps	×0.6	or	×0.75
50 ps	×0.55	and	×0.65
40 ps	×0.45	and	×0.55
30 ps	×0.3	and	×0.4
20 ps	×0.255	and	×0.365
10 ps	×0.2	and	×0.3