Current Source Modeling in the Presence of Body Bias

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Outline

- Motivation and Problem Statement
- Current Source Model (CSM) – Sensitivity Model
- Compact CSM Storage
- Our Waveform Sensitivity Model
- Results

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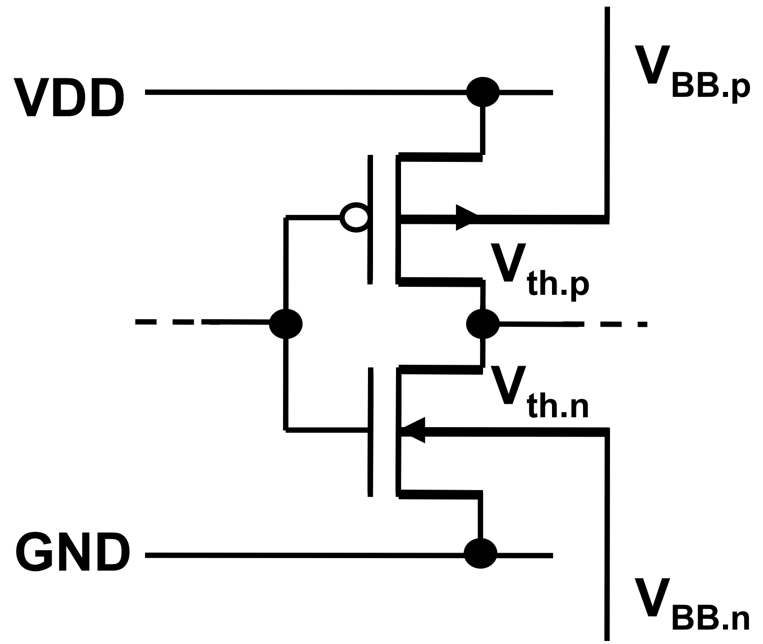
Motivation – Industrial Designs

Adaptive Body Bias (ABB)

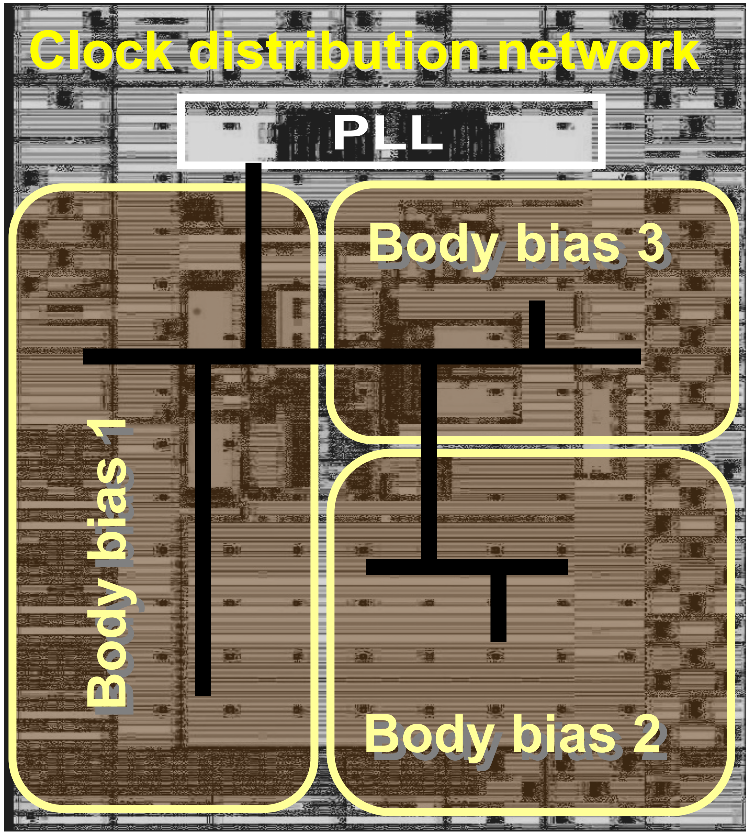
- Compensates for performance variability
- Yields desired timing characteristics in presence of variations
- Kuroda, ISSCC96: well-level ABB



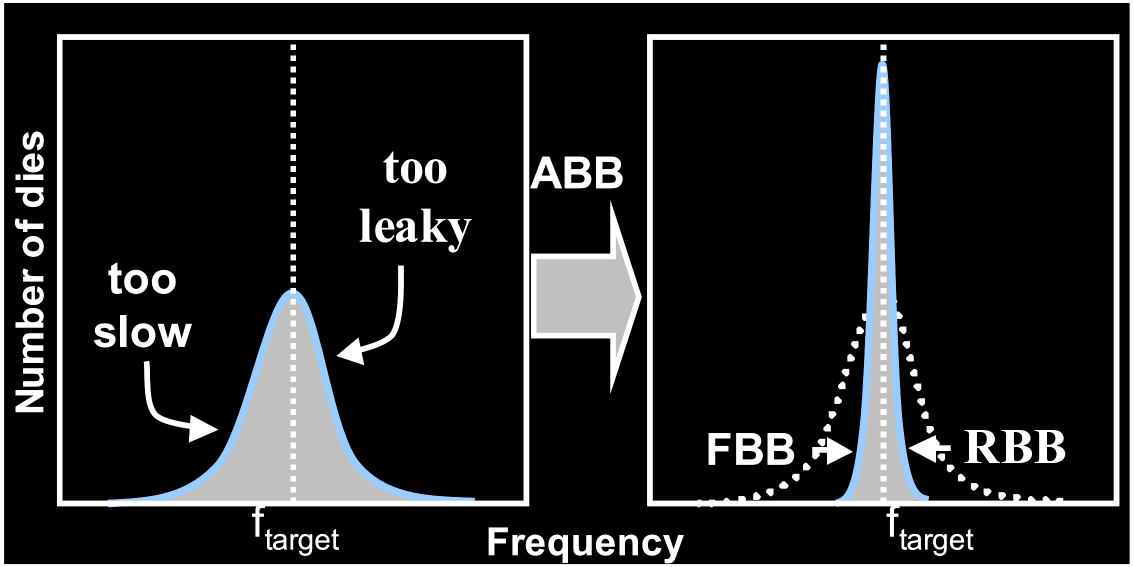
Motivation – Industrial Designs

Chip level ABB [INTEL]

- Maximum operational frequency and minimum leakage



WID ABB concept



Use of FBB and RBB to tighten die distribution

Motivation and Problem Statement

ABB compensation for performance variability

- RBB
- FBB

Needs timing response precharacterization with body bias

Current Source Modeling

- 100x faster simulations than Hspice
- Near Hspice accuracy

Can yield rapid timing characterizations

Enable CSMs to obtain timing response at multiple body bias points

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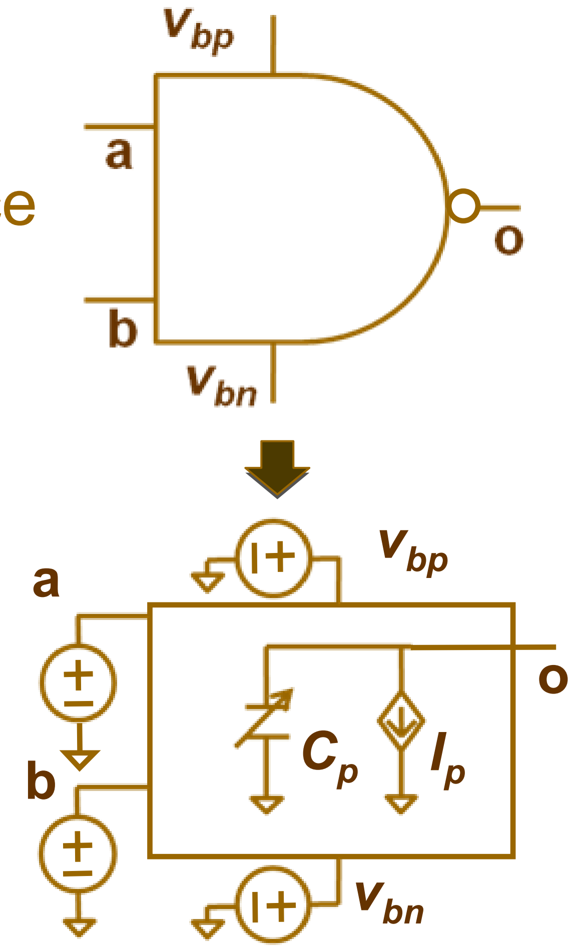
Current Source Models



- CSM represents cell as a controlled source
- Port modeled as
  - nonlinear current source
  - nonlinear capacitance
  - lookup tables indexed by port voltages

Previous work:

- Croix *et al.*, DAC 2003: Blade and Razor
- Keller *et al.*, ICCAD 2004: Signal integrity
- Li and Acar, ICCD 2005: Receiver input modeling

Current Source Models

- Amin *et al.*, DAC 2006: Multiport CSM (MCSM)
- Kashyap *et al.*, ICCAD 2007; Amelifard *et al.*, DATE 2008: Internal node effects
- Vrudhula *et al.*, DATE 2008: Orthogonal functions
- Raja *et al.*, DAC 2008: Fast transistor models

- **Impact of body bias not yet investigated.**

- **Our CSM** - Blade Model with nonlinear capacitance
  - $I_p = F(V_i, V_o, v_{bp}, v_{bn})$ – Current source characterized by DC simulations (Blade Model)
  - $Q_p = G(V_i, V_o, v_{bp}, v_{bn})$ – Capacitance characterized by transient simulations (MCSM)

Presence of body bias — speedup overview

***b* points for v_{bp}**
***b* points for v_{bn}**

Straightforward extension
$2b^2$ lookup tables
b^2 waveform evaluations

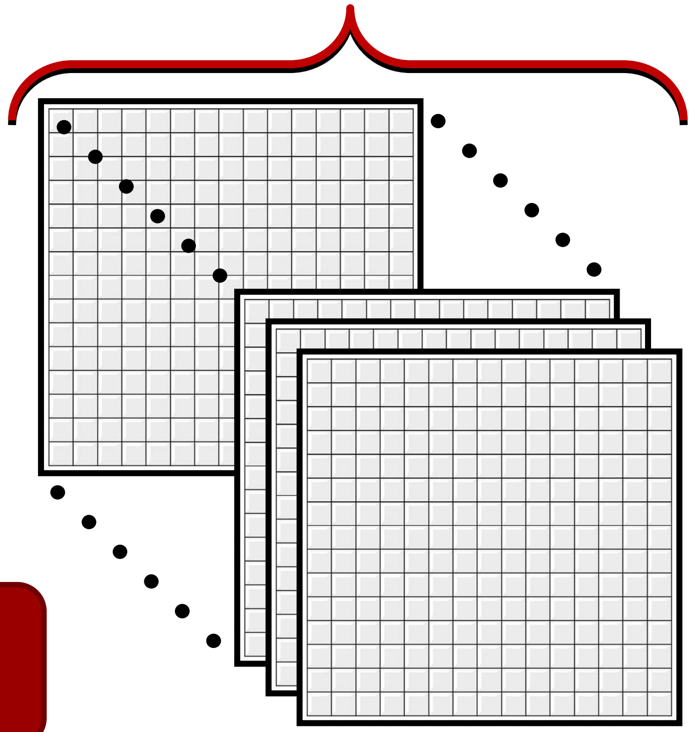
Intermediate enhancement
2+4 lookup tables
b^2 waveform evaluations

Final enhancement
2+4 lookup tables
3 waveform evaluations.

Characterization over all (v_{bp}, v_{bn})

- Full characterization: ***b*** values of v_{bp}, ***b*** values of v_{bn}
  - Needs ***b·b*** characterizations
  - Computationally intensive
  - Requires huge storage space

10x10 tables,
each of size 30x30



- Example
  - 10 values for each of v_{bp}, v_{bn}
  - Table size for zero body bias: 900
  - Total characterization size: 90000
  - Size increase: 100x

Can we reduce the storage overhead of these tables?

Solution - CSM Sensitivities

- Linear polynomial expansion -

$$I_p = I_p^Z \cdot [1 + a_I (V_i, V_o) \cdot v_{bp} + b_I (V_i, V_o) \cdot v_{bn}]$$
$$Q_p = Q_p^Z \cdot [1 + a_Q (V_i, V_o) \cdot v_{bp} + b_Q (V_i, V_o) \cdot v_{bn}]$$

At zero body bias ⇩ 2 lookup tables

$$a_I = \frac{\partial I_p}{\partial v_{bp}} \qquad a_Q = \frac{\partial Q_p}{\partial v_{bp}}$$

$$b_I = \frac{\partial I_p}{\partial v_{bn}} \qquad b_Q = \frac{\partial Q_p}{\partial v_{bn}}$$

⇨ 4 lookup tables

- Average error = 2%

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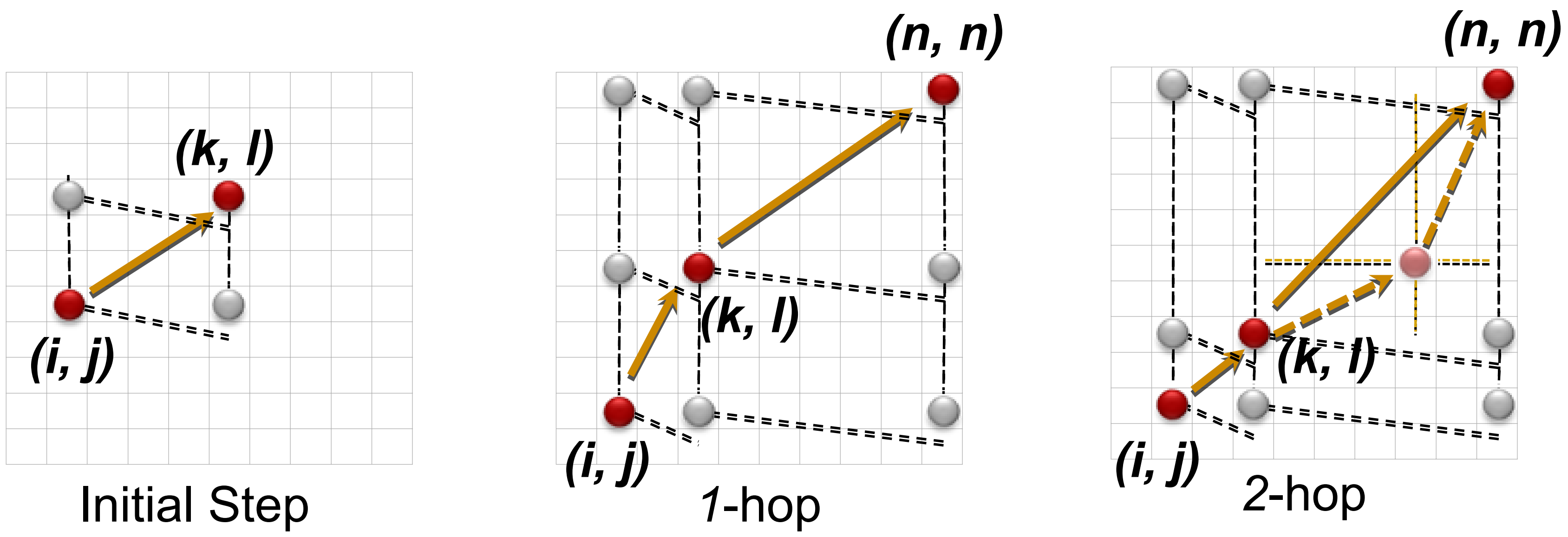
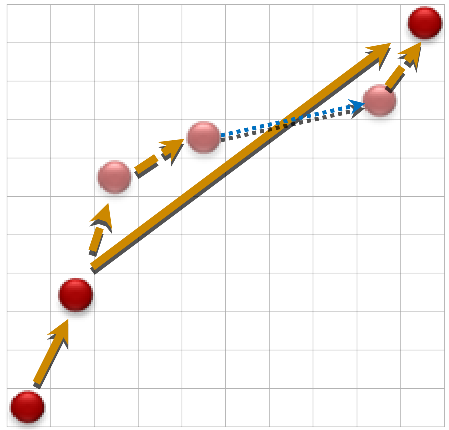
Existing Approach for Size Reduction

- Croix and Wong, DAC 1997
- Store a subset of points - use interpolation
- Algorithmic steps:
  - Initial step: compute errors from *(i, j)* to *(k, l)*
  - Minimal error 1-hop from *(i, j) to (n, n)*
  - Minimal error 2-hop from *(i, j) to (n, n)*



Existing Approach for Size Reduction

- Optimal *(m-1)*-hop error – final reduced table size = $m \times m$
- Dynamic programming

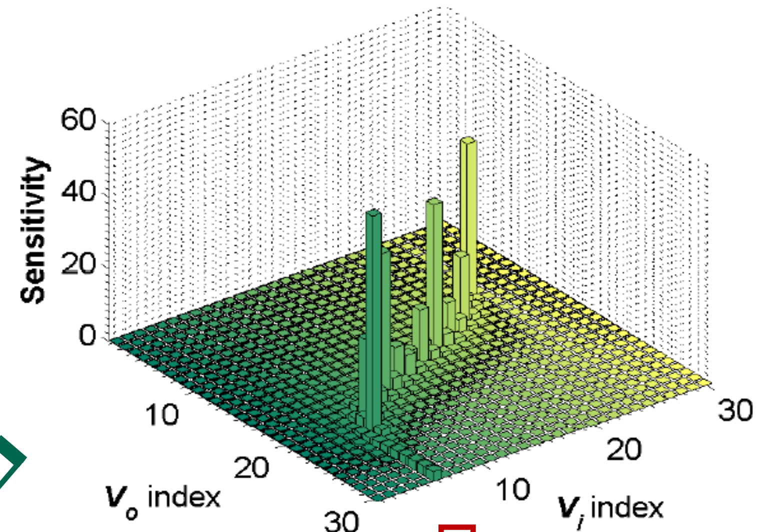


(m-1)-hop: $m \times m$ *table*

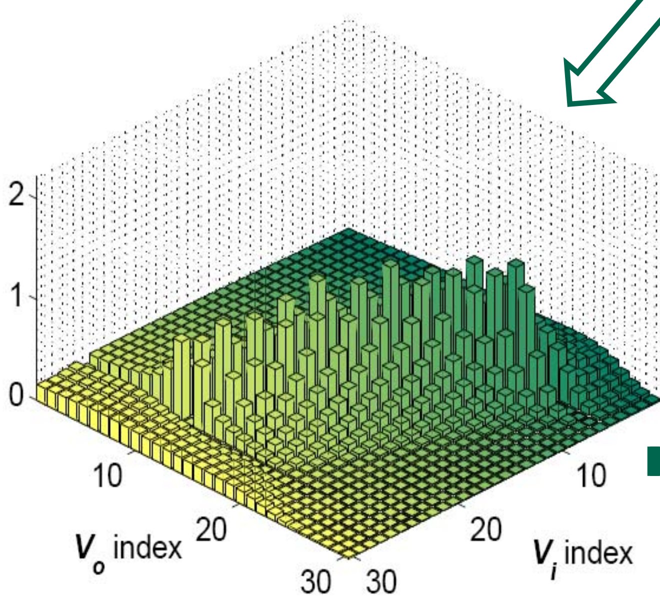
- **Works well with I_p , Q_p tables**
- **Poor compression with sensitivity parameter tables**

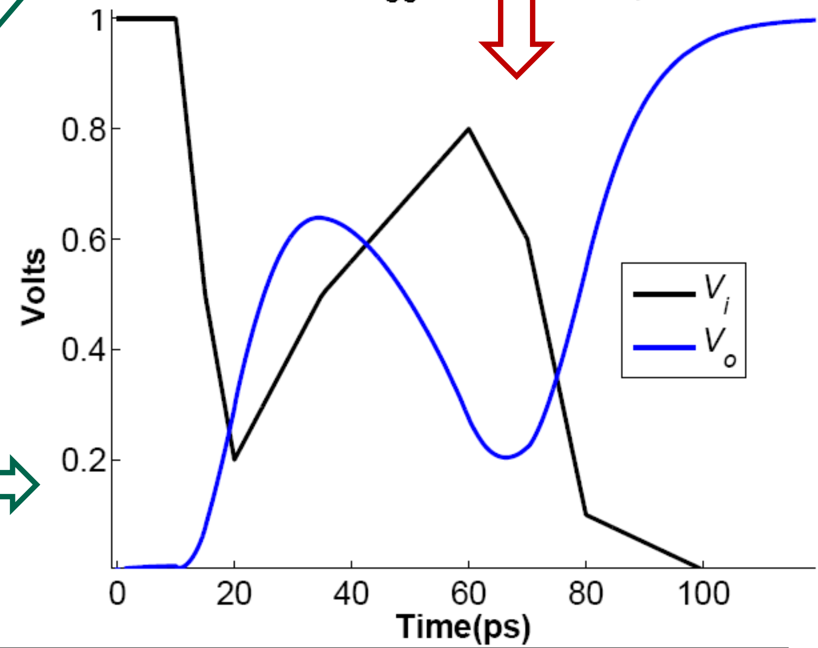
Our Approach for Sensitivities

- Outliers in sensitivity lookup tables
  - Poor compression
  - Kinks in the waveforms
- Our solution:
  - Store outliers separately: entry over k=2 variances from the mean



V_i	V_o	Outliers
10	25	42.6
13	22	18.9
16	16	15.53
.	.	.
.	.	.
22	7	60.7





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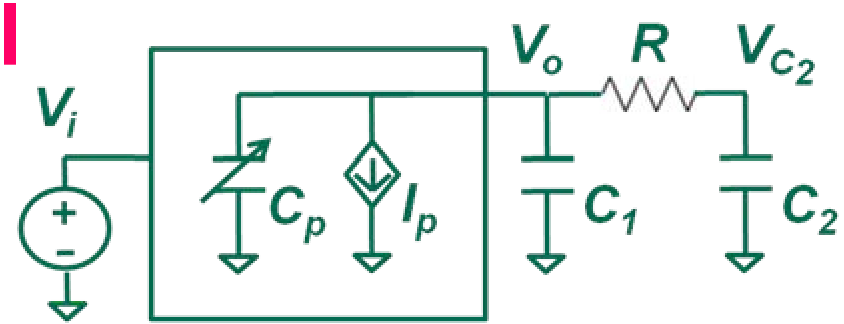
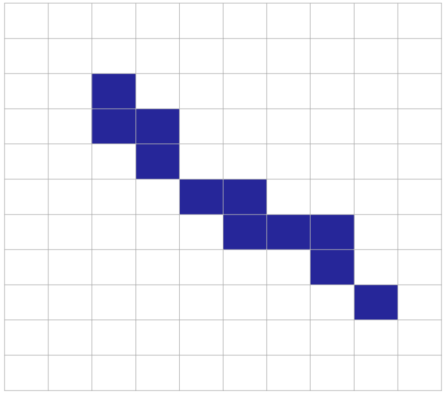
Solving the Macromodel



Absence of body bias:

- Gate output driving π-load
- Output voltage waveform: Newton-Raphson (NR) solver
  - *Timestepping:* Backward Euler
  - *Linearization:* Newton-Raphson iterations
  - Each iteration: table lookups for I_p and Q_p

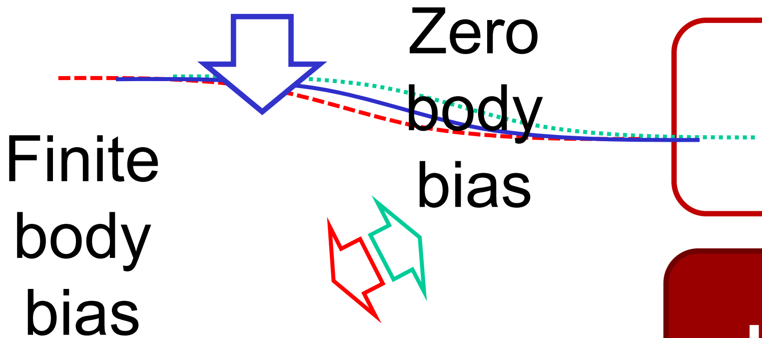


Presence of body bias:

- Waveforms for b points of v_{bp}, v_{bn} each: b^2 computations and enormous table lookups

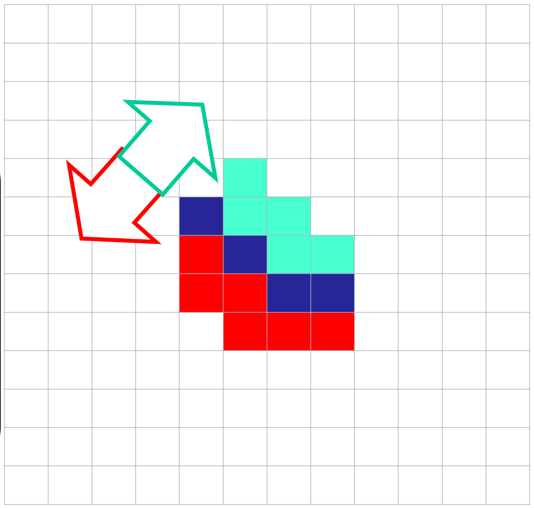
Need a framework for cheap evaluation of waveforms with body bias

Intuition for Our Model



Waveform with body bias: perturbation to the nominal case

How to capture this perturbation?



Body bias evaluations
Multiple accesses to the look-up tables for I_p and Q_p

Accessed entries in each table relatively close to each other

Accessed entries captured as perturbations to the nominal case

Waveform Sensitivity Model

- Formulate:

$$V_o(t) = V_o^Z(t) + \alpha(v_{bp}, v_{bn}, t)\cdot v_{bp} + \beta(v_{bp}, v_{bn}, t)\cdot v_{bn}$$

$$\alpha(v_{bp}, v_{bn}, t) = \frac{\partial V_o(t)}{\partial v_{bp}} \qquad \beta(v_{bp}, v_{bn}, t) = \frac{\partial V_o(t)}{\partial v_{bn}}$$

$\alpha(v_{bp}, v_{bn}, t)$, $\beta(v_{bp}, v_{bn}, t)$ - time varying perturbation parameters

- Waveform at any body bias can be reproduced

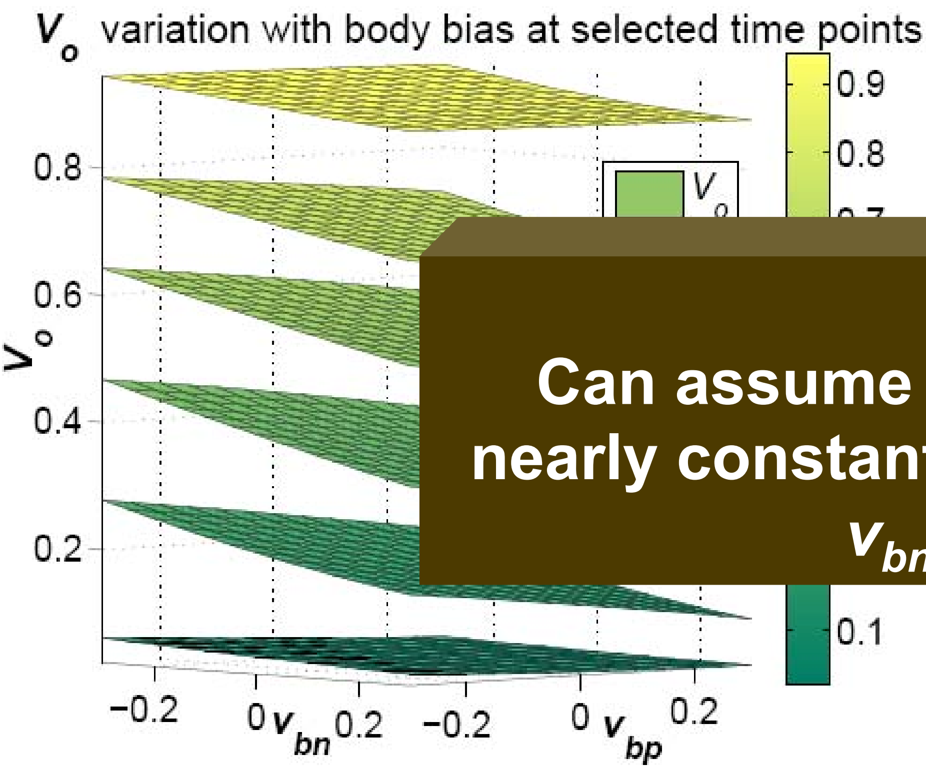
- Need to compute α, β for b points of v_{bp}, v_{bn} each
  - b^2 waveforms evaluations
  - Multiple accesses to lookup tables

Can We Reduce the Computations?

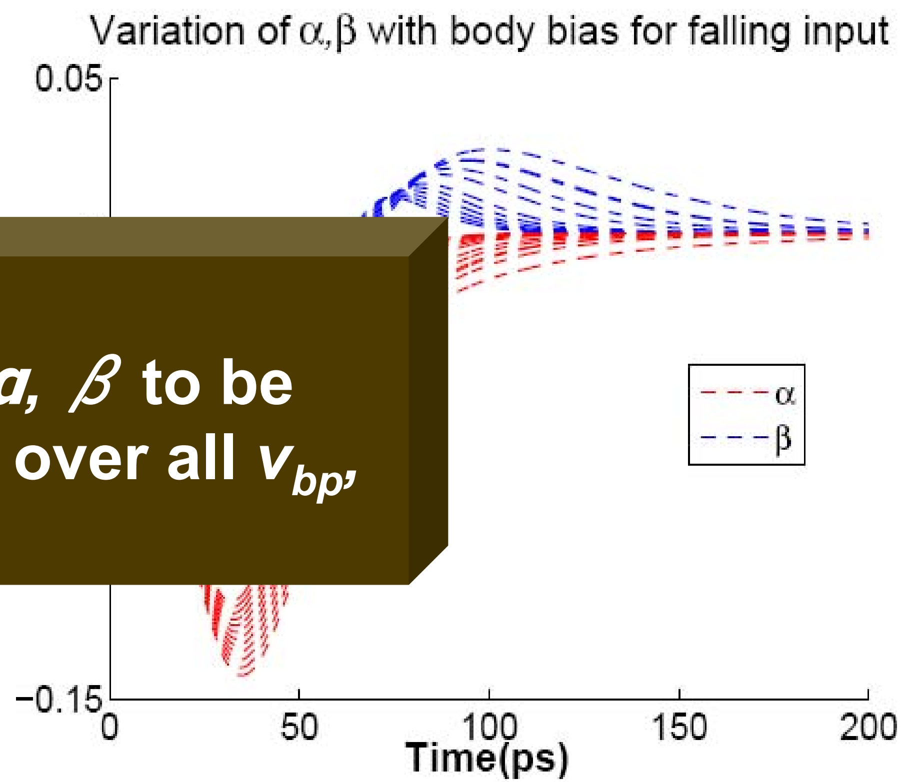
- Investigate dependencies of the V_o on α, β

V_o *(t)* variation nearly linear over all (v_{bp}, v_{bn})

α, β variations: less than 0.1
Only 3% maximum change in V_o *(t)*



Can assume α, β to be nearly constant over all v_{bp}, v_{bn}



Simplified Waveform Sensitivity Model

- Use α, β for the zero body bias case for all v_{bp}, v_{bn} point

$$\alpha(v_{bp}, v_{bn}, t) \approx \alpha_0(t) = \alpha(v_{bp}=0, v_{bn}=0, t)$$

$$\beta(v_{bp}, v_{bn}, t) \approx \beta_0(t) = \beta(v_{bp}=0, v_{bn}=0, t)$$

$$V_o(t) = V_o^Z(t) + \alpha_0(t) \cdot v_{bp} + \beta_0(t) \cdot v_{bn}$$

- Computational efficiency enhanced greatly; accuracy still maintained

b points for v_{bp}
b points for v_{bn}

Enumerative approach (NR Solver)	Our approach (Waveform Sensitivities)
b^2 waveform evaluations Extensive use of lookup tables	Just 3 waveform evaluations $V_o^Z(t)$, $\alpha_0(t)$ and $\beta_0(t)$

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Table Size Reduction

- **Results for table with original size: 900**
- Reduction for various bounds on total allowable error

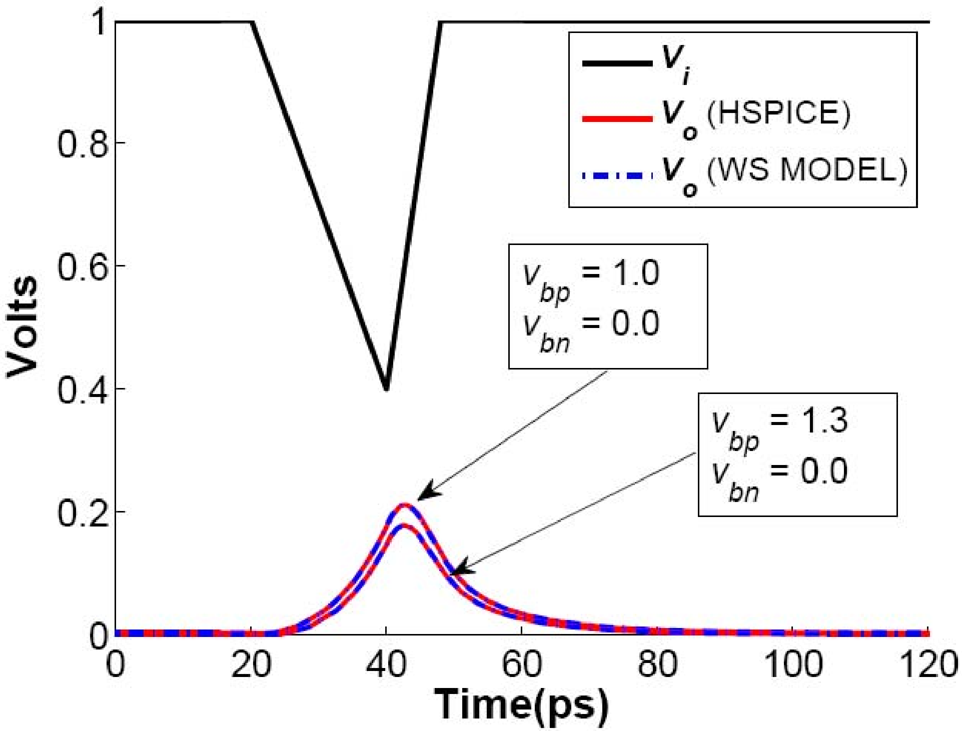
CELL	Reduced Table Size With Error Bounds					
	Original Approach			Our Approach		
	2%	5%	10%	2%	5%	10%
INV	41.2%	46.2%	64.0%	75.0%	81.2%	88.9%
NAND2	36.0%	46.2%	67.9%	78.2%	84.0%	91.0%
NOR2	0.0%	12.8%	36.0%	64.0%	71.5%	81.2%
NAND3	30.6%	41.2%	71.5%	81.2%	84.0%	91.0%
NOR3	6.6%	19.0%	46.2%	67.9%	75.0%	84.0%
AOI21	36.0%	41.2%	46.2%	78.2%	81.2%	88.9%
AOI22	41.2%	46.2%	59.9%	75.0%	81.2%	91.0%

LESS REDUCTION

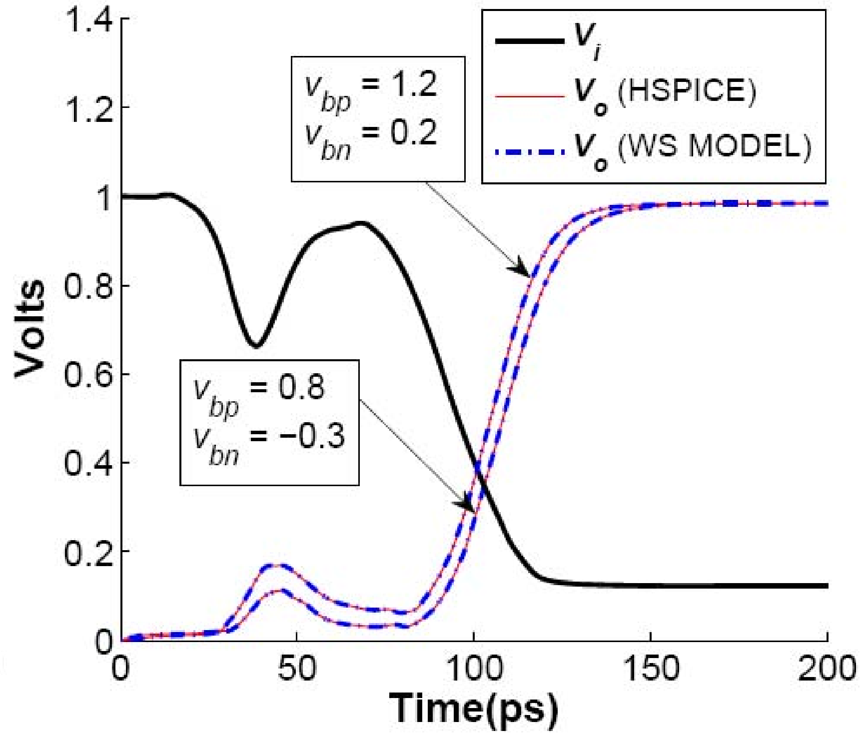
HIGH REDUCTION

Accurate Waveform Generation

- Simplified waveform sensitivity (WS) model compared with HSPICE: arbitrary π-load



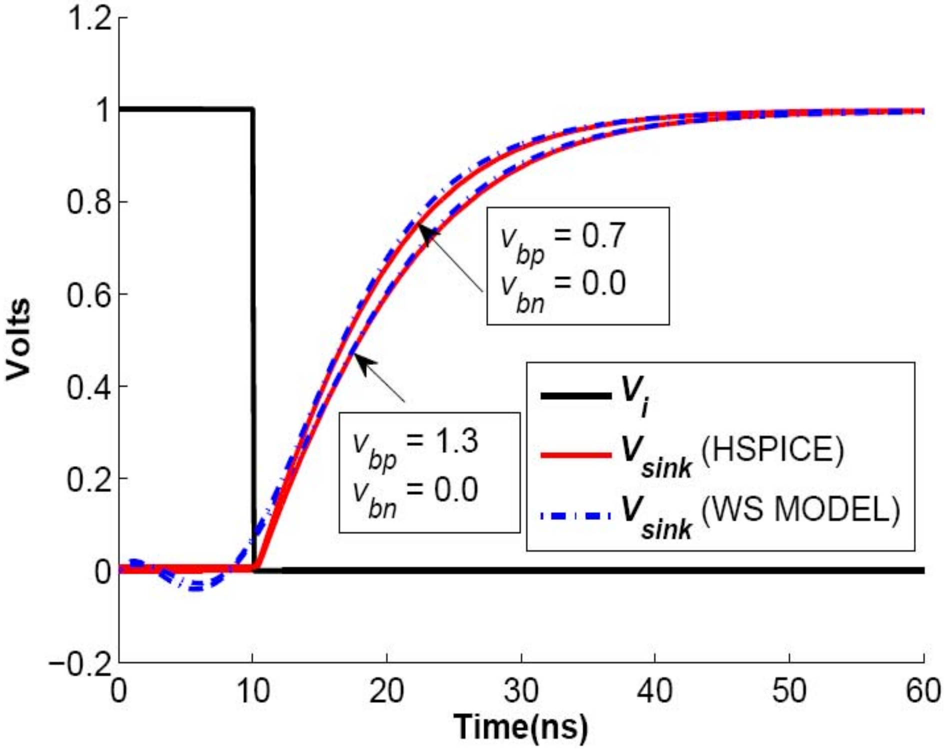
Output for a glitch



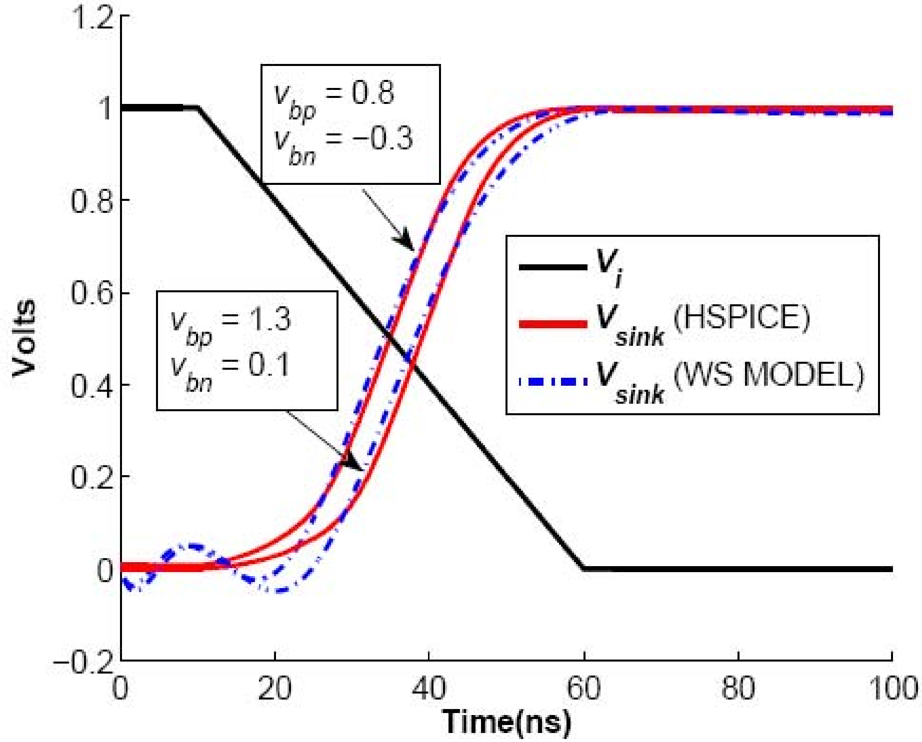
Output for a nonmonotone input.

Accurate Waveform Generation

- RC interconnect benchmarks reduced to π-loads (O'Brien/Savarino reduction with Pade approximation)



Benchmark – *20l.net*
Output at sink node 52



Benchmark – *45l.net*
Output at sink node 103

Speedup

- Speedup of simplified waveform sensitivity (WS) model over HSPICE and NR solver

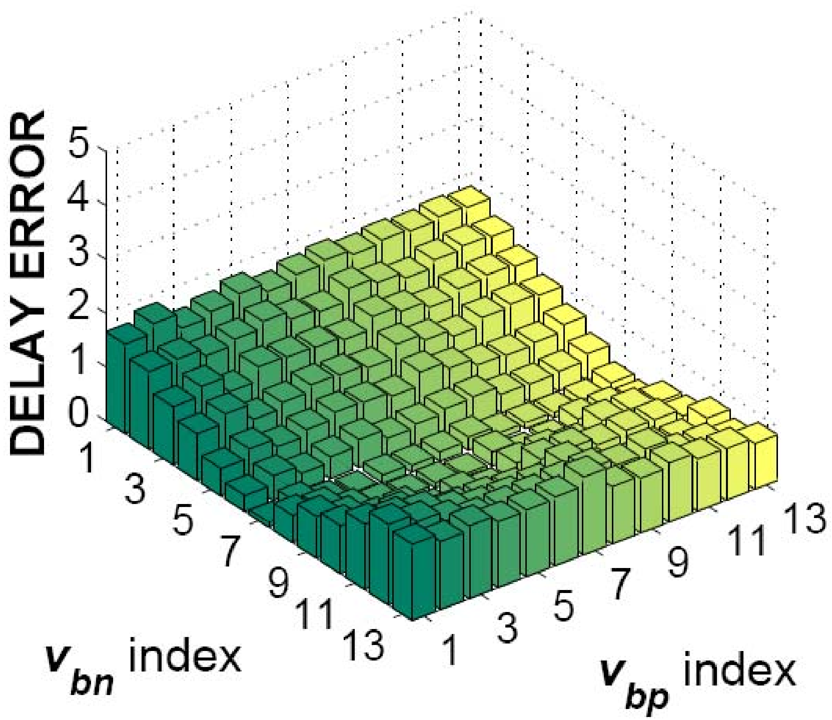
CELL	WS Model Speedup	
	Over HSPICE	Over NR Solver
INV	8.9×10^4	65.36
NAND2	9.6×10^4	66.29
NOR2	9.2×10^4	69.23
NAND3	9.6×10^4	66.67
NOR3	8.9×10^4	72.15
AOI21	1.1×10^5	66.80
AOI22	1.1×10^5	69.36

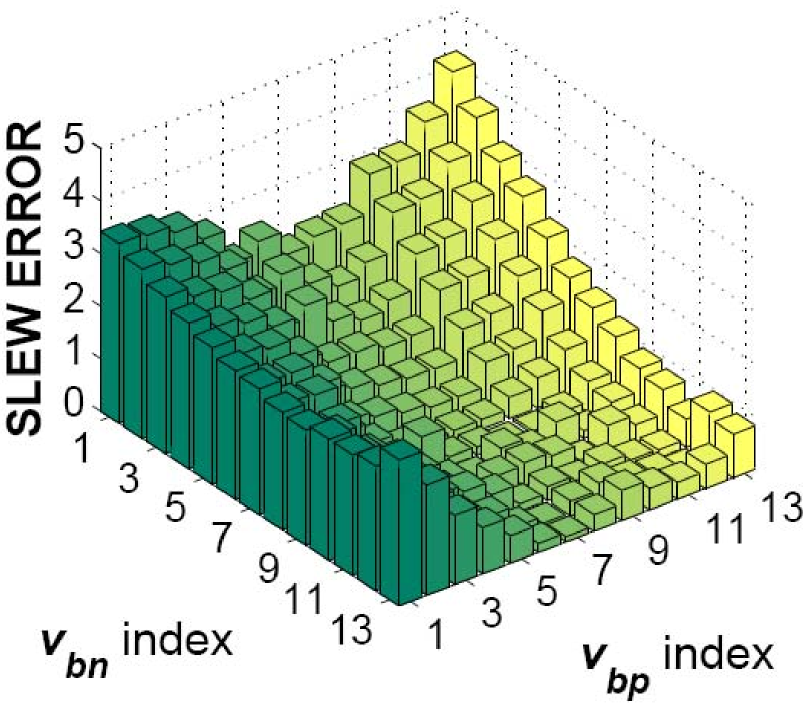
Five orders of magnitude speedup!

Approximately 70x speedup!

Delay/Slew Error Results

- **Results for cell output node**

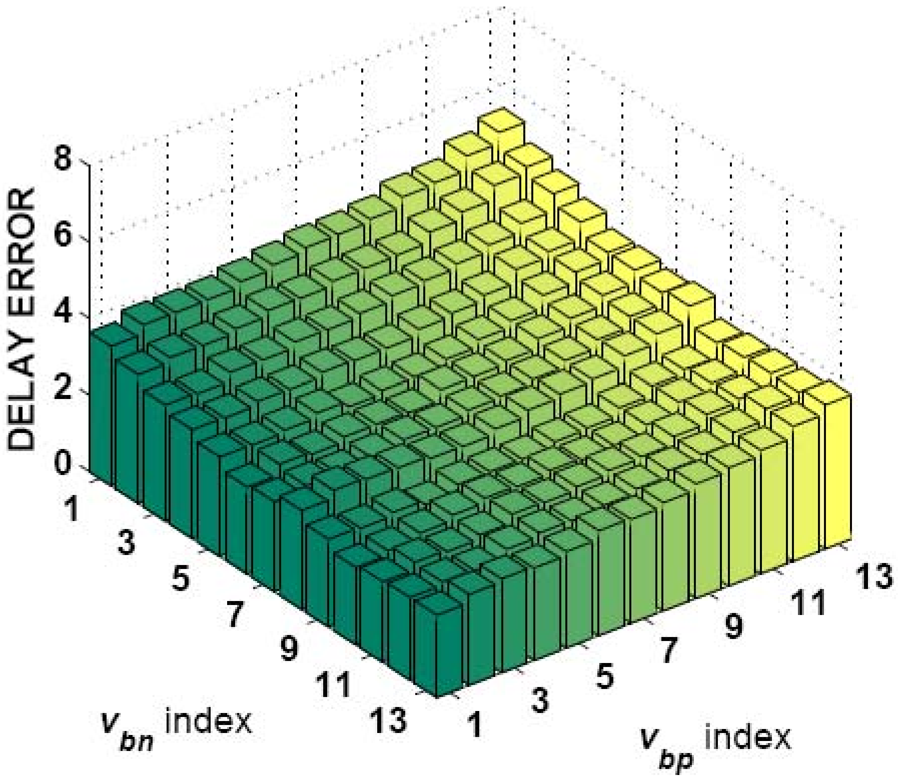


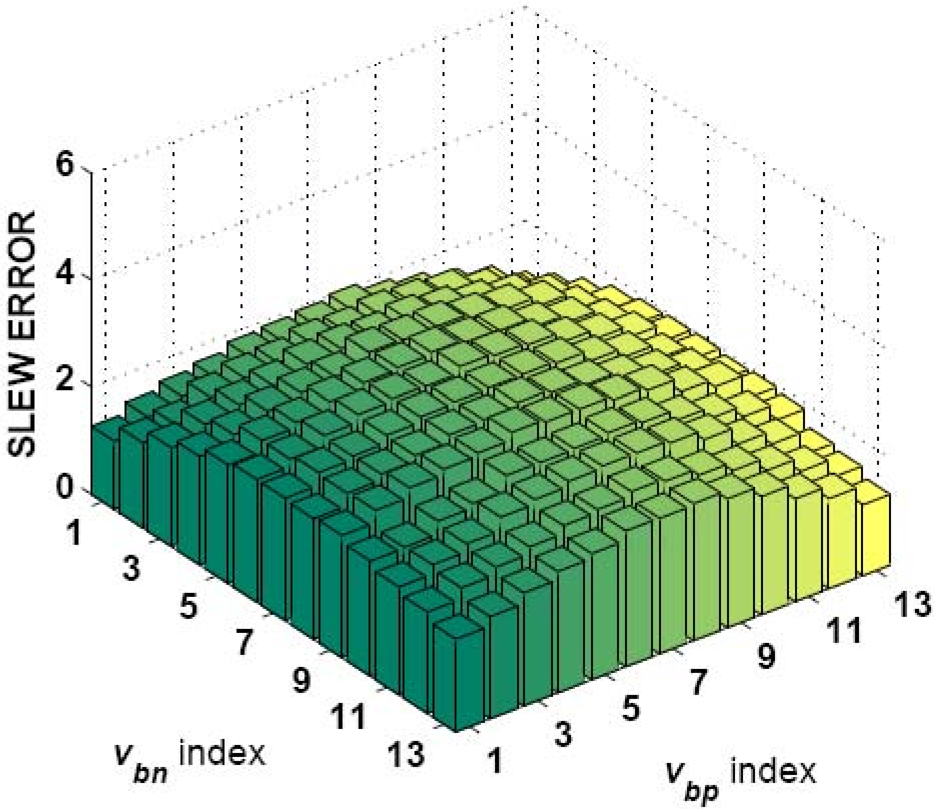


- Percentage delay/slew errors relative to HSPICE
- Worst case delay/slew error = 5%

Delay/Slew Error Results

- **Results for interconnect (*20l.net*) sink node 52**





- Worst case delay/slew error = 8%

Summary

- Existing CSMs for ABB: large increase in library size and characterization time
- Sensitivity model for capturing variations in CSM components with body bias
  - Compact storage of CSM sensitivity parameters
- New waveform sensitivity model for body bias effects
  - Accurate waveforms at any body bias
  - Five orders of speedup over HSPICE
  - About 70x speedup over conventional CSMs

QUESTIONS?