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# IBIS Model Simulation Accuracy Improvement with Slew Rate Correction

Yifan Ding, Missouri University of Science and Technology

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# Outline

- **Introduction**

- Motivation
- Previous Work and Limitation
  - Lookup Table-based Correction Coefficients Adjustment (v0)
  - Jitter Sensitivity-Based Ku/Kd Modification with Correction Coefficients (v1)
  - Jitter Sensitivity-Based Direct Ku/Kd Modification (v2)

- **Jitter Sensitivity-Based Direct Ku/Kd Modification with Slew Rate Correction (v3)**

- Methodology
  - Ratio Modification
  - Time Difference Compensation
- Validation

- **Conclusion**



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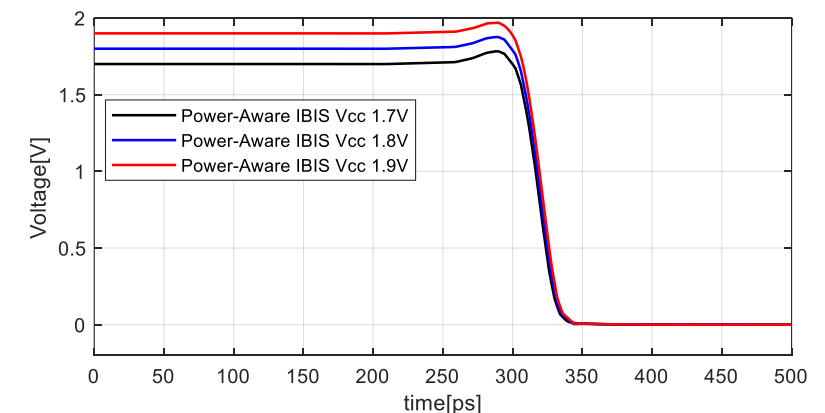
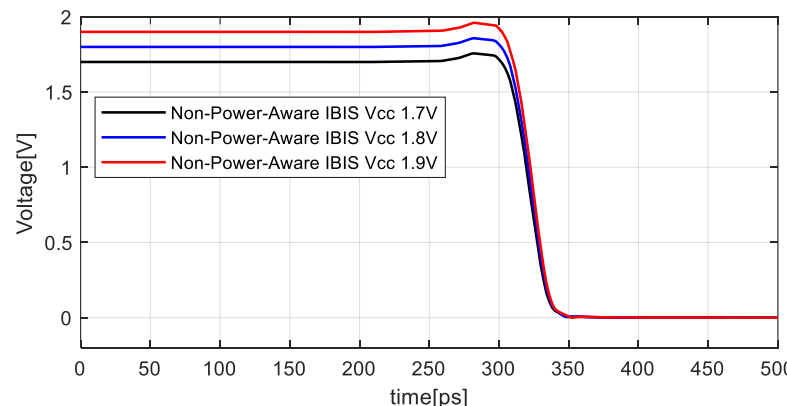
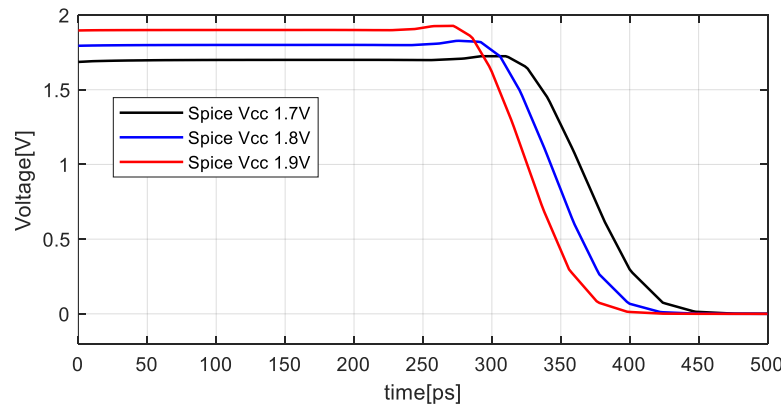
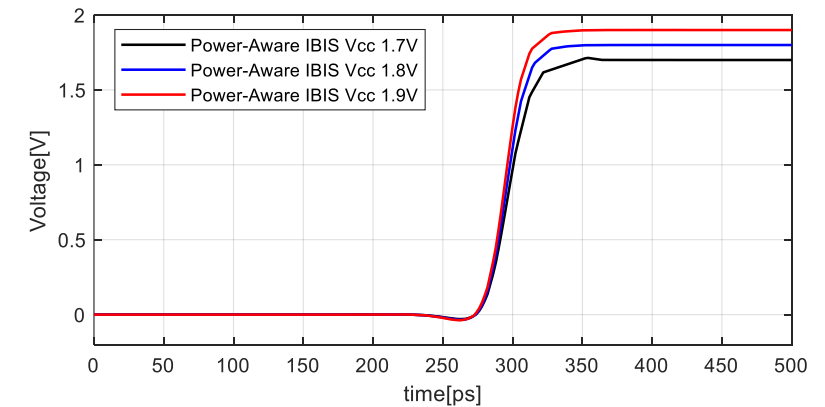
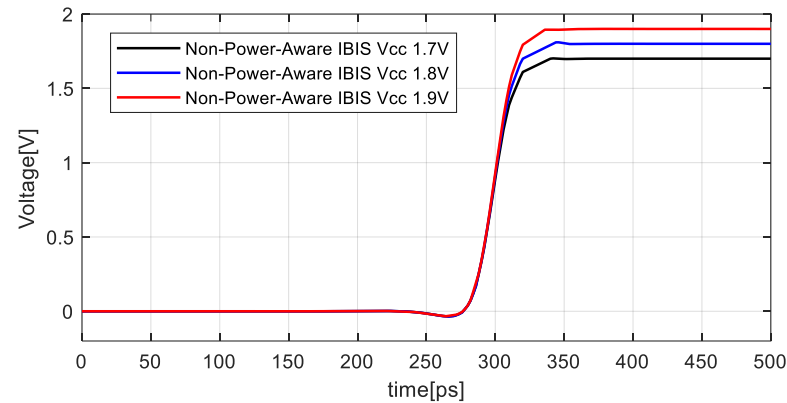
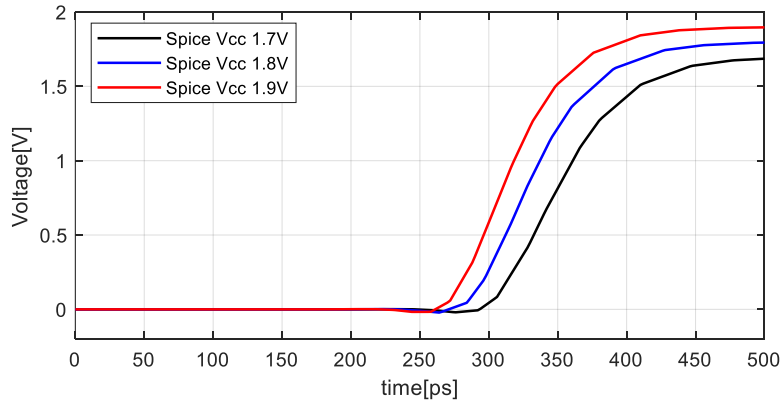
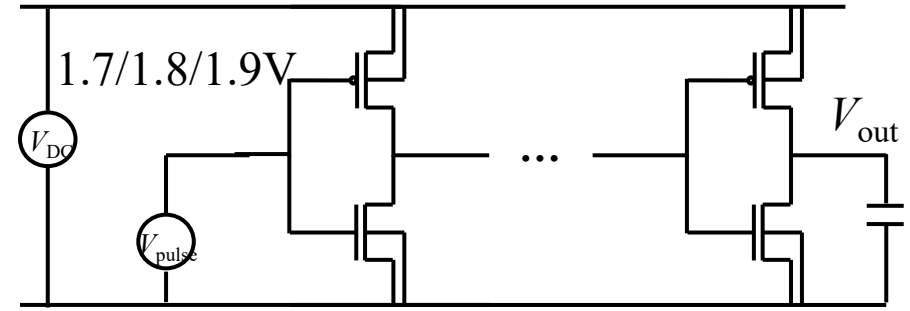
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# Introduction and Motivation

- **IBIS Model cannot** account for the delay change caused by power noise correctly.
- Example: an inverter chain output, change power voltage to 1.7/1.8/1.9V, respectively



<SPICE>

<Non-power-aware IBIS Model>

<Power-aware IBIS Model>



# Lookup Table-based Correction Coefficients Adjustment (v0)

- Modify  $K_u(t)$ ,  $K_d(t)$  as a function of **time averaged** power rail voltage  $V_{cc}(t)$ ;
- Introduce correction coefficient B and A as a function of **time**.

$$K_u(t) = K_{u0}(t) + B_u(t) \cdot \left[ \frac{\int_0^t V_{cc}(\tau) d\tau}{t} - V_{cc0} \right] + A_u(t) \left[ \frac{\int_0^t V_{cc}(\tau) d\tau}{t} - V_{cc0} \right]^2$$

$$K_d(t) = K_{d0}(t) + B_d(t) \cdot \left[ \frac{\int_0^t V_{cc}(\tau) d\tau}{t} - V_{cc0} \right] + A_d(t) \left[ \frac{\int_0^t V_{cc}(\tau) d\tau}{t} - V_{cc0} \right]^2$$

$K_u, K_d$  under nominal Vcc      Linear fitting coefficient      Quadratic fitting coefficient      Averaged Vcc(t) after the switching event happens;

- 2 equations, 2 unknowns' algorithm to extract  $K_u(t)$ ,  $K_d(t)$  for **typ/min/max**

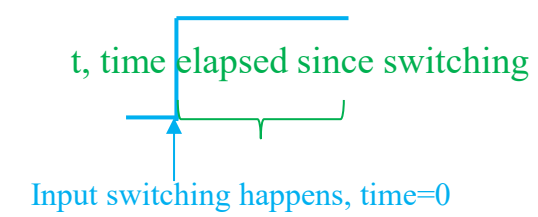
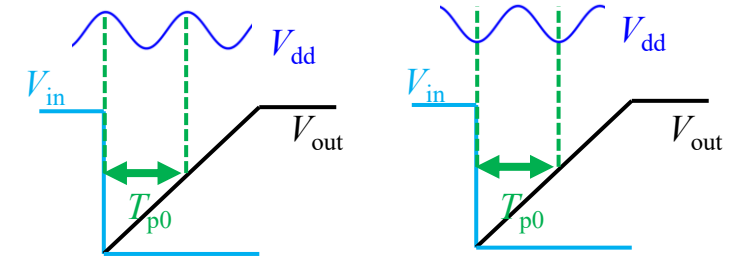
$$K_u(t) * I_u(V_1) + K_d(t) * I_d(V_1) = I_{out}(V_1)$$

$$K_u(t) * I_u(V_2) + K_d(t) * I_d(V_2) = I_{out}(V_2)$$

- 2 equations, 2 unknowns' algorithm to extract  $B_u(t)$ ,  $A_u(t)$  and  $B_d(t)$ ,  $A_d(t)$

$$K_{u\_max}(t) = K_{u0}(t) + B_u(t)(V_{cc\_max} - V_{cc0}) + A_u(t)(V_{cc\_max} - V_{cc0})^2$$

$$K_{u\_min}(t) = K_{u0}(t) + B_u(t)(V_{cc\_min} - V_{cc0}) + A_u(t)(V_{cc\_min} - V_{cc0})^2$$



- Achieved by adding delay elements that store
- The time of switching edges
  - Time averaged Vcc since switching event happens

## Limitation

- $K_u/K_d$  correction coefficients B and A are related to **Process, Voltage and Temperature** instead of only the supply voltage fluctuation.

# Jitter Sensitivity-Based Ku/Kd Modification with Correction Coefficients (v1)

“PSIJS modification v1”: use DC Jitter sensitivity, time-averaged power noise and correction coefficients to do IBIS switching coefficients modification

Step 1:  $K_u(t)$ ,  $K_d(t)$  extraction for typ voltage supply

$$\begin{aligned} K_u(t)I_u(V_1) + K_d(t)I_d(V_1) &= I_{out}(V_1) \\ K_u(t)I_u(V_2) + K_d(t)I_d(V_2) &= I_{out}(V_2) \end{aligned}$$



Step 2:  $K_u(t)$ ,  $K_d(t)$  extraction for min/max voltage supply

$$K_u/K_{d\_max/min}(t) = K_u/K_{d\_typ}(t \pm \Delta t) \pm \text{Pre-driver DC Jitter sensitivity} \times \Delta V_{dd}$$



Step 3:  $B_u(t)$ ,  $A_u(t)$  and  $B_d(t)$ ,  $A_d(t)$  extraction

$$\begin{aligned} K_{u\_max}(t) &= K_{u0}(t) + B_u(t)(V_{cc\_max} - V_{cc0}) + A_u(t)(V_{cc\_max} - V_{cc0})^2 \\ K_{u\_min}(t) &= K_{u0}(t) + B_u(t)(V_{cc\_min} - V_{cc0}) + A_u(t)(V_{cc\_min} - V_{cc0})^2 \end{aligned}$$

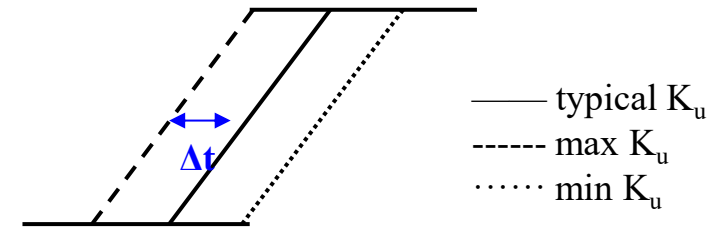


Step 4:  $K_u(t)$ ,  $K_d(t)$  modification

Time-averaged power supply noise

$$\begin{aligned} K_u(t) &= K_{u0}(t) + B_{pu}(t) \left[ \frac{\int_0^t V_{cc}(\tau) d\tau}{t} - V_{cc0} \right] + A_{pu}(t) \left[ \frac{\int_0^t V_{cc}(\tau) d\tau}{t} - V_{cc0} \right]^2 \\ K_d(t) &= K_{d0}(t) + B_{pd}(t) \left[ \frac{\int_0^t V_{cc}(\tau) d\tau}{t} - V_{cc0} \right] + A_{pd}(t) \left[ \frac{\int_0^t V_{cc}(\tau) d\tau}{t} - V_{cc0} \right]^2 \end{aligned}$$

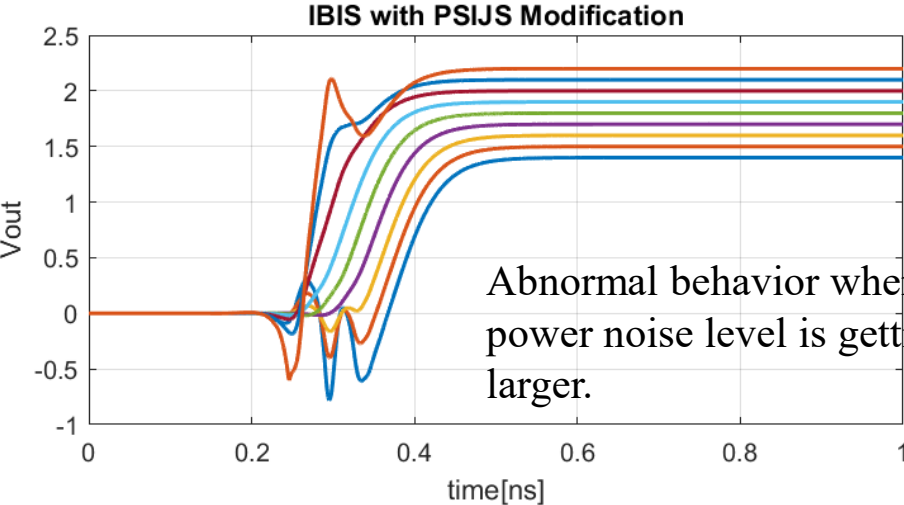
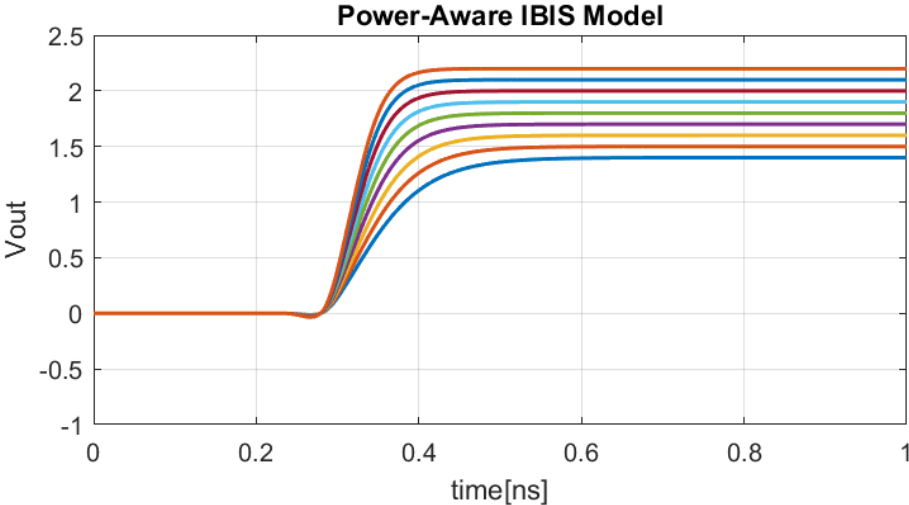
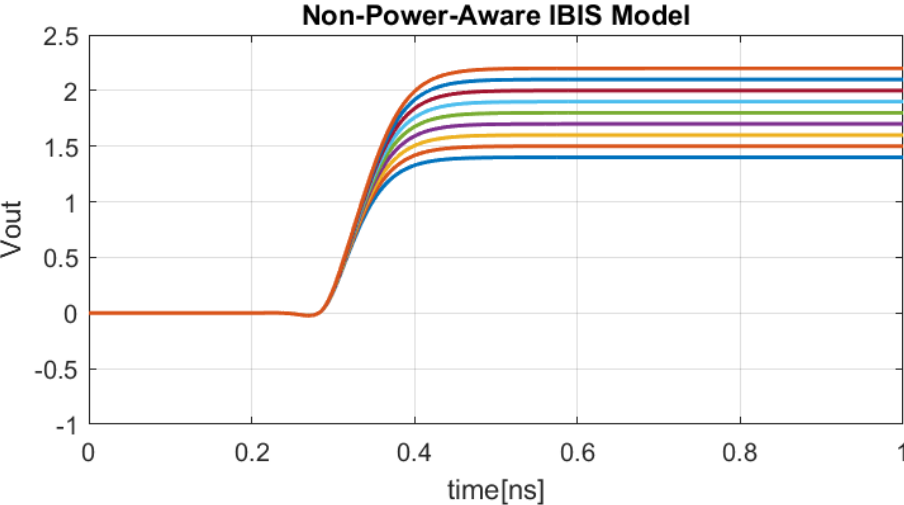
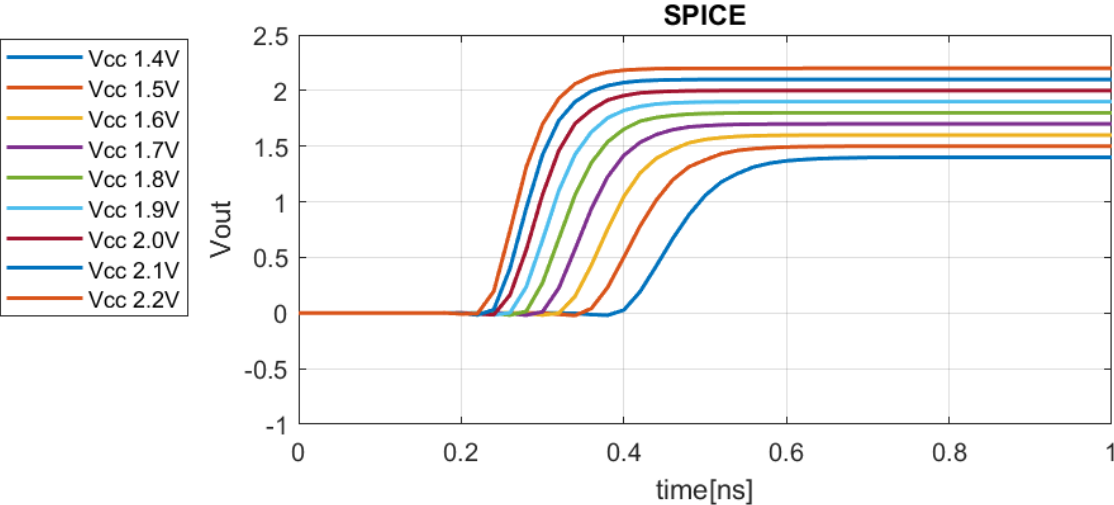
Two correction coefficients



<Switching coefficient  $K_u$  for output rising edge>

# Limitation: When Power Noise is Getting Larger

- The modified model has poor compatibility with high levels of power noise.



# Jitter Sensitivity-Based Direct Ku/Kd Modification (v2)

“PSIJS modification v2”: use **nonlinear DC Jitter sensitivity**, **time-averaged power noise** ~~and correction coefficients~~ to do IBIS switching coefficients modification

**Step 1: At any given time  $t_i$ , the time-averaged power supply noise that has accumulated since the input switching**

$$\Delta V_{cc}(t_i) = \frac{\int_0^{t_i} V_{cc}(\tau) d\tau}{t_i} - V_{cc0}$$



**Step 2: The delay difference  $\Delta t_i$  induced by the averaged power noise (with nonlinear jitter sensitivity)**

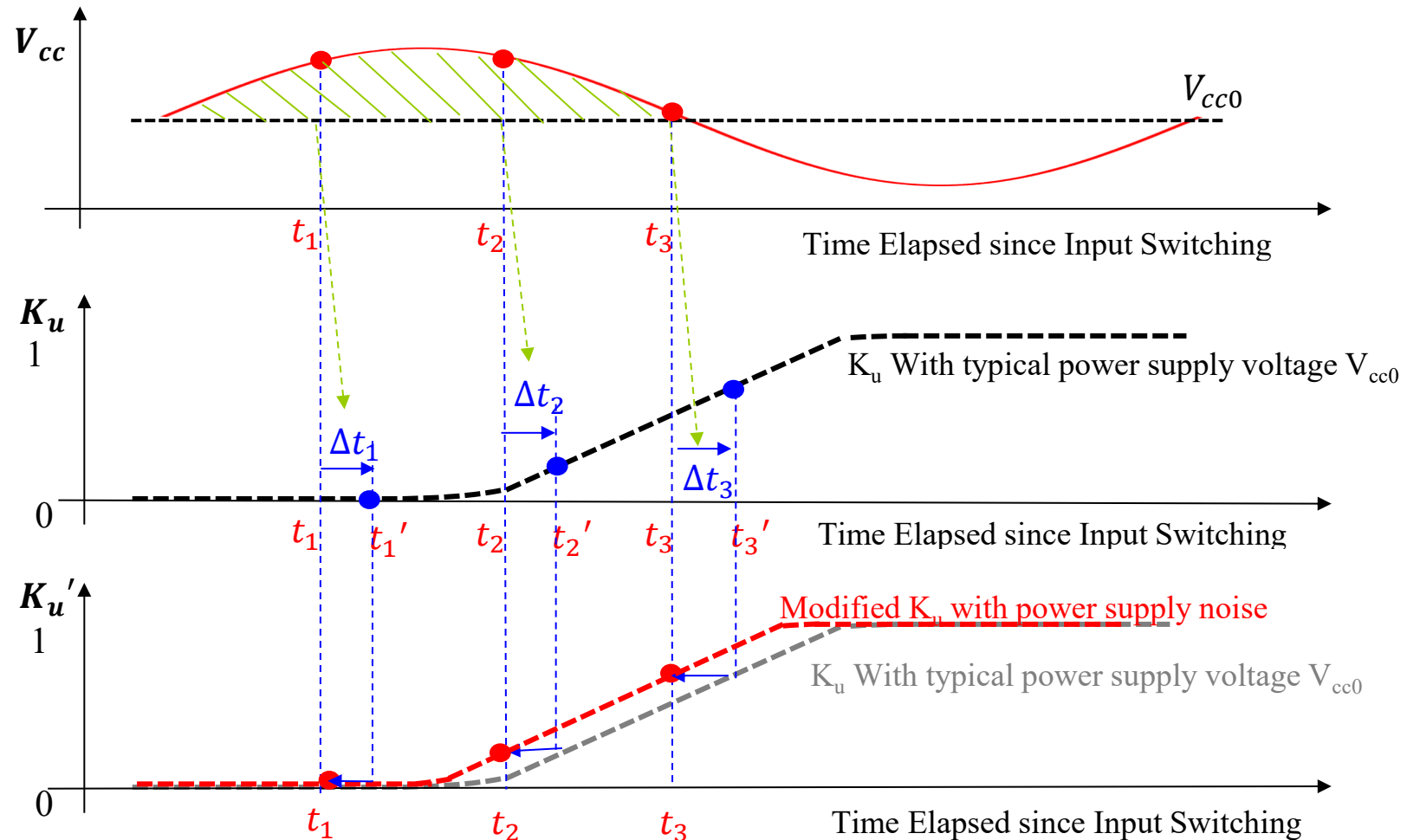
$$\Delta t_i = \Delta V_{cc}(t_i) \times DC\_PSIJS(\Delta V_{cc}(t_i))$$



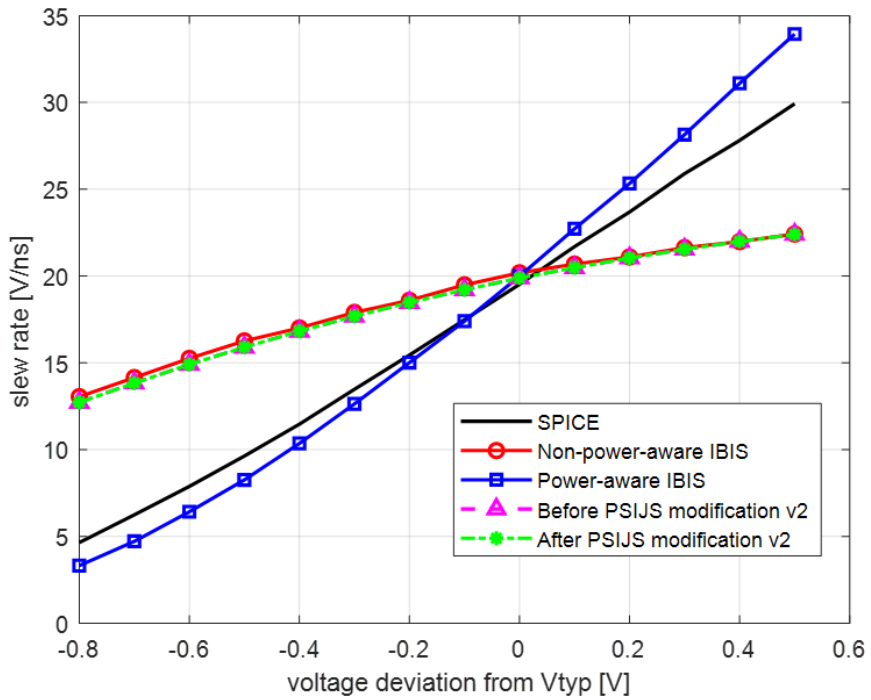
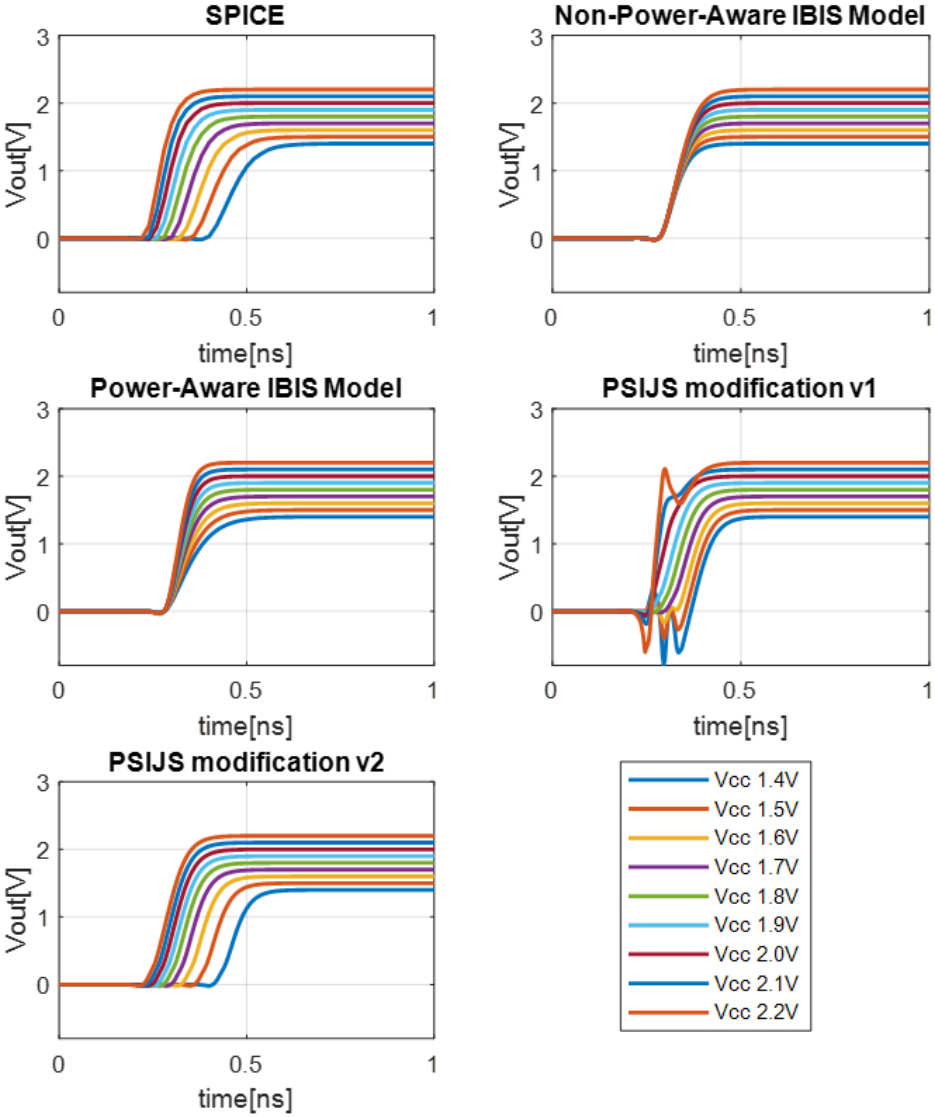
**Step 3: The modified switching coefficient**

$$K_{pu}(t_i) = K_{pu0}(t_i') = K_{pu0}(t_i + \Delta t_i)$$

$$K_{pd}(t_i) = K_{pd0}(t_i') = K_{pd0}(t_i + \Delta t_i)$$



# Limitation: Output Waveform and Slew Rate Comparison



- Limitation in the implementation process: the **conversion tool** only supports the **non-power aware** IBIS model.
- Power aware characteristics should be applied in the modification.





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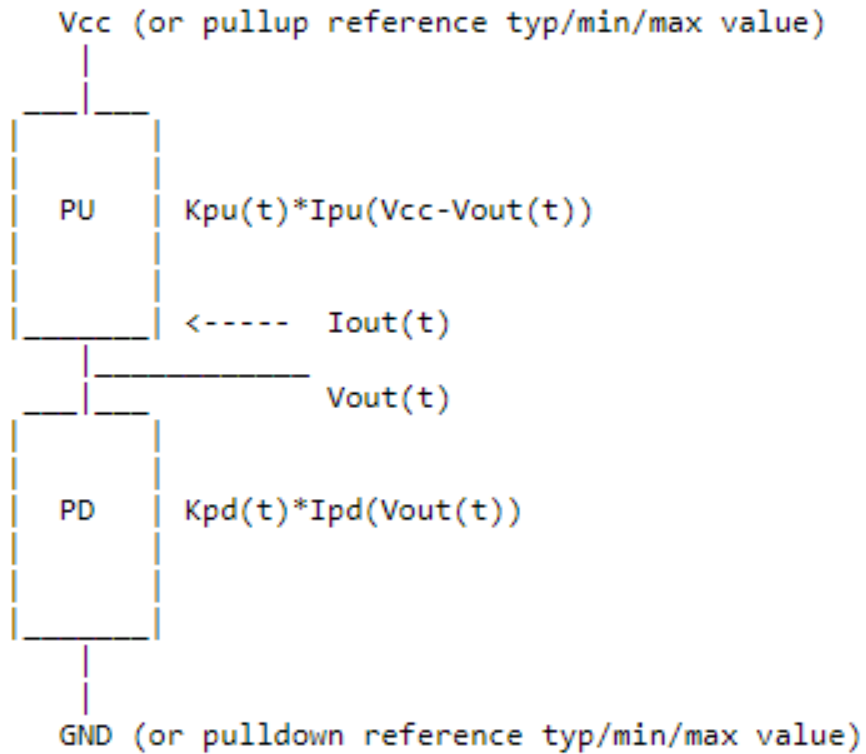
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  - Ratio Modification
  - Time Difference Compensation
- Validation

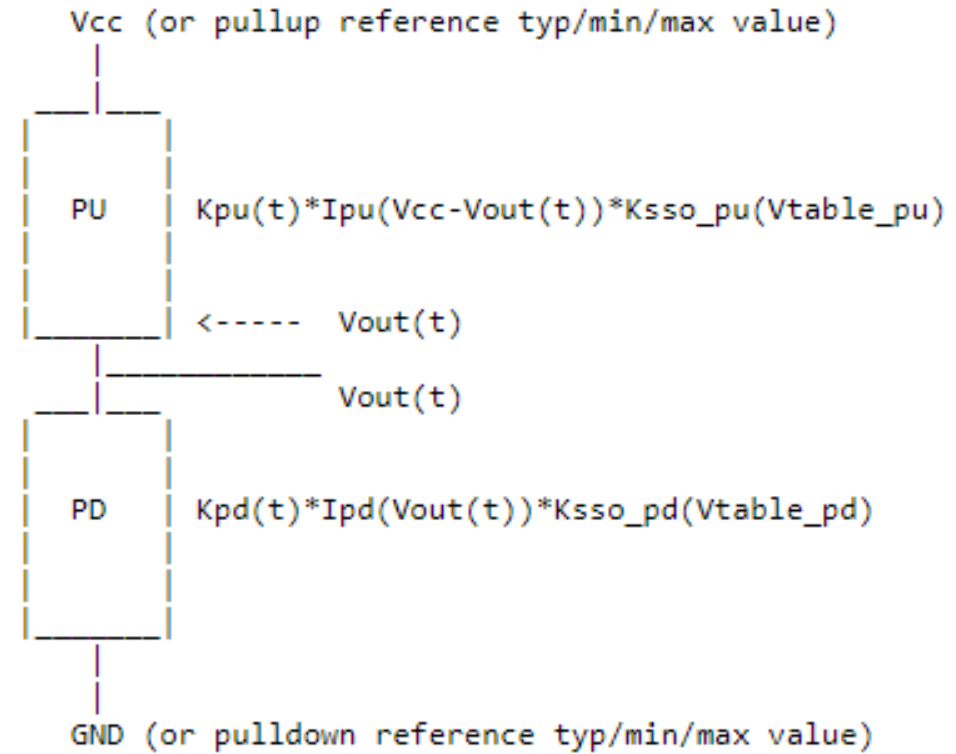
- **Conclusion**

# Difference between Non-power-aware and Power-aware IBIS Model

Non-power-aware IBIS model



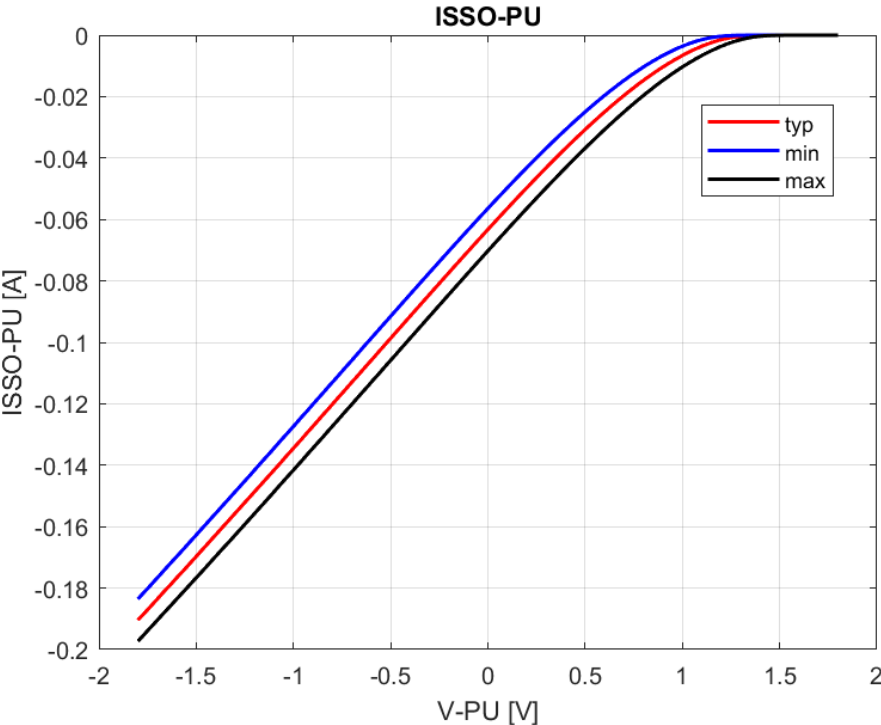
Power-aware IBIS model



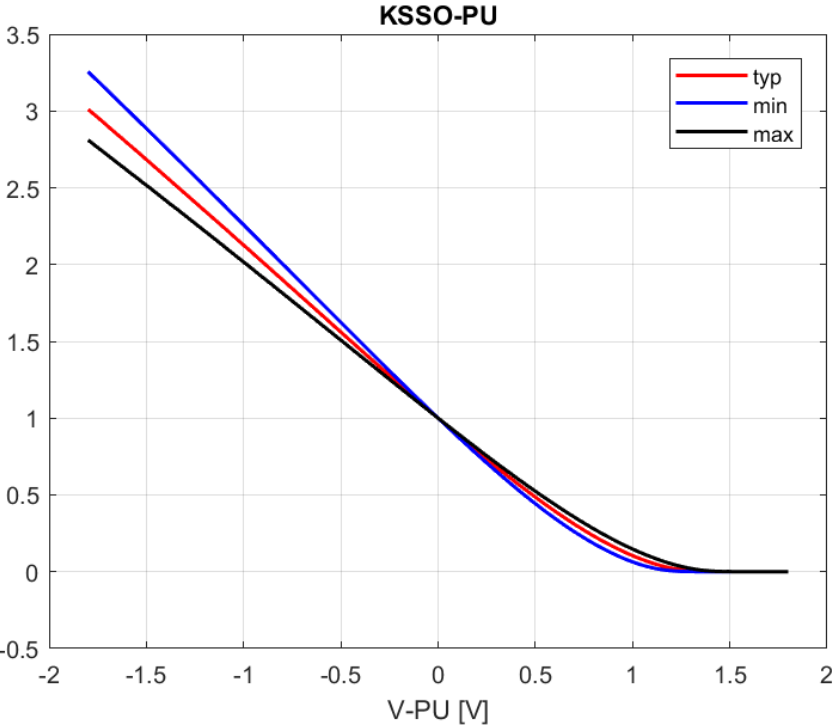
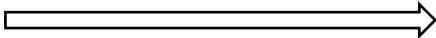
A. Muranyi, A. Girardi, G. Bernardi, R. Izzi, and B. Ross, "BIRD98.3: Gate Modulation Effect", Oct. 2007, <http://ibis.org/birds/bird98.3.txt>.

# Output Ratio Modification

Step 1: Extract  $K_{SSO\_pu}$



$$K_{SSO\_pu}(V) = \frac{I_{SSO\_pu}(V)}{I_{SSO\_pu}(0)}$$



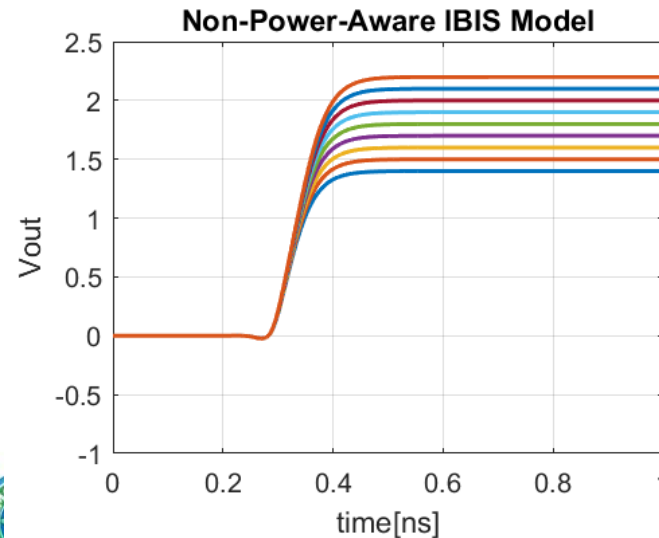
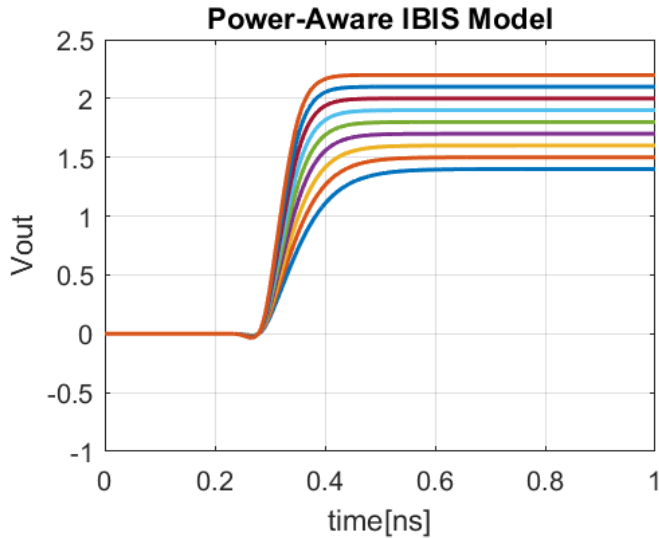
Step 2: Apply  $K_{SSO\_pu}$  on  $K_{pu}$  Driver output:  $K_{SSO\_pu}(t)K_{pu}(t)I_{pu}(V) + K_{pd}(t)I_{pd}(V) = I_{out}(V)$

- Can the ratio modification on  $K_{pu}$  represent the ratio change in output?

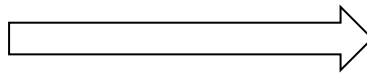


# $K_{SSO\_pu}$ Effect on Output Waveform

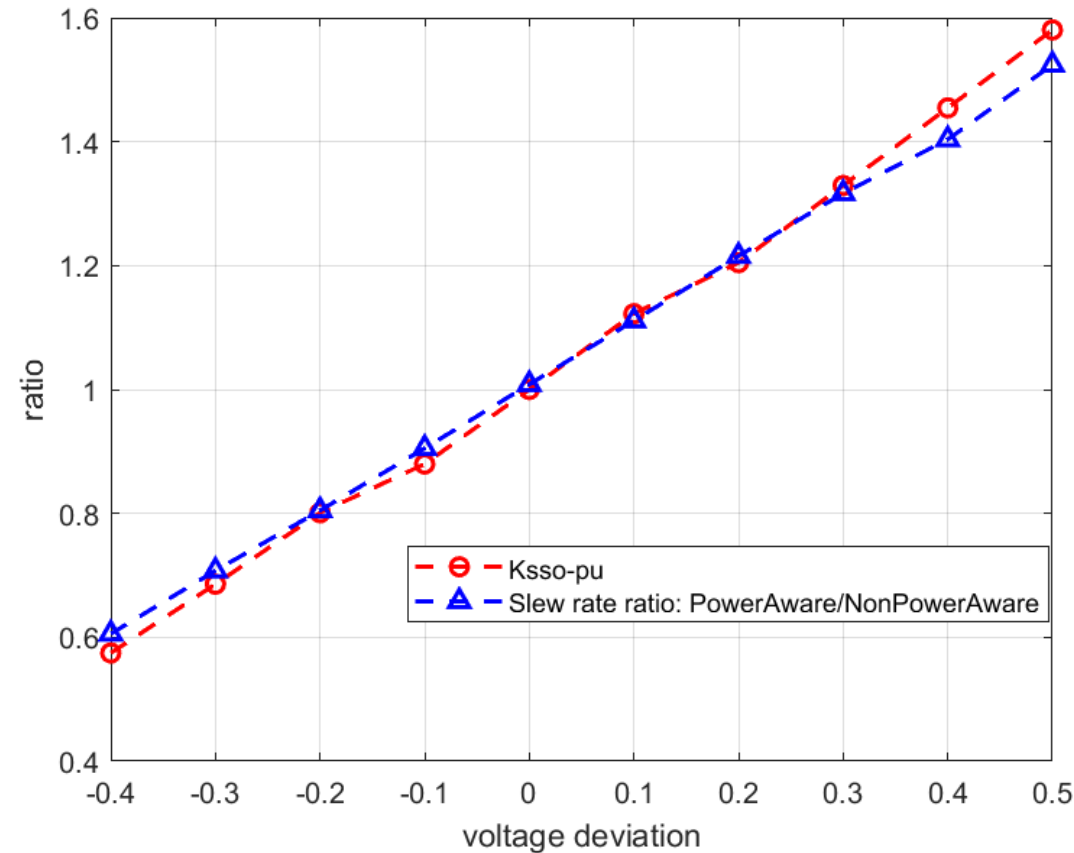
Compare  $K_{SSO\_pu}$  coefficient and output waveform slew rate ratio between power-aware and non-power-aware IBIS model.



$$slew\ rate = \frac{V_{out@80\%} - V_{out@20\%}}{t_{Vout@80\%} - t_{Vout@20\%}}$$

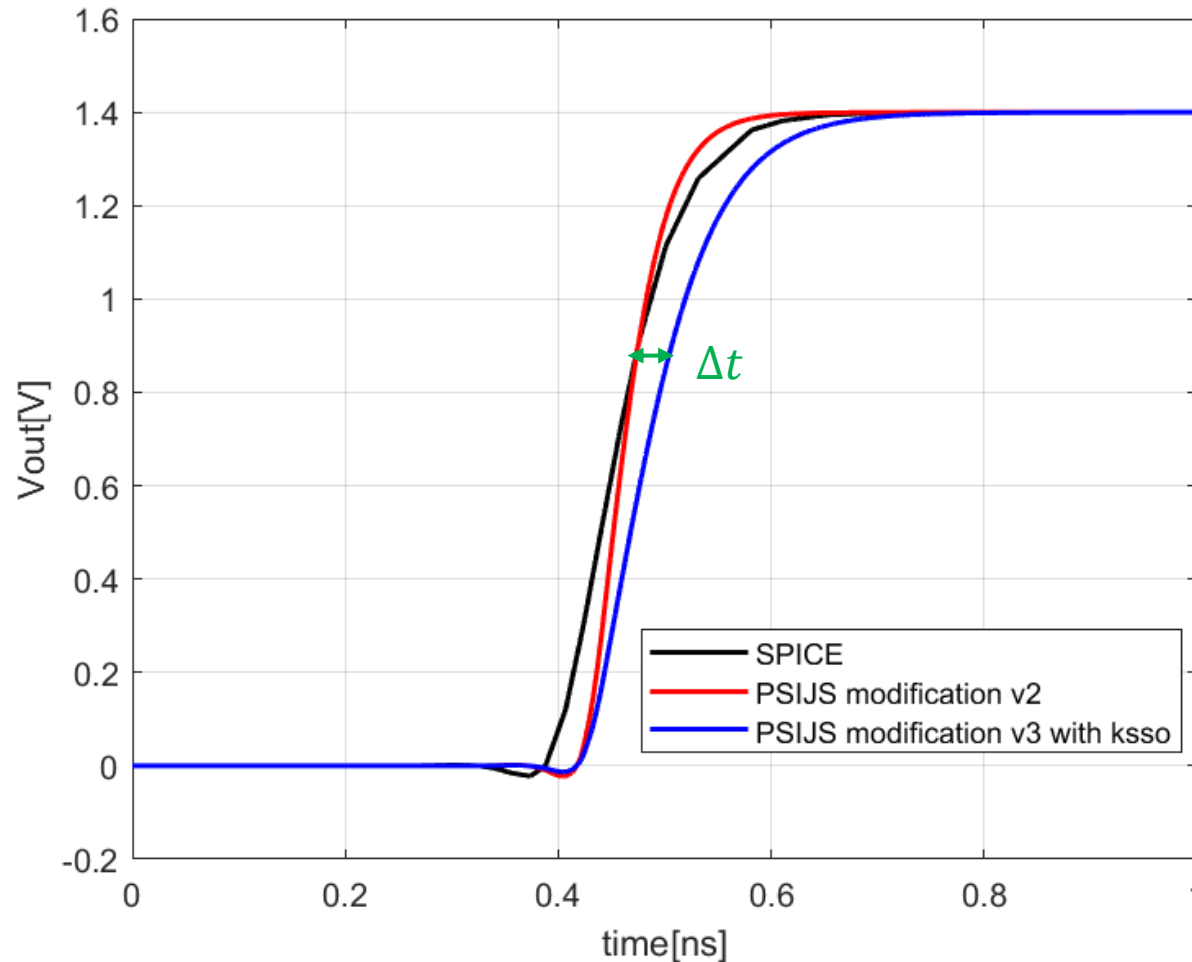


$$slew\ rate\ ratio = \frac{slew\ rate\ PA}{slew\ rate\ NPA}$$



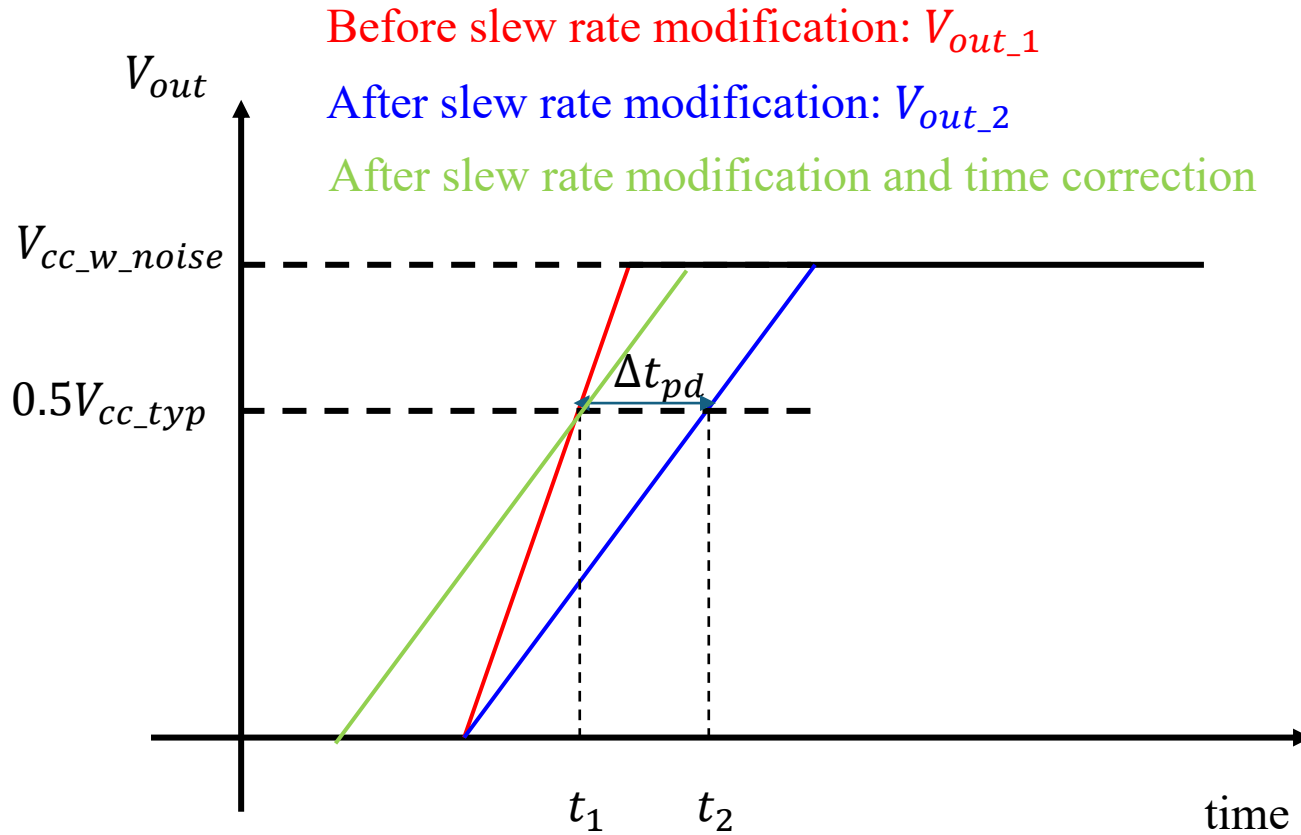
- The ratio modification applied on the  $K_{pu}$  switching coefficient can represent the ratio modification on output waveform.

# With $K_{SSO\_pu}$ Ratio Modification



- After ratio modification, the slew rate of the output waveform is improved.
- The slew rate change introduces time difference.

# Time Difference Correction



Propagation delay difference

$$\Delta t_{pd} = (1 - r) / (r \cdot k) \cdot 0.5 \cdot V_{cc\_typ}$$

Assume the output rising edge is a linear function

$$V_{out\_1} = k \cdot t + b_1$$

$$V_{out\_2} = r \cdot k \cdot t + r \cdot b_1$$

where

$k$  : slew rate of the non-power-aware IBIS model

$r$  : ratio modification coefficient KSSO

Time difference at any voltage level

$$V_{out\_1} = V_{out\_2}$$

$$k \cdot t_1 + b_1 = r \cdot k \cdot t_2 + r \cdot b_1$$

$$t_2 = 1/r \cdot t_1 + (1 - r) / (r \cdot k) \cdot b_1$$

$$\Delta t_i = t_2 - t_1$$

$$= (1 - r) / (r \cdot k) \cdot (k \cdot t_1 + b_1)$$

$$= (1 - r) / (r \cdot k) \cdot V_{out\_1}(t_1)$$



# Jitter Sensitivity-Based Direct Ku/Kd Modification with Slew Rate Correction (v3)

“PSIJS modification v3”: apply **ratio modification** on the IBIS switching coefficients modification in addition to the last version.  
 The first 3 steps are the same as v2.

**Step 1: At any given time  $t_i$ , the time-averaged power supply noise that has accumulated since the input switching**

$$\Delta V_{cc}(t_i) = \frac{\int_0^{t_i} V_{cc}(\tau) d\tau}{t_i} - V_{cc0}$$



**Step 2: The delay difference  $\Delta t_i$  induced by the averaged power noise (with nonlinear jitter sensitivity)**

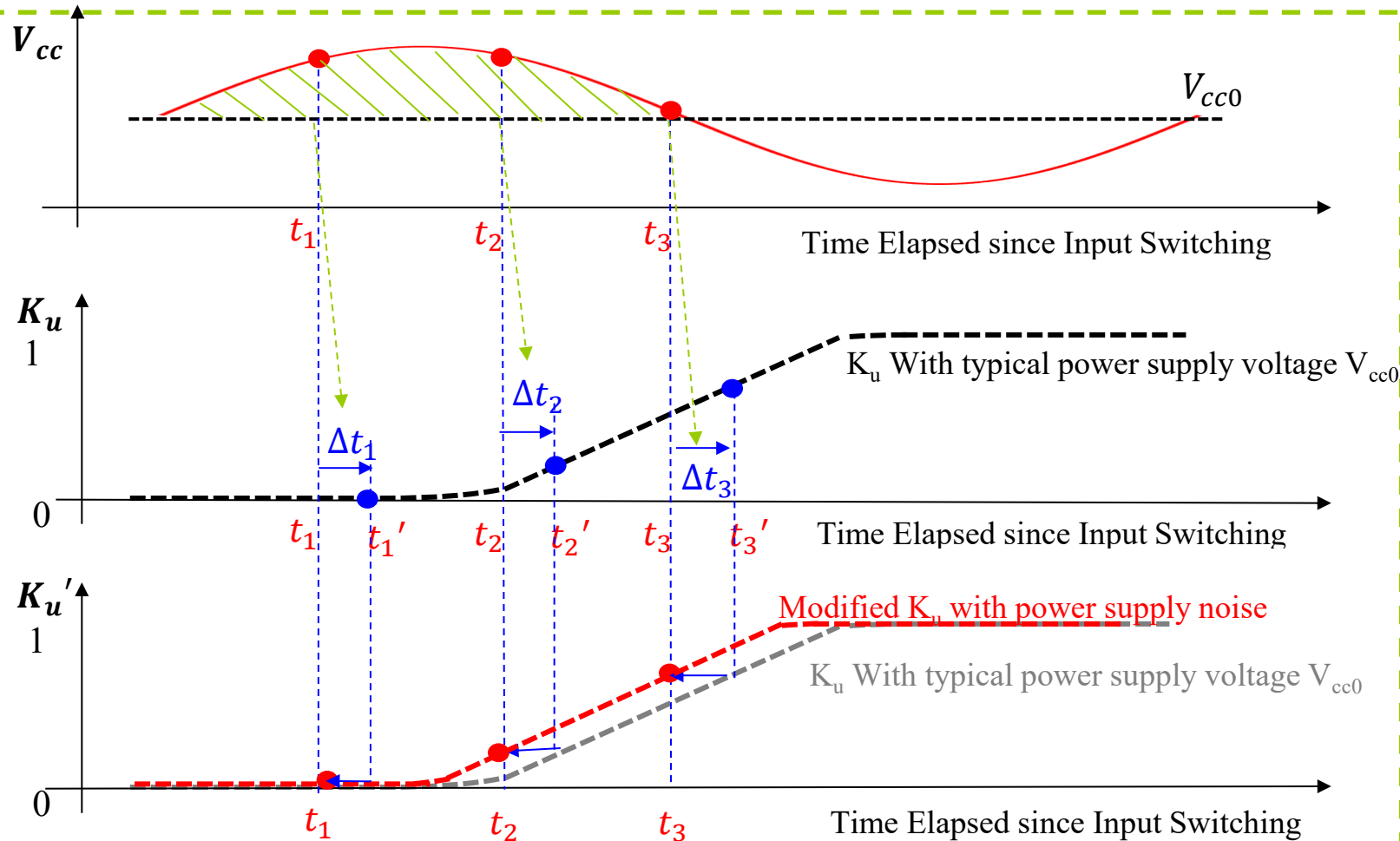
$$\Delta t_i = \Delta V_{cc}(t_i) \times DC\_PSIJS(\Delta V_{cc}(t_i))$$



**Step 3: The modified switching coefficient**

$$K_{pu}(t_i) = K_{pu0}(t_i') = K_{pu0}(t_i + \Delta t_i)$$

$$K_{pd}(t_i) = K_{pd0}(t_i') = K_{pd0}(t_i + \Delta t_i)$$



# Jitter Sensitivity-Based Direct Ku/Kd Modification with Slew Rate Correction (v3)

“PSIJS modification v3”: apply **ratio modification** on the IBIS switching coefficients modification in addition to the last version.



Additional steps in v3

**Step 4: Apply the ratio modification  $K_{SSO\_pu}$  on the updated switching coefficient**

$$K_{pu2}(t_i) = K_{pu1}(t_i) \times K_{SSO\_pu}(\Delta V_{cc}(t_i))$$



**Step 5: The delay difference  $\Delta t_i$  induced by the ratio modification**

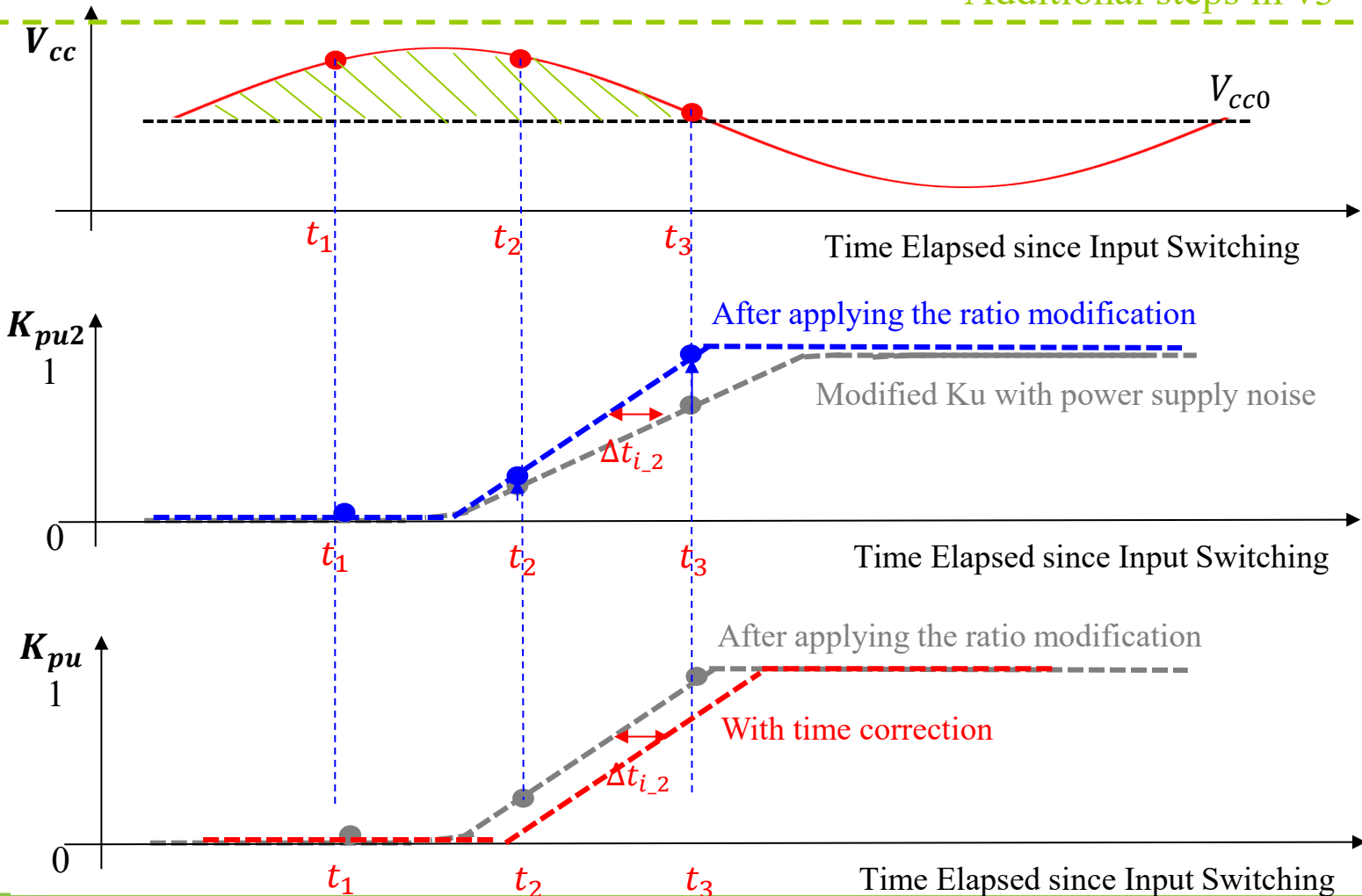
$$\Delta t_{i,2} = \frac{1 - K_{SSO\_pu}(\Delta V_{cc}(t_i))}{K_{SSO\_pu}(\Delta V_{cc}(t_i)) \cdot \text{slew rate}_{NPA}} \cdot 0.5 \cdot V_{cc\_typ}$$



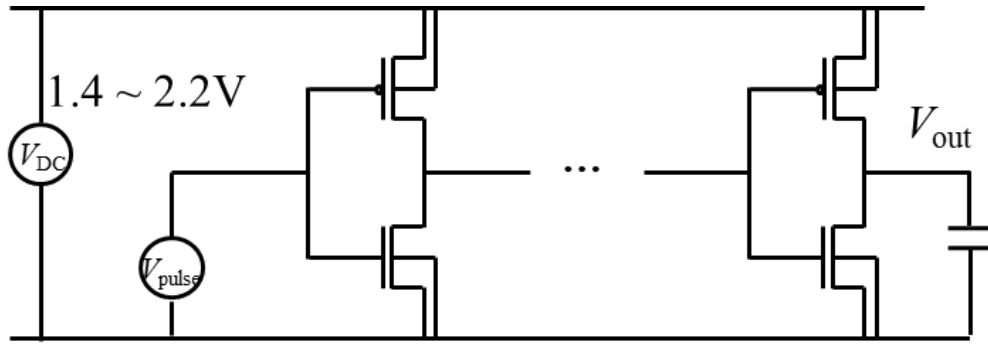
**Step 6: The modified switching coefficient**

$$K_{pu}(t_i) = K_{pu2}(t'_i) = K_{pu2}(t_i + \Delta t_{i,2})$$

$$K_{pd}(t_i) = K_{pd1}(t_i)$$

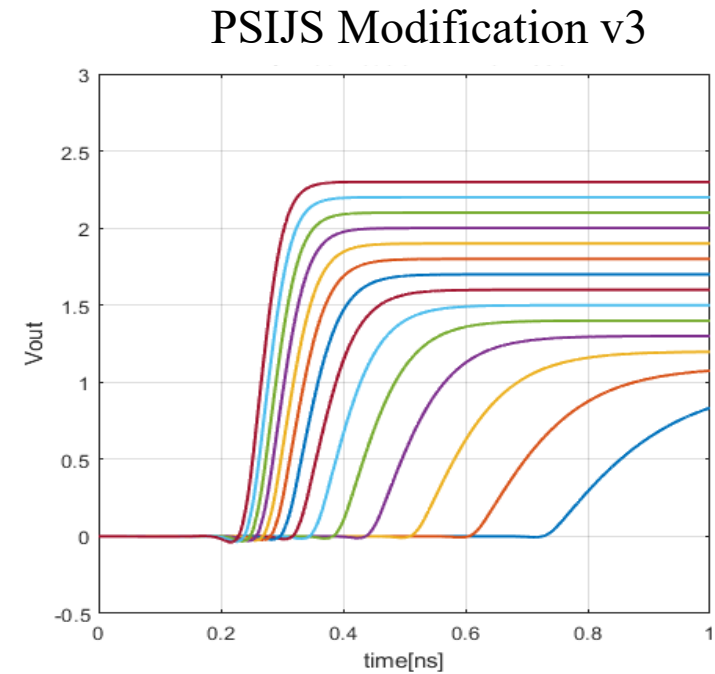
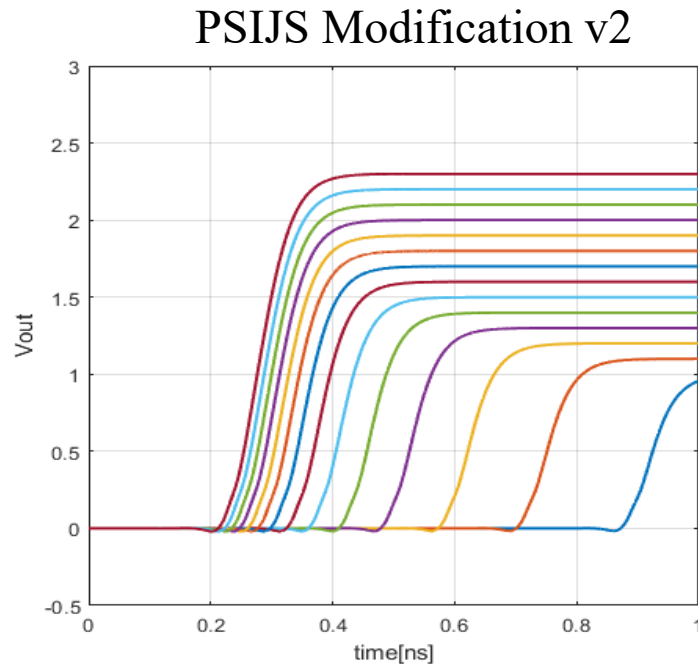
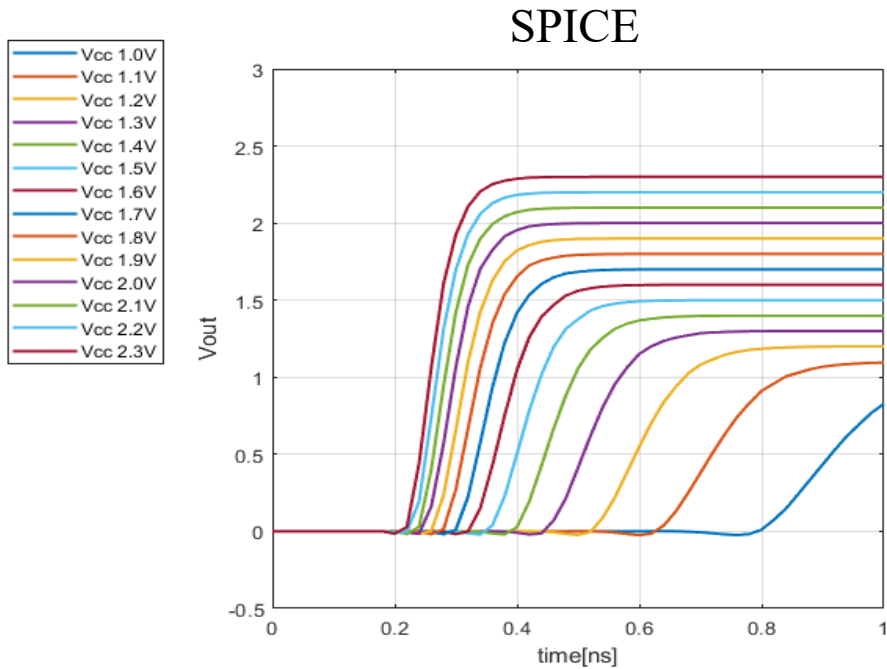


# Validation: With Power Supply DC Voltage Noise

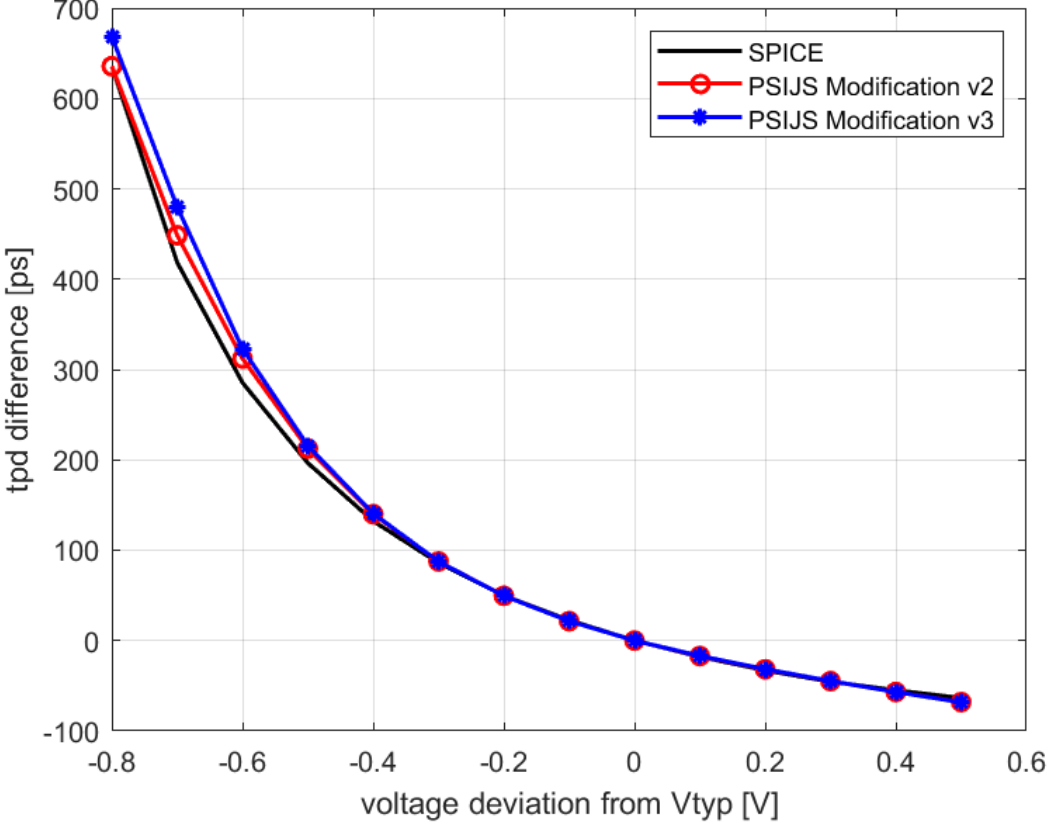
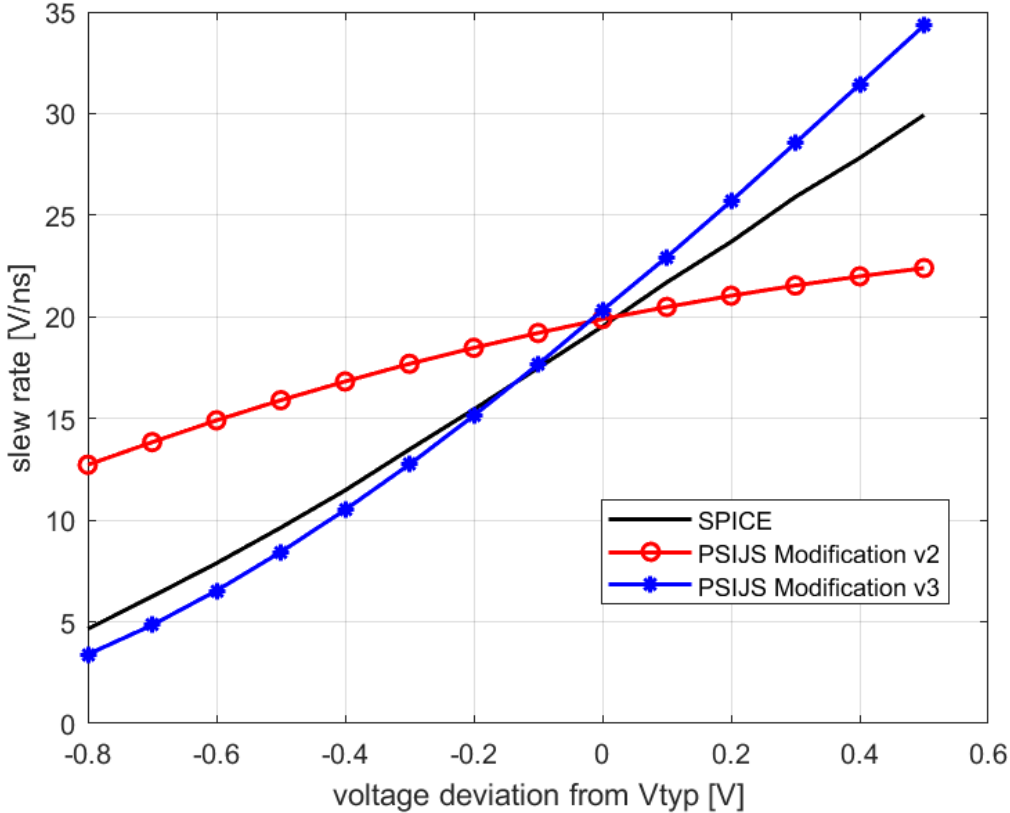


- After implementing the  $K_{SSO}$  ratio modification, the output waveform behavior is improved.

<8-Stage Inverter Chain Simulation Setup with DC Power Noise>



# Slew Rate and Jitter Comparison

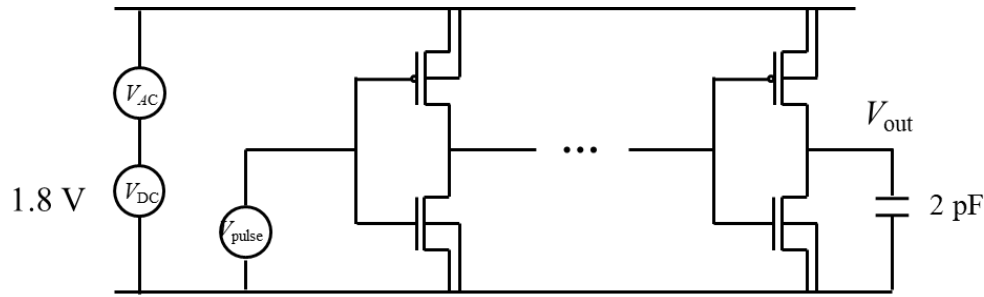


- The modified model has improved slew rate behavior for the output waveform.
- The modified model can also capture the jitter when voltage noise varies.



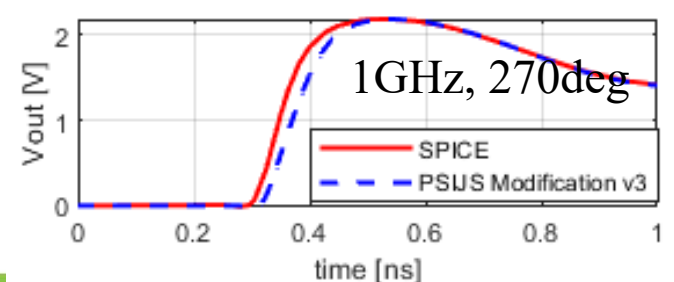
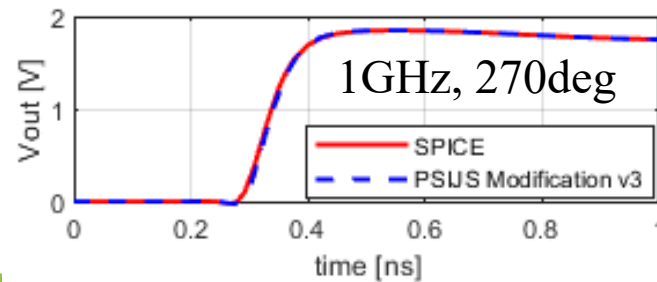
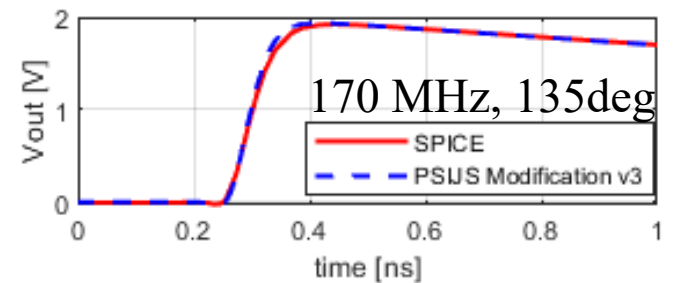
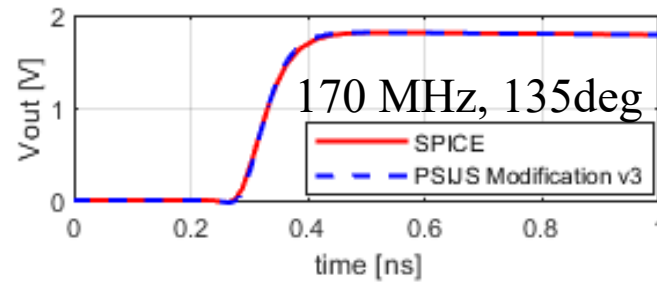
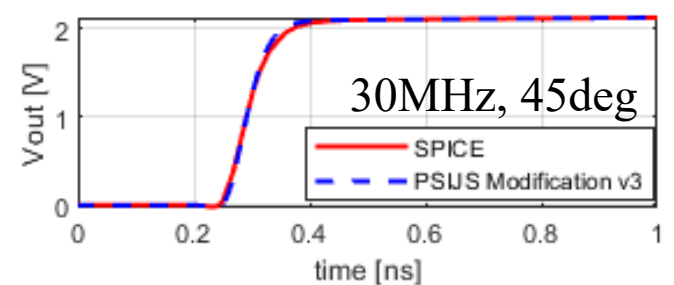
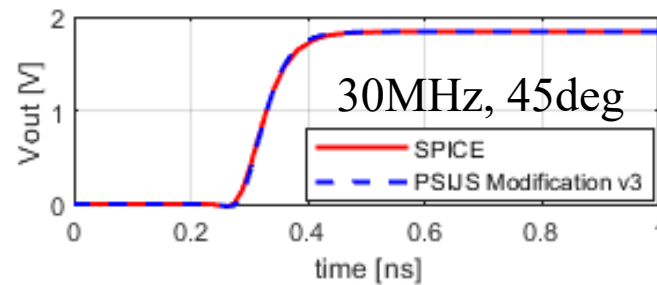
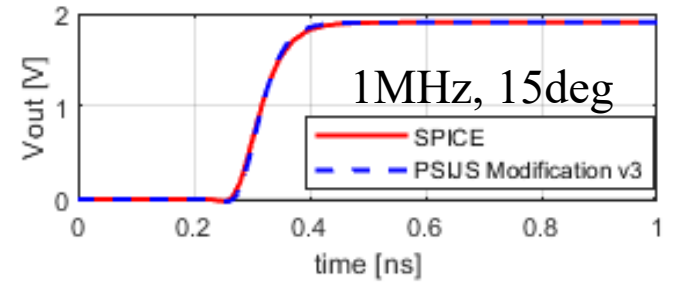
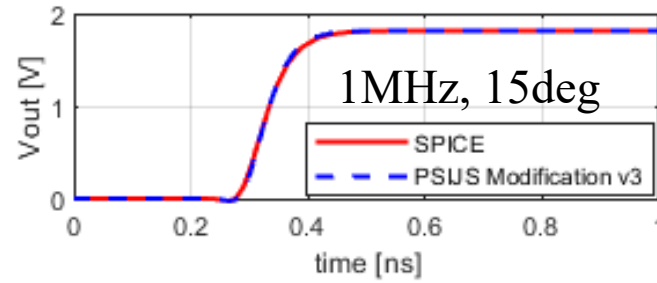
# Validation: With Power Supply AC Voltage Noise – Single-frequency

$$V_{AC} = \text{Amp} \times \sin(\omega t + \varphi)$$



<8-Stage Inverter Chain Simulation Setup with AC Power Noise>

- With single-tone AC noise, the output slew rate and jitter can be correctly modeled with the new algorithm.



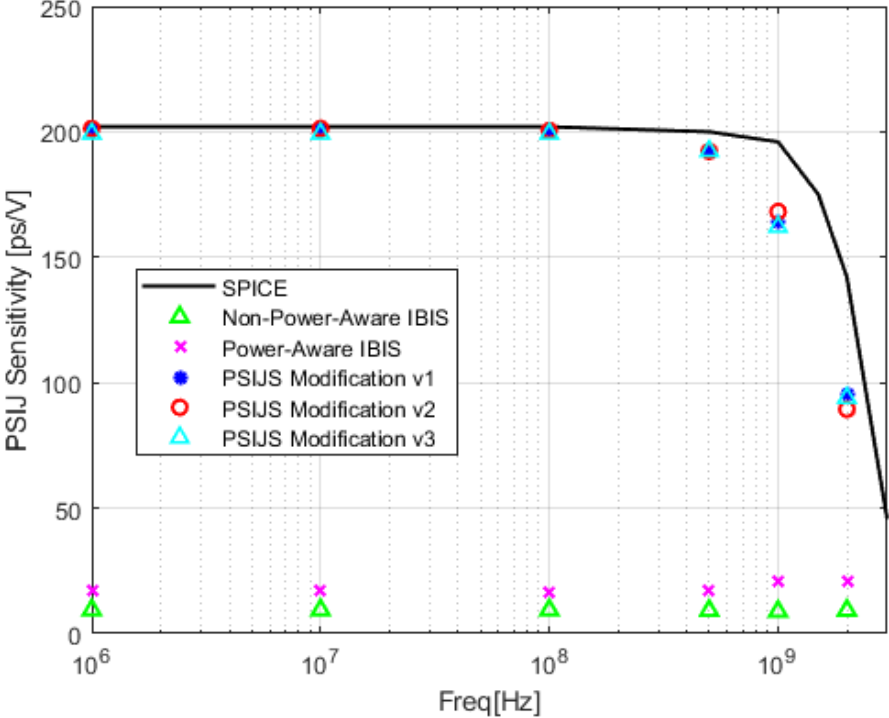
Amp = 0.05V

Amp = 0.4V

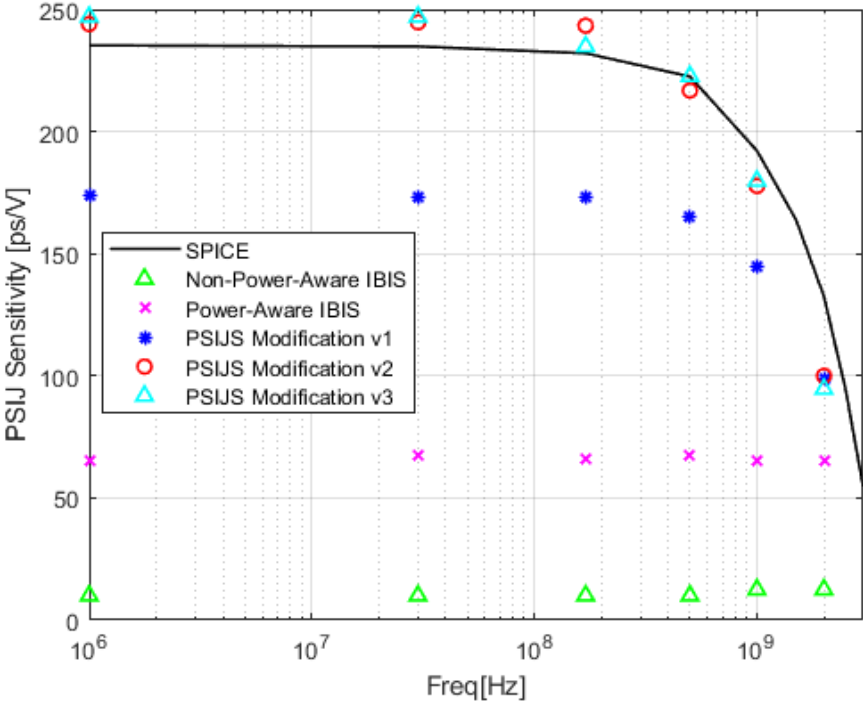


# Validation: With Power Supply AC Voltage Noise – Single-frequency

Frequency-dependent jitter sensitivity response



Noise amplitude 0.05V

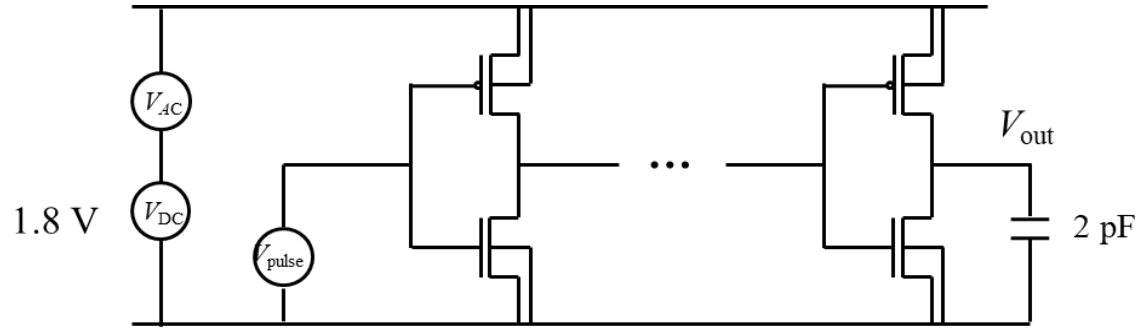


Noise amplitude 0.4V



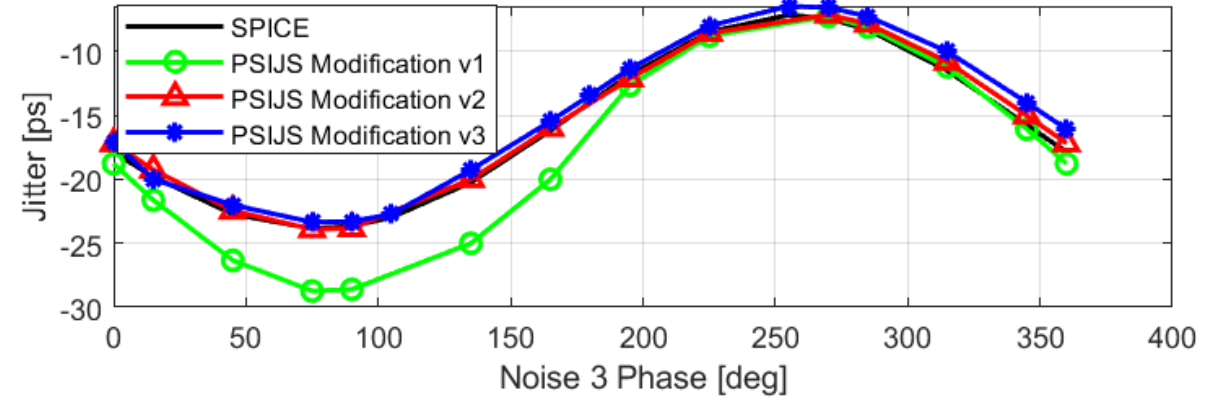
# Validation: With Power Supply AC Voltage Noise – Multi-frequency

$$V_{AC} = \text{Amp}_1 \times \sin(\omega_1 t + \varphi_1) + \text{Amp}_2 \times \sin(\omega_2 t + \varphi_2) + \dots$$

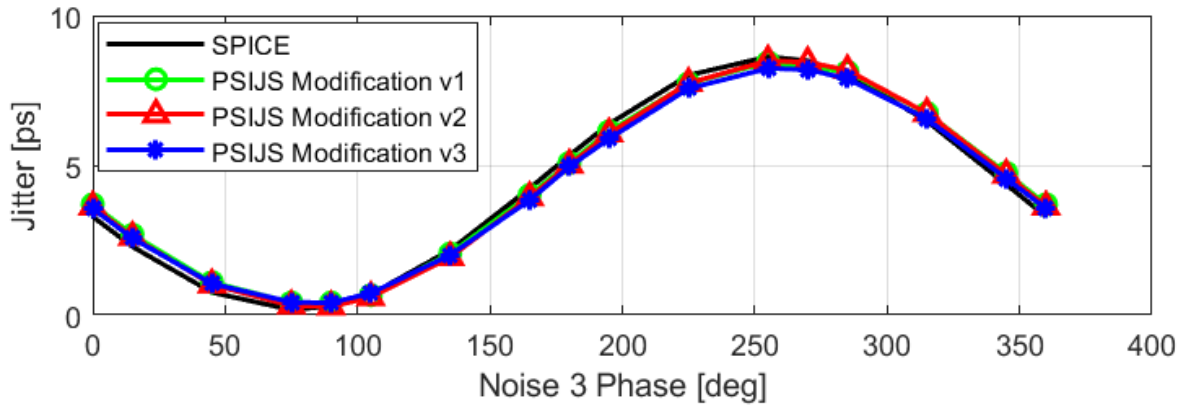


<8-Stage Inverter Chain Simulation Setup with AC Power Noise>

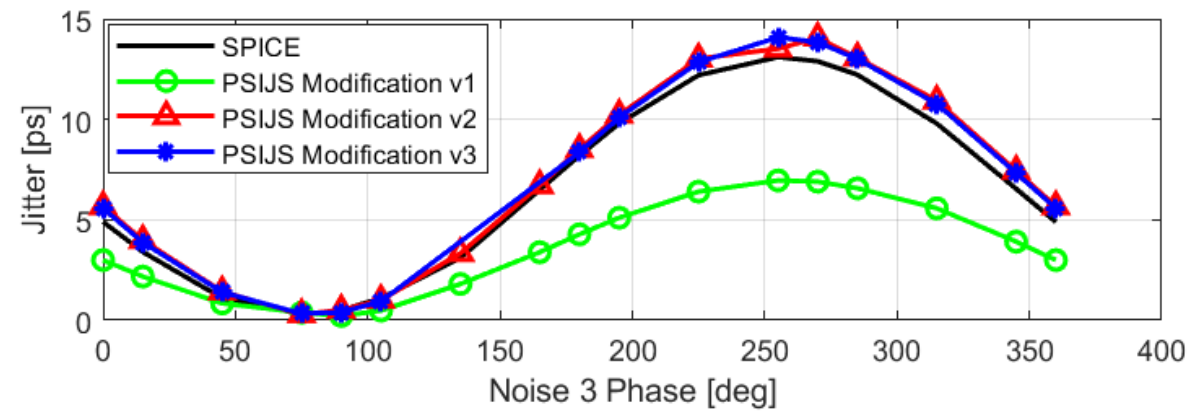
$$V_{CC} = 1.8V + 0.05 \times \sin(1MHz \times t + 90^\circ) + 0.05 \times \sin(30MHz \times t + 45^\circ) + 0.05 \times \sin(170MHz \times t + \varphi_3)$$



$$V_{CC} = 1.8V + 0.1 \times \sin(1MHz \times t + 225^\circ) + 0.05 \times \sin(30MHz \times t + 90^\circ) + 0.02 \times \sin(170MHz \times t + \varphi_3)$$



$$V_{CC} = 1.6V + 0.1 \times \sin(1MHz \times t + 225^\circ) + 0.05 \times \sin(30MHz \times t + 90^\circ) + 0.02 \times \sin(170MHz \times t + \varphi_3)$$



- The modified model is also valid with multi-tone power noise.



# Outline

- **Introduction**
  - Motivation
  - Previous Work and Limitation
    - Lookup Table-based Correction Coefficients Adjustment (v0)
    - Jitter Sensitivity-Based Ku/Kd Modification with Correction Coefficients (v1)
    - Jitter Sensitivity-Based Direct Ku/Kd Modification (v2)
- **Jitter Sensitivity-Based Direct Ku/Kd Modification with Slew Rate Correction (v3)**
  - Methodology
    - Ratio Modification
    - Time Difference Compensation
  - Validation
- **Conclusion**

# 4 Stages of the IBIS Model PSIJ Simulation Accuracy Improvement

## 1 – Lookup Table-based Correction Coefficients Adjustment (v0)

Step 1:  $K_u(t)$ ,  $K_d(t)$  extraction for **typ/min/max** case



Step 2:  $B_u(t)$ ,  $A_u(t)$  and  $B_d(t)$ ,  $A_d(t)$  extraction



Step 3:  $K_u(t)$ ,  $K_d(t)$  modification with **B, A correction coefficients** and time averaged effect

### Pros

- Can account for the delay change caused by power noise.

### Cons

- Modification process includes processing corner information.

## 2 – Jitter Sensitivity-Based $K_u/K_d$ Modification with Correction Coefficients (v1)

Step 1:  $K_u(t)$ ,  $K_d(t)$  extraction for **typ case**



Step 2:  $K_u(t)$ ,  $K_d(t)$  extraction for **max/min supply voltage case with DC jitter sensitivity**



Step 3:  $B_u(t)$ ,  $A_u(t)$  and  $B_d(t)$ ,  $A_d(t)$  extraction



Step 4:  $K_u(t)$ ,  $K_d(t)$  modification with **B, A correction coefficients** and time averaged effect

### Pros

- Straightforward modification based on only one keyword relates to power supply voltage fluctuation.

### Cons

- Not applicable with large voltage noise.

## 3 – Jitter Sensitivity-Based Direct $K_u/K_d$ Modification (v2)

Step 1:  $K_u(t)$ ,  $K_d(t)$  extraction for **typ case**



Step 2: **Nonlinear** DC jitter sensitivity and time averaged effect caused **time shift** calculation



Step 3:  $K_u(t)$ ,  $K_d(t)$  direct modification with the time difference

### Pros

- More simple and efficient process.
- Applicable with large voltage noise.

### Cons

- Output waveform slew rate cannot be characterized.

## 4 – Jitter Sensitivity-Based Direct $K_u/K_d$ Modification with Slew Rate Correction (v3)

Step 1:  $K_u(t)$ ,  $K_d(t)$  extraction for **typ case**



Step 2: DC jitter sensitivity and time averaged effect caused time shift calculation



Step 3:  $K_u(t)$ ,  $K_d(t)$  direct modification with the time difference



Step 4: Apply the **ratio modification** on  $K_u(t)$



Step 5: Calculate the **time difference** caused by ratio modification



Step 6:  $K_u(t)$  modification with the time difference

### Pros

- Both jitter and slew rate can be accurately predicted.

### Limitations

- Depends on parameter extraction.



# Reference

- IBIS Open Forum Committee, "I/O Buffer Information Specification (IBIS) Version 5.0", August 2008, [https://ibis.org/ver5.0/ver5\\_0.ibs](https://ibis.org/ver5.0/ver5_0.ibs)
- A. Muranyi, A. Girardi, G. Bernardi, R. Izzi, and B. Ross, "BIRD98.3: Gate Modulation Effect", Oct. 2007, <http://ibis.org/birds/bird98.3.txt>.
- Y. Sun and C. Hwang, "Improving Power Supply Induced Jitter Simulation Accuracy for IBIS Model," 2021 IEEE International Joint EMC/SI/PI and EMC Europe Symposium, Raleigh, NC, USA, 2021, pp. 1127-1132.
- Y. Ding, "IBIS Model Simulation Accuracy Improvement by Including Power-Supply-Induced Jitter Effect," IEEE Trans. Signal Power Integr., vol. 3, pp. 21-29, 2024.
- Y. Ding, "IBIS Model Simulation Accuracy Improvement by Including Nonlinear Power-Supply-Induced Jitter Effect," IEEE Trans. Signal Power Integr., submitted.

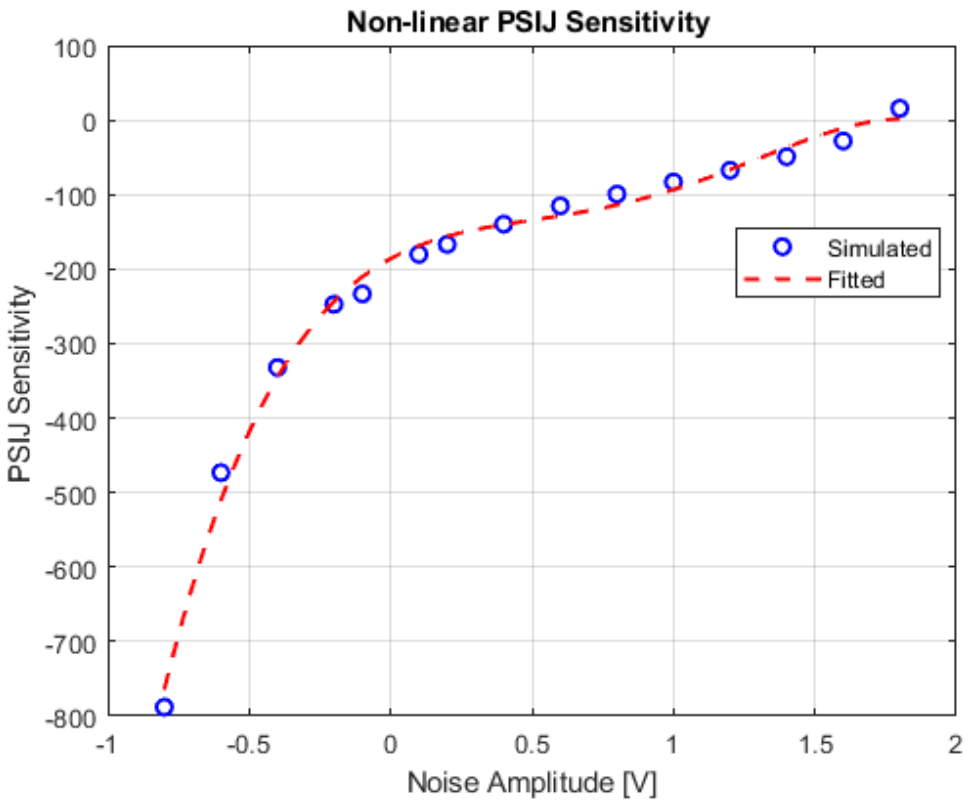
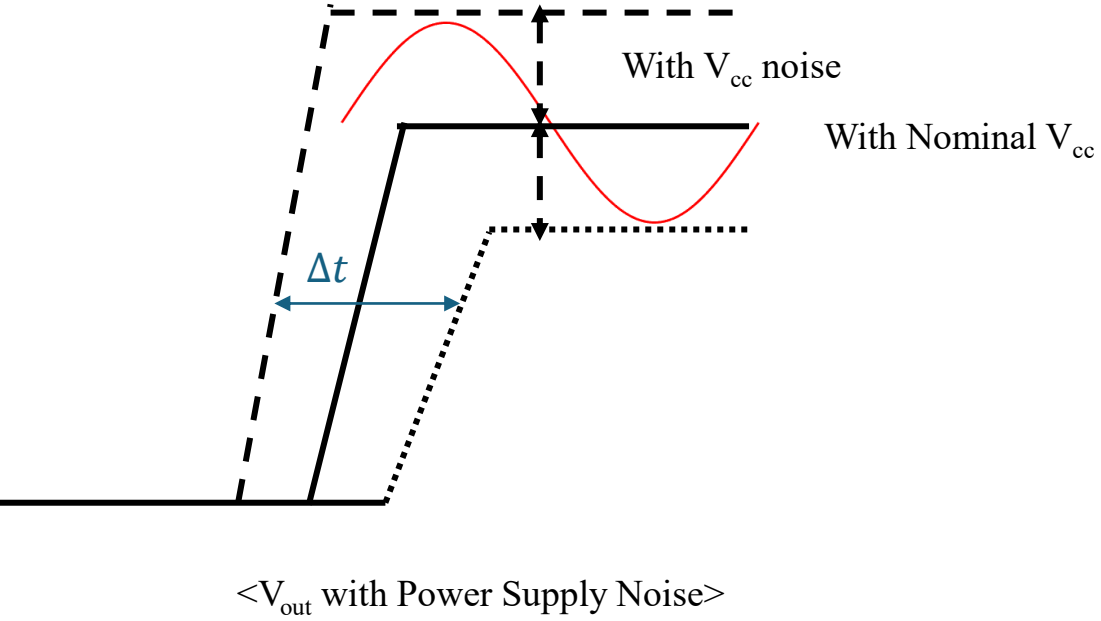


Thanks for Listening!

Q&A



# Non-linear DC Jitter Sensitivity



<Non-linear DC Jitter sensitivity>

$$PSIJS = \frac{T_{pd} - T_{pd\_typ}}{V - V_{typ}}$$

- The DC PSIJ sensitivity is a function of power supply noise amplitude.
- When the noise amplitude is small, DC jitter sensitivity can be treated as linear.
- When noise is larger, jitter sensitivity shows obvious non-linear behavior.

