An Accurate PLL Behavioral Model for Fast Monte Carlo Analysis under Process Variation

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*** : speaker**

Outline

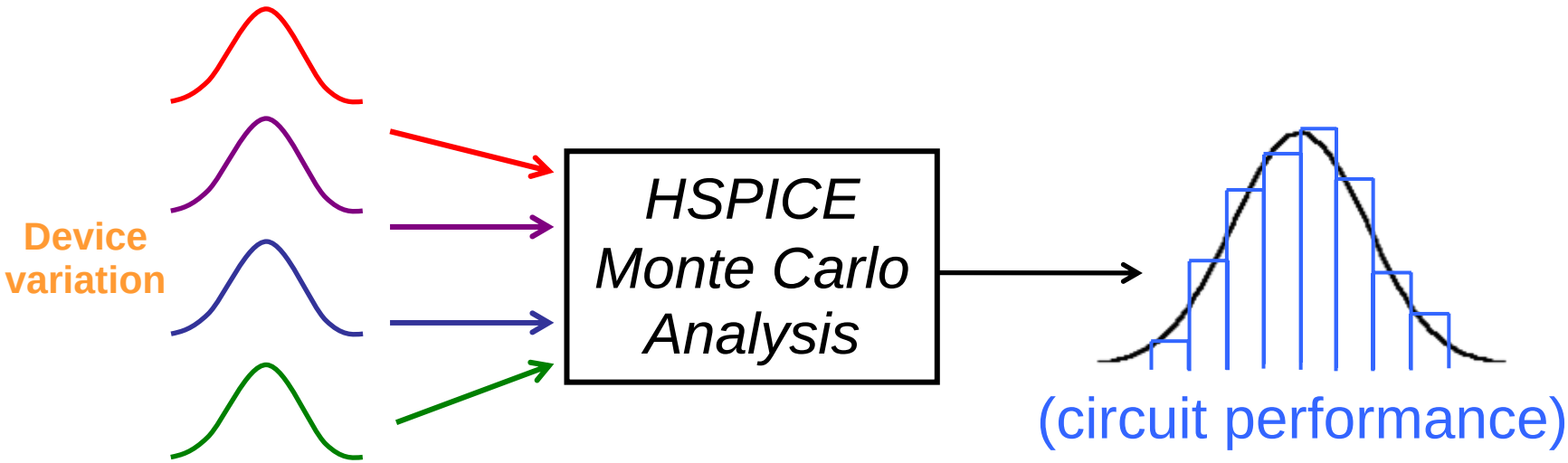
- **Introduction**
- Bottom-up Behavioral Modeling
- Modified Sensitivity Analysis
- Experimental Results
- Conclusions

Process Variation Effects

- In deep-submicron technology, impacts of device parameter variation become major factors limiting circuit performance
- Process variation aware analysis is necessary in the early design stage (re-design↓)
- Monte Carlo Simulation (MCS) is often used
  - Statistical analysis
  - Much random data for analysis
  - Many simulation times → time-consuming

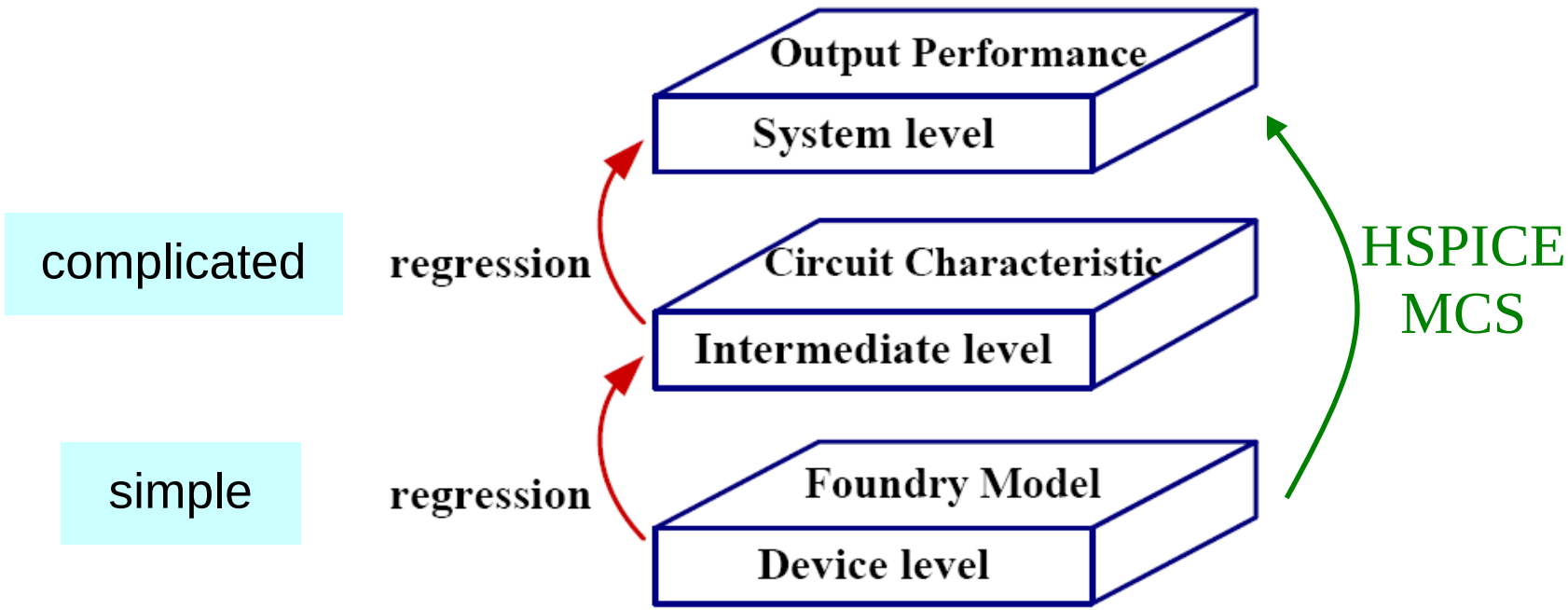
Traditional Statistical Analysis

- Transistor-level Monte Carlo Simulation (MCS)
- Based on the statistical models of transistor parameters from IC foundry
  - High accuracy
  - Long simulation time



Hierarchical Statistical Analysis

- Solve the speed issue of traditional MC analysis
- Response Surface Methodology (RSM) technique
  - Regression-based method
  - Numeric statistical results



Regression Cost of RSM

- 1st-order RSM : $Y = a_0 + a_1 X_1 + a_2 X_2 + \ldots + a_k X_k$
- 2nd-order RSM : $Y = a_0 + \sum_{i=1}^{k} a_i X_i + \sum_{i=1}^{k} \sum_{j=1}^{k} a_{ij} X_i X_j$
- Number of training samples is **at least 4 times** greater than the number of unknown coefficients
  - Even if a simplified algorithm is used
- Example: If k =4
  - 1st RSM : 5 unknown coefficients ➔ □20 training samples
  - 2nd RSM : 15 unknown coefficients ➔ □ 60 training samples

ref: Xin Li, Jiayong Le, Pileggi, L.T., Strojwas, A., "Projection-based performance modeling for inter/intra-die variations**",** *ICCAD*, 2005.

Our Targets

		Hierarchical Statistical Analysis	
	HSPICE MCS	Pure RSM-based	Our *BMCS
Regression cost	N/A	Worse	Good
Accuracy	Better	Based on complexity	Good
Simulation time	Worse	Better	Good
Observability (waveforms)	Better	Worse	Good

Developed methods

*S_E - like analysis

efficient PLL behavioral model

*BMCS: Behavioral Monte Carlo Simulation

*S_E: Sensitivity Analysis

Sensitivity Analysis (S_E)

- Delay under process variation :

$$\Delta T_d = T_d(\Delta x_i) - T_{d0} \approx \frac{\partial T_d}{\partial x_i} \times \Delta x_i$$

T_{d0} : Nominal delay

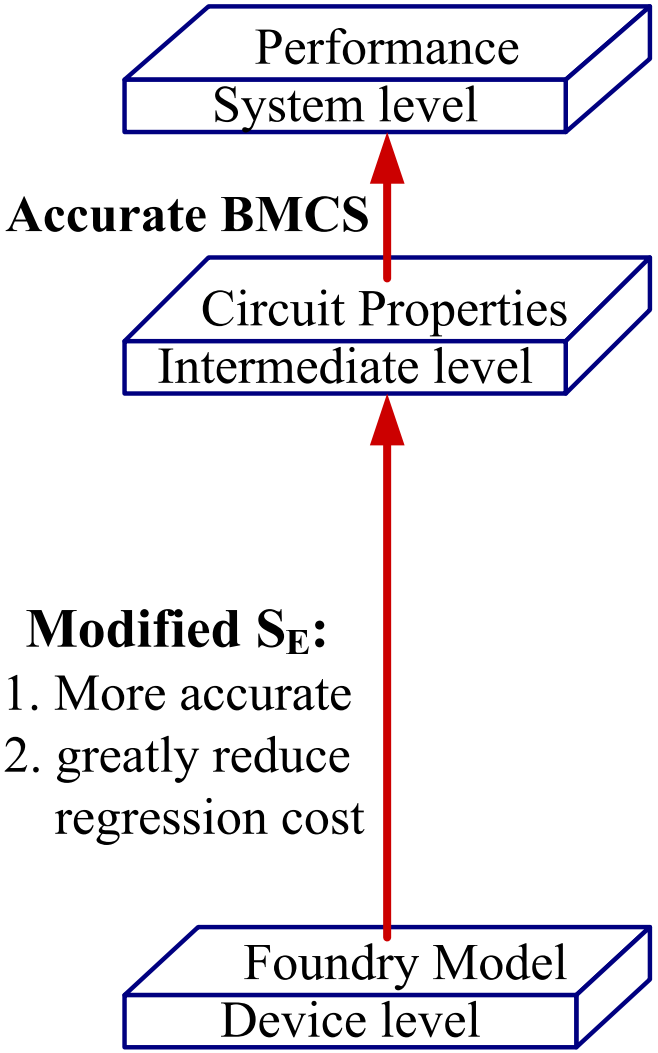
$\frac{\partial T_d}{\partial x_i}$: Delay sensitivity to device parameter x_i

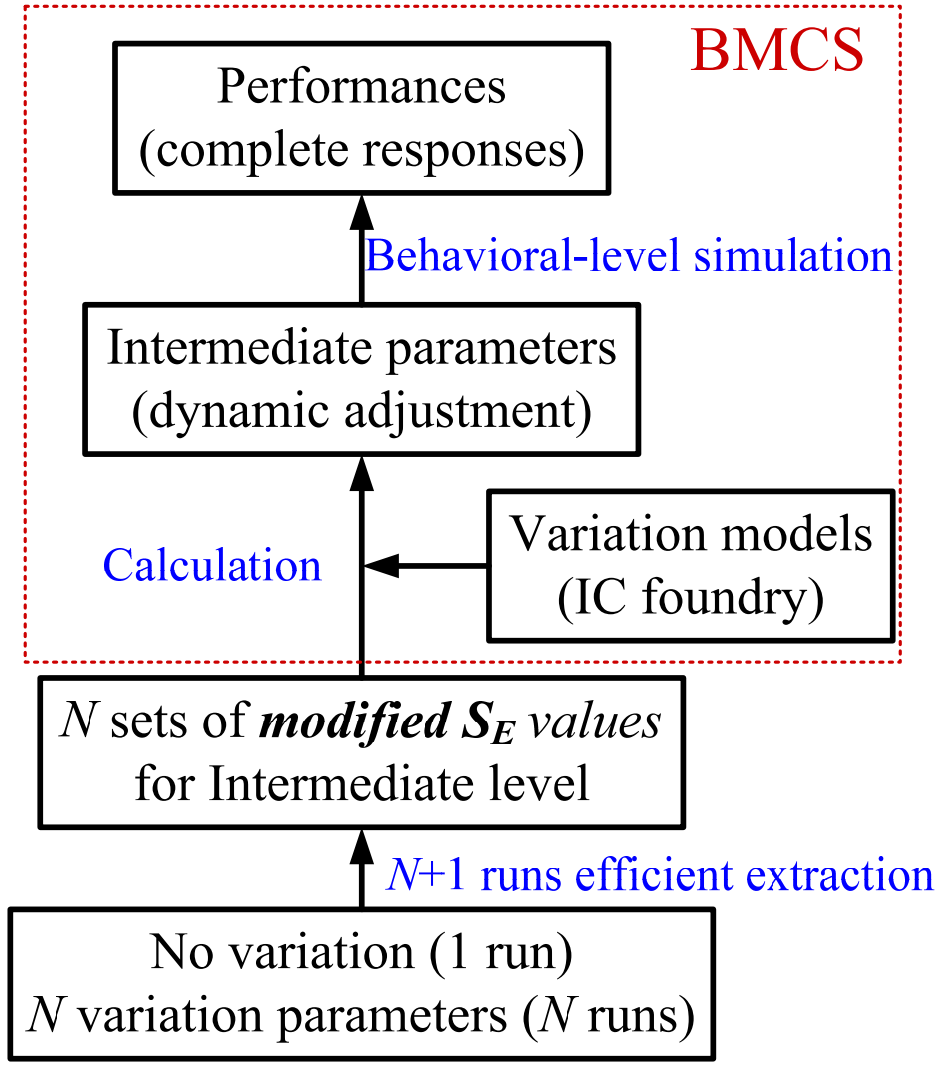
- Use sensitivity analysis (S_E) to reflect the process variation effects in behavioral parameters
  - Can save considerable regression time for complicated curve fitting
- Disadvantage: Traditional sensitivity analysis may have larger error at analog blocks
- We propose **modified sensitivity analysis** for analog circuits, without extra simulation cost

Behavioral MCS

- Behavioral Monte Carlo Simulation (BMCS)
  - Analyze process variation effects at behavioral level
  - Simulation results include detailed output waveforms and performance shift
- The accuracy of the behavioral models is the most critical issue in BMCS-based approaches
  - Directly affect the statistical results
  - Ideal top-down model is not suitable
  - Use bottom-up modeling method to extract actual circuit properties to improve the accuracy

Our BMCS Flow





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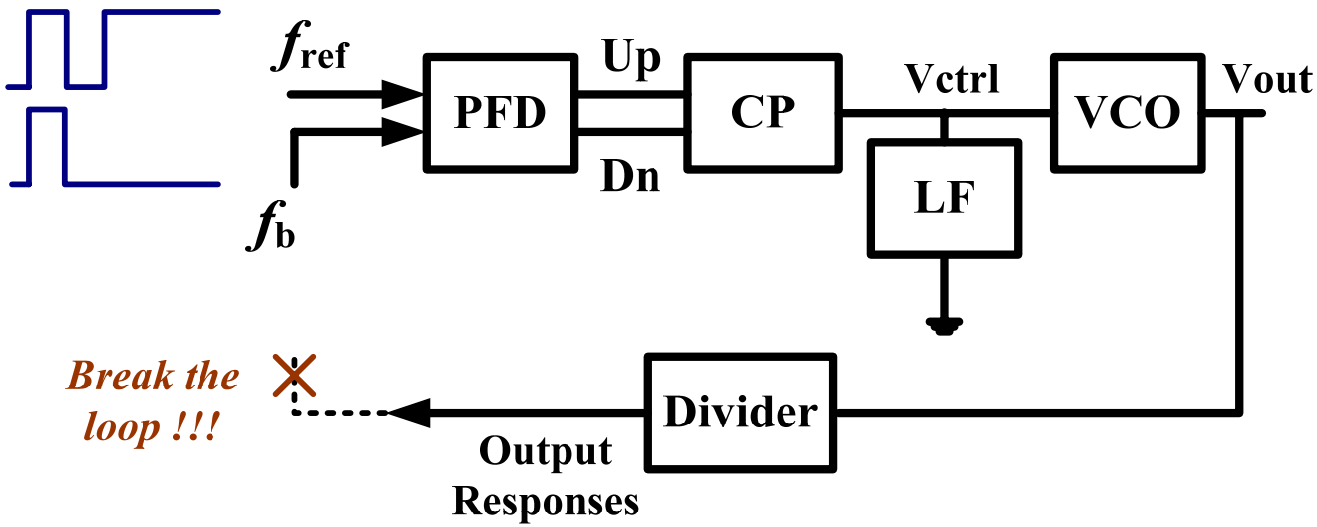
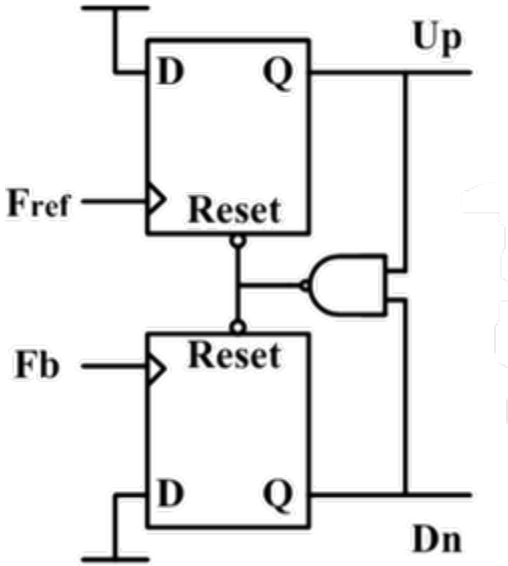
Characterization Mode

- Charge pump PLL
- Only one extraction pattern
- Automatically consider parasitic and loading effects
- Can extract all required characteristic parameters from simulation results

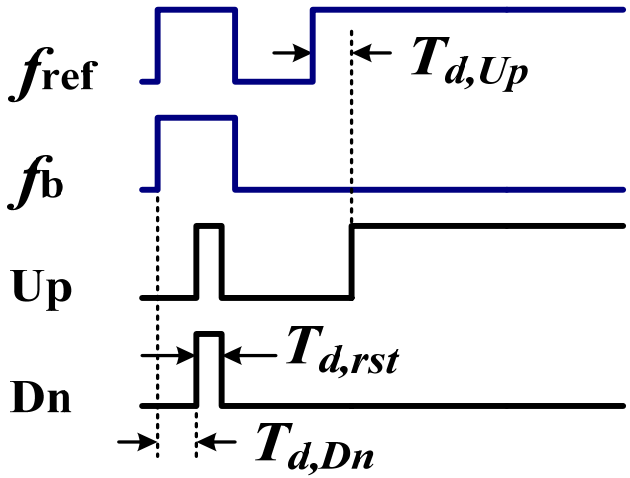


PFD & FD

- Phase frequency detector and Frequency divider
- Characteristic parameters:
  - *delay time transition time and reset time for PFD*



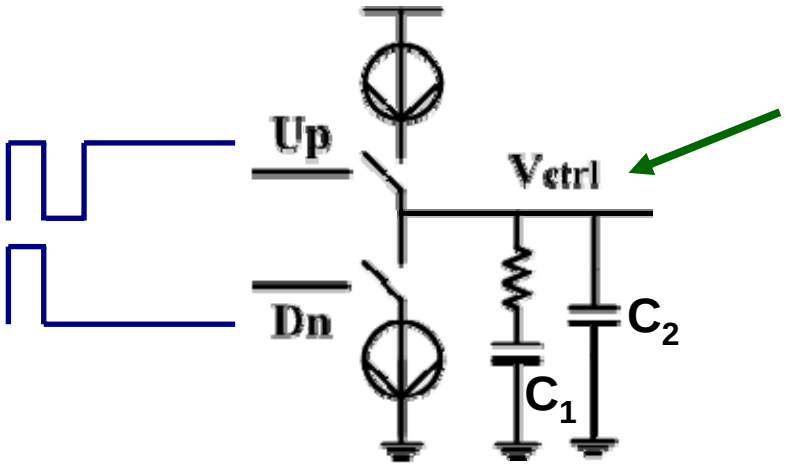
typical PFD structure



PFD output responses

CP & LF

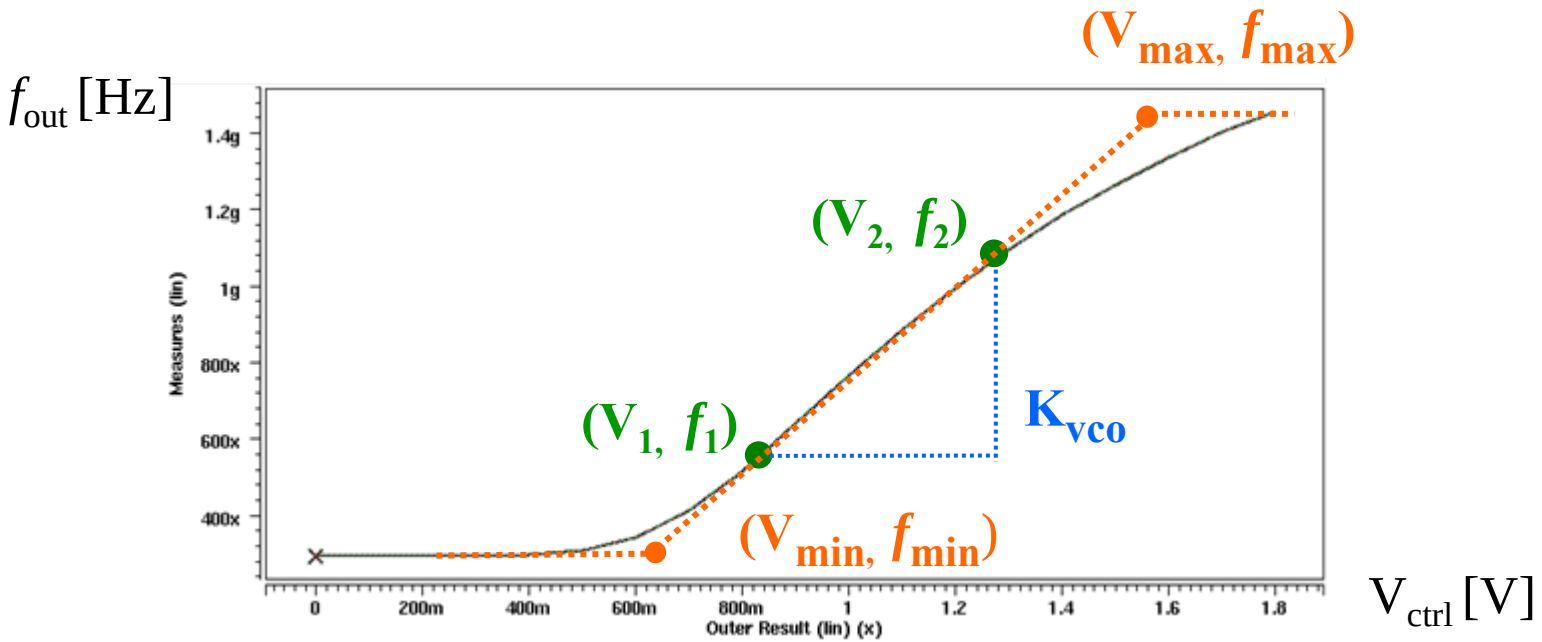
- Charge Pump and Loop Filter
- Characteristic parameters:
  - *Source current (I_{Up}) & current mismatch (I_{Up} - I_{Dn})*
  - *Impedance of LF*
  - *Equivalent switch on/off time*



Extract from V_{ctrl} output waveform

VCO

- Voltage-controlled oscillator
- Linear VCO model
  - Simpler approach
- Characteristic parameters: V_{min}, f_{min}, V_{max}, f_{max}, K_{VCO}



S_E Analysis for Process Variation

- Find the relationship of behavioral parameters under device parameter variation
  - Just for timing parameters in our behavioral model
- Delay change under width variation : $\Delta T_{d,\Delta W}$
- Extract the sensitivity value ($S_{E,T_d\_\Delta W}$):

$$S_{E,T_d\_\Delta W} = \frac{\partial T_{d,\Delta W}}{\partial W} \approx \frac{\Delta T_{d,\Delta W}}{\Delta W} = constant$$

- Extend to be a process variation aware model:

$$T_d(\Delta W, \Delta L, \Delta V_t, \Delta T_{ox}) = T_{d0} + \Delta W \times S_{E,T_d\_\Delta W} + \Delta L \times S_{E,T_d\_\Delta L} + \Delta V_t \times S_{E,T_d\_\Delta V_t} + \Delta T_{ox} \times S_{E,T_d\_\Delta T_{ox}}$$

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Current Variation in CP

- Drain current of MOS in saturation region:

$$I_D = \frac{\mu_n}{2}\frac{\varepsilon}{T_{ox}}\frac{W}{L}(V_{GS}-V_t)^2$$

← S_E may not suitable

Sensitive analysis (S_E)

- Current variation ratio under V_t variation:

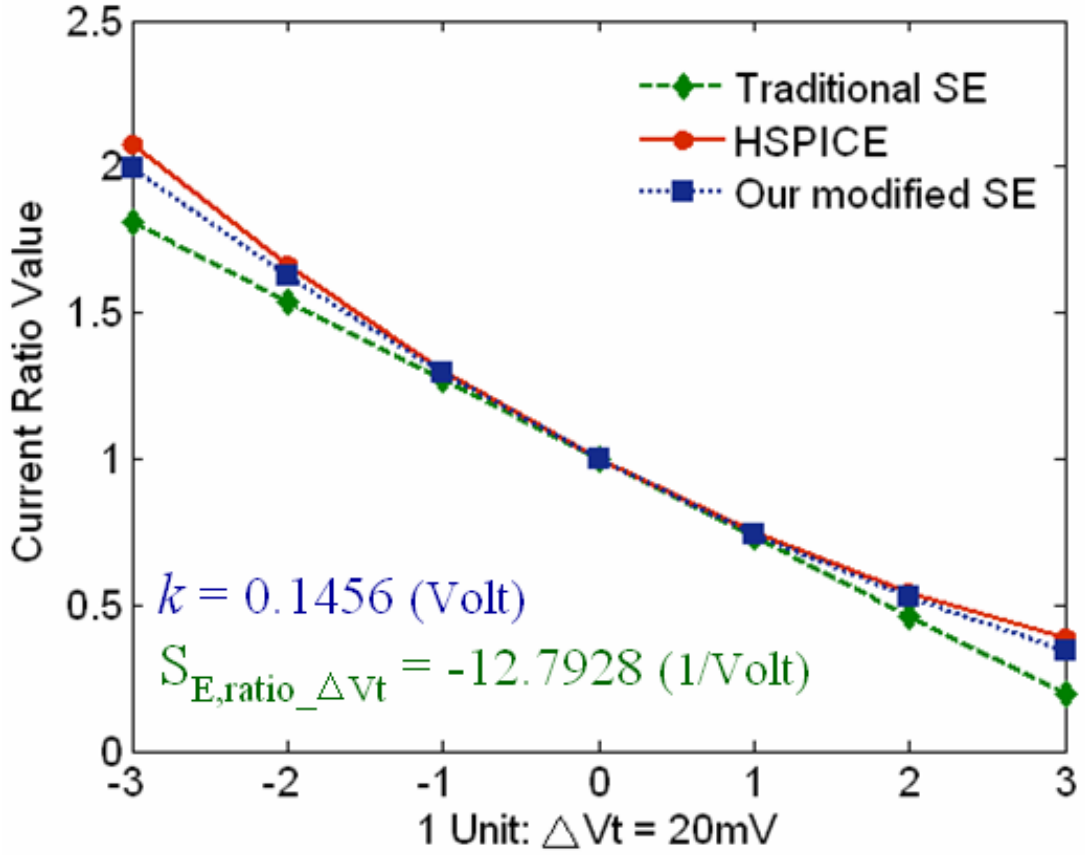
$$ratio(\Delta V_t) = \frac{I_D^{'}(\Delta V_t)}{I_D} \cong \frac{[V_{GS}-(V_t+\Delta V_t)]^2}{(V_{GS}-V_t)^2} = \left(\frac{(V_{GS}-V_t)-\Delta V_t}{V_{GS}-V_t}\right)^2$$

$$= \left(1-\frac{\Delta V_t}{V_{GS}-V_t}\right)^2 = \left(1-\frac{\Delta V_t}{k}\right)^2$$

Only need to find k

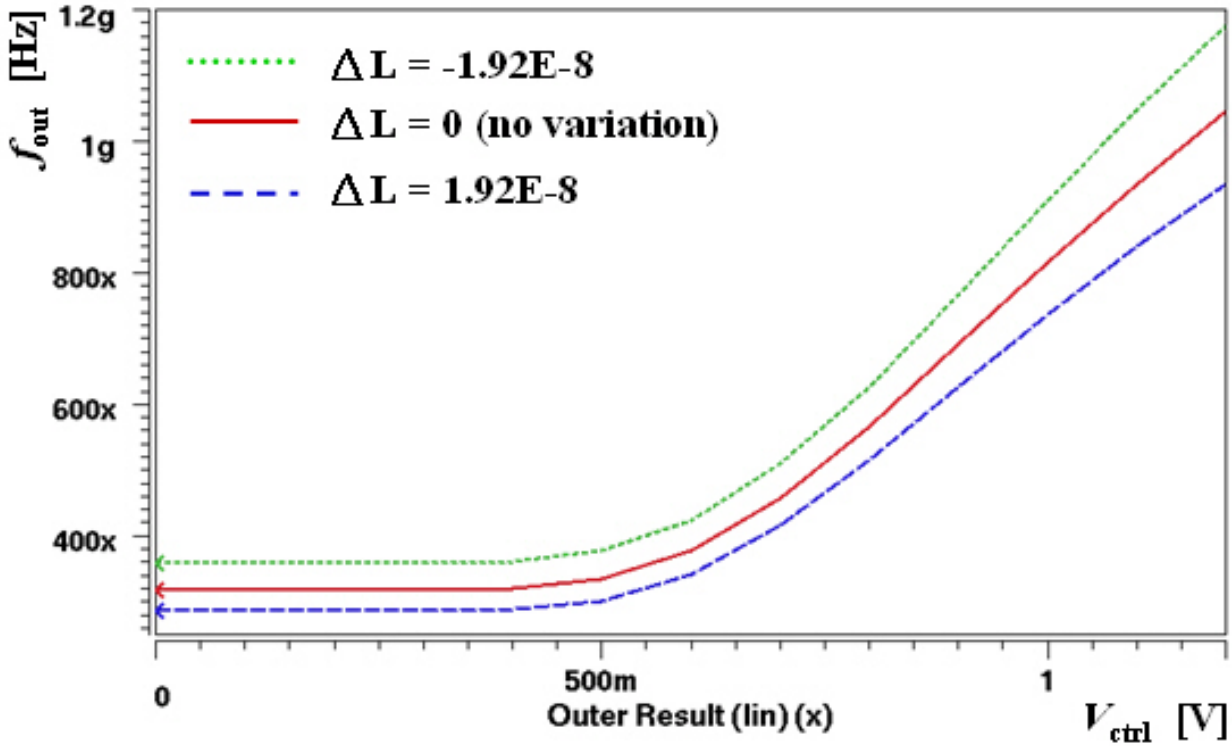
Our Method vs. Traditional S_E

- Same extraction time
- More accurate: more similar to the HSPICE results



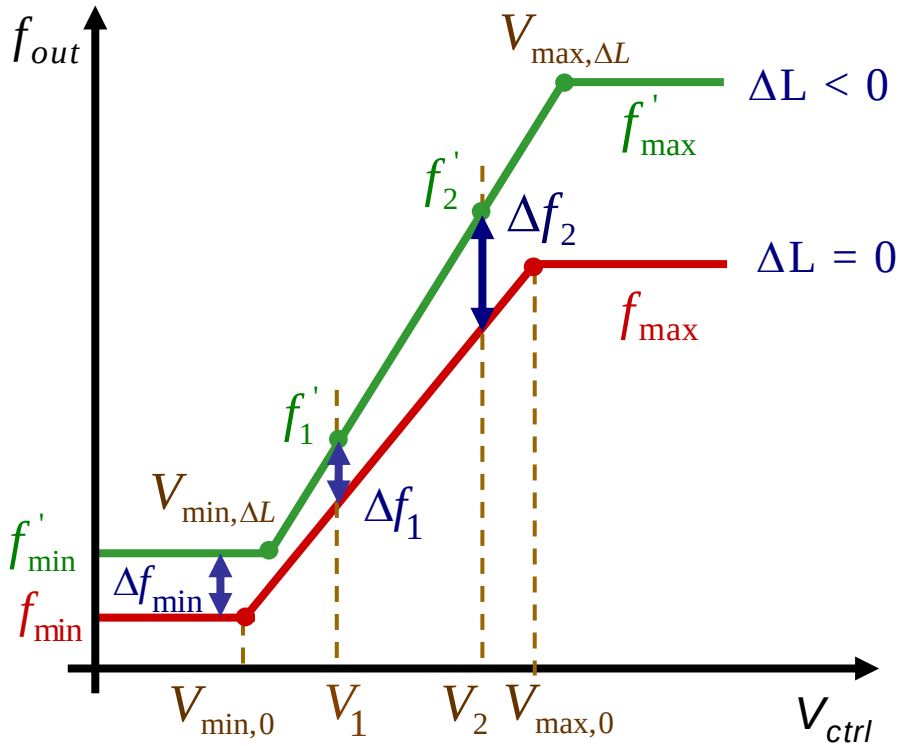
Modeling Strategy for VCO (1/3)

- VCO transfer curve under length variation
- Traditional S_E method: $S_{E,f\_\Delta L} = \frac{\Delta f}{\Delta L} \not\equiv constant$



Modeling Strategy for VCO (2/3)

- Consider V_{ctrl} effects:



$$S_{E,f_{min}\_\Delta L} = \frac{\Delta f_{min}}{\Delta L} \;;\; S_{E,f_1\_\Delta L} = \frac{\Delta f_1}{\Delta L}$$

$$S_{E,f_2\_\Delta L} = \frac{\Delta f_2}{\Delta L} \;;\; S_{E,f_{max}\_\Delta L} = \frac{\Delta f_{max}}{\Delta L}$$

$$\varepsilon_{\Delta L} = \frac{\Delta L \times (S_{E,f_2\_\Delta L} - S_{E,f_1\_\Delta L})}{V_2 - V_1}$$

$$V_{min,\Delta L} = V_1 - \frac{f'_1 - f'_{min}}{slope_{\Delta L} + K_{VCO}}$$

$$V_{max,\Delta L} = V_2 + \frac{f'_{max} - f'_2}{slope_{\Delta L} + K_{VCO}}$$

Modeling Strategy for VCO (3/3)

$$S_{E,f\_\Delta L}(\Delta L, V_{ctrl}) = \begin{cases} S_{E,f_{\min}\_\Delta L} & ,if\ \ V_{ctrl}(t) \le V_{\min,\Delta L} \\ S_{E,f_{\max}\_\Delta L} & ,if\ \ V_{ctrl}(t) \ge V_{\max,\Delta L} \\ S_{E,f_{\min}\_\Delta L} + [V_{ctrl}(t) - V_{\min,\Delta L}] \times \varepsilon_{\Delta L} & ,otherwise \end{cases}$$

Our modified S_E

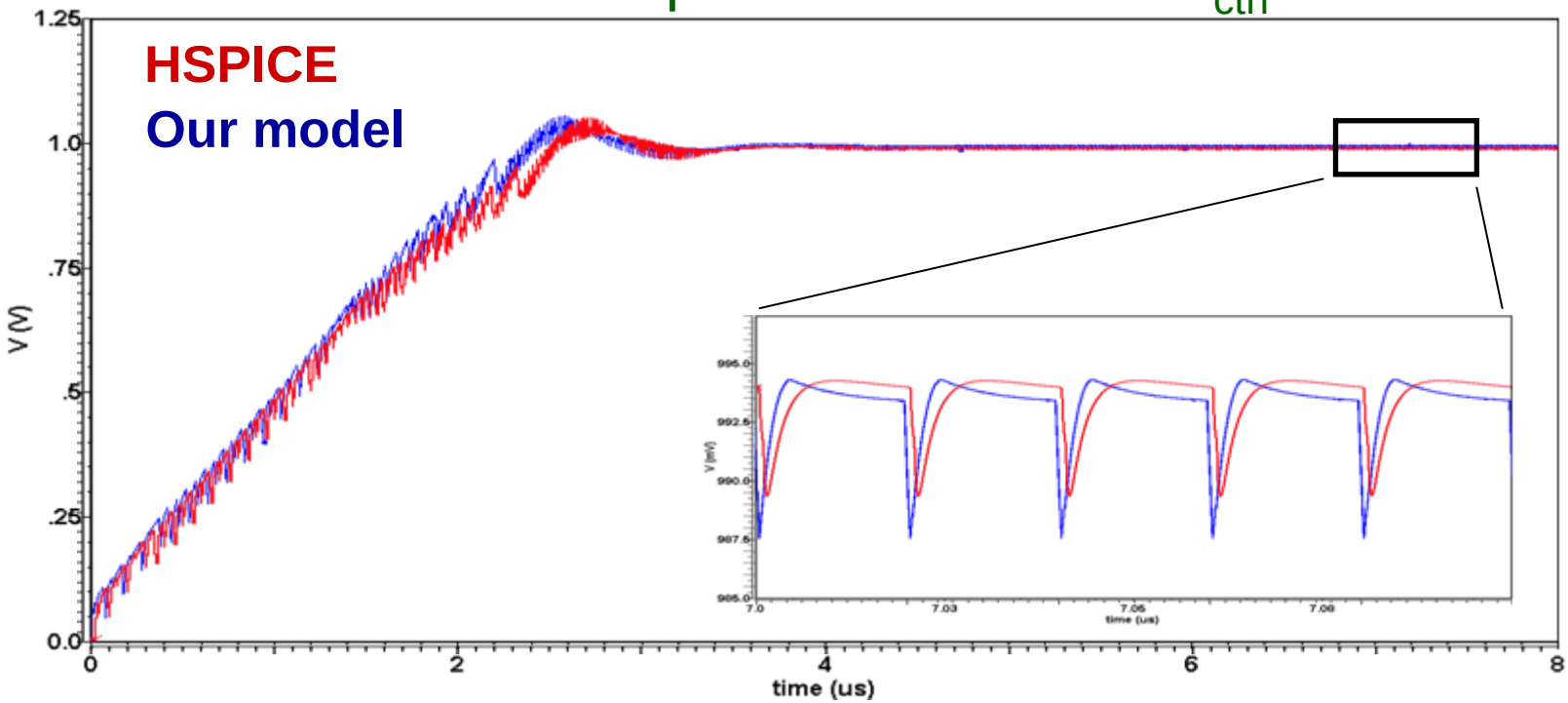
$$\phi_{\Delta L} = \begin{cases} 2\pi(\Delta L \times S_{E,f_{\min}\_\Delta L})t & ,if\ V_{ctrl}(t) \le V_{\min,\Delta L} \\ 2\pi(\Delta L \times S_{E,f_{\max}\_\Delta L})t & ,if\ V_{ctrl}(t) \ge V_{\max,\Delta L} \\ 2\pi\left\{(\Delta L \times S_{E,f_{\min}\_\Delta L})t + \int\left([V_{ctrl}(t) - V_{\min,\Delta L}] \times \varepsilon_{\Delta L}\right)dt\right\} & ,otherwise \end{cases}$$

$$\Rightarrow \quad \Delta\phi = \phi_{\Delta W} + \phi_{\Delta L} + \phi_{\Delta V_t} + \phi_{\Delta T_{ox}}$$

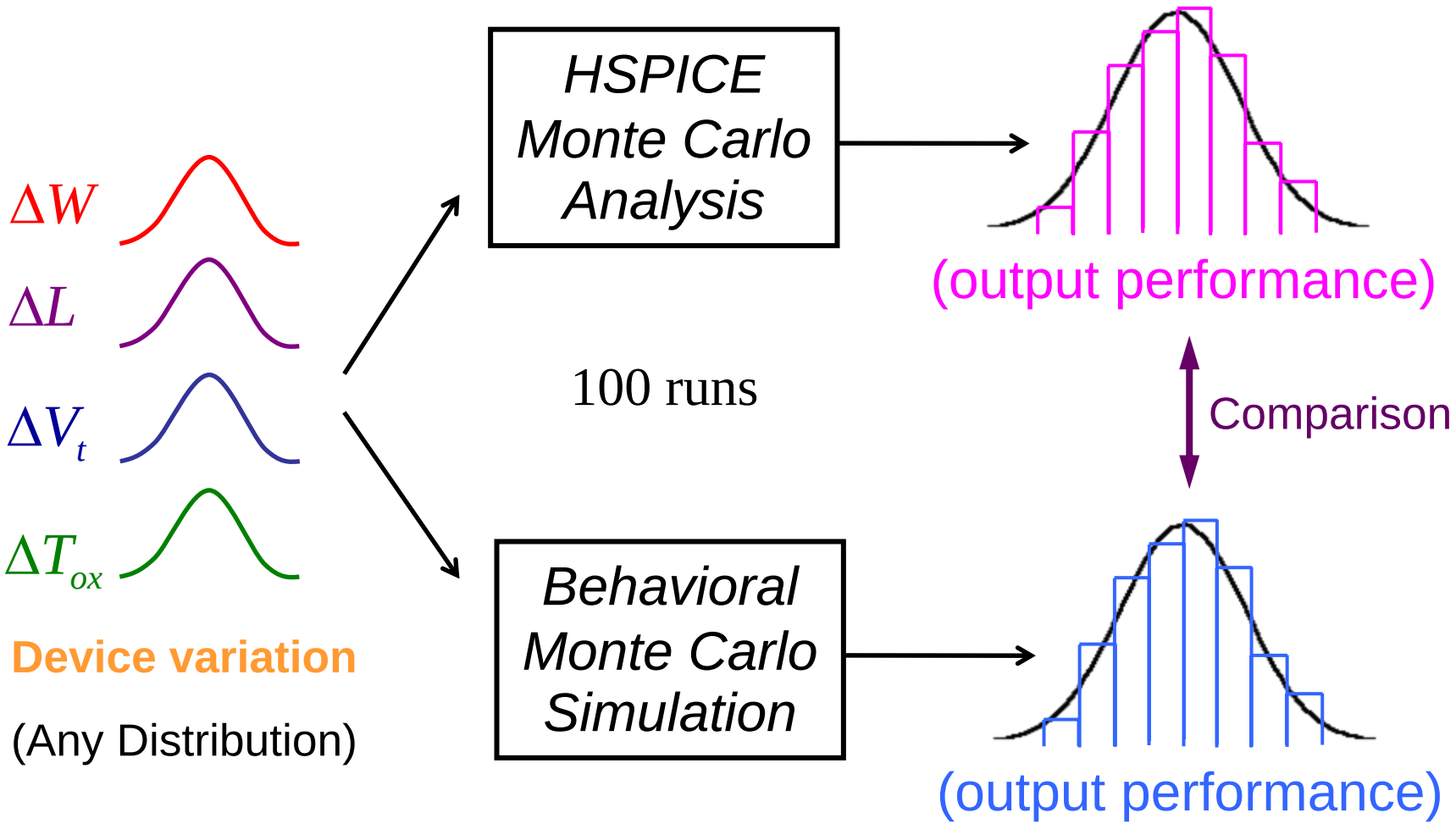
Experimental Results

- Charge pump PLL with TSMC RF 0.18μm process
- Use Verilog-A language to describe our PLL model
- Simulation environment: Analog Artist (Cadence)

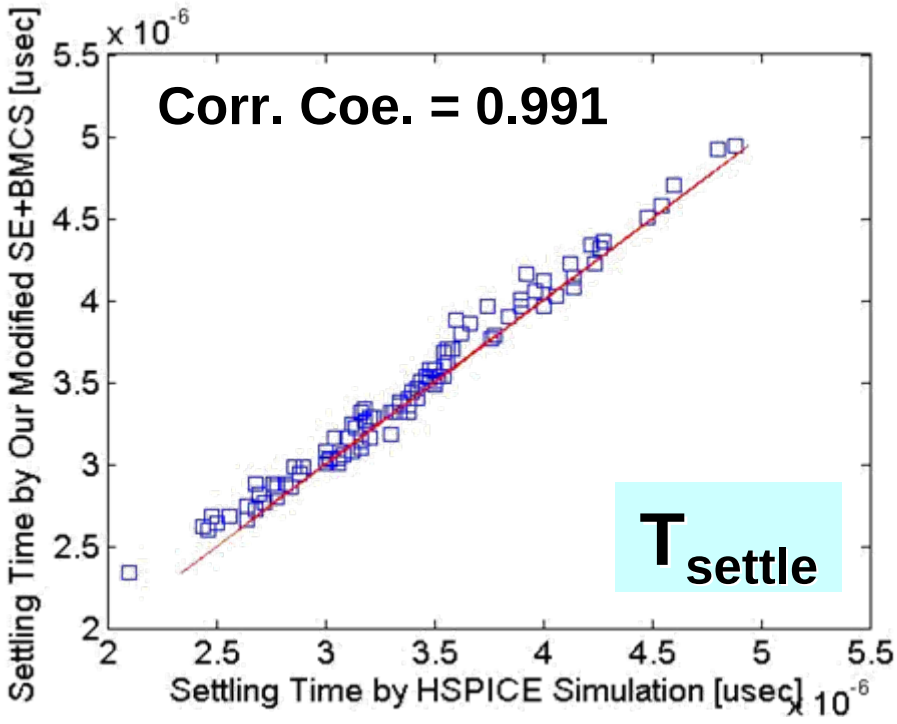
No process variation: V_{ctrl} waveform



Process Variation Experiments

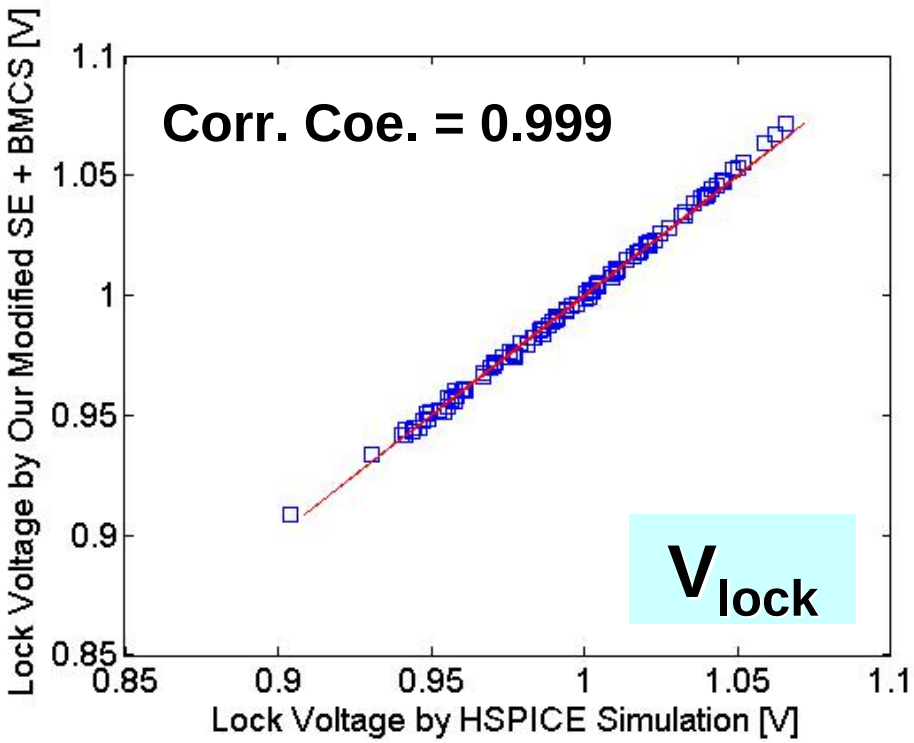


Our BMCS vs. HSPICE MCS



*Corr. Coe. : Correlation Coefficient

*Perfect match: points on the red line (slope = 1)



100 Runs MC Simulation Results

Standard Deviation (St. Dev.)		1st RSM + BMCS		Trad. S_E + BMCS		Modified S_E + BMCS		HSPICE
V_{lock} (V)	Mean	0.993	-0.1%	0.993	-0.1%	**0.995**	**0.1%**	0.994
	St. Dev.	0.036	5.9%	0.045	32.4%	**0.035**	**2.9%**	0.034
T_{settle} (μs)	Mean	3.449	2.2%	3.441	2.0%	**3.438**	**1.9%**	3.374
	St. Dev.	0.573	-0.5%	0.541	-6.1%	**0.572**	**-0.8%**	0.576
$Jitter_{pk-pk}$ (ps)	Mean	12.2	-7.6%	12.4	-6.1%	**12.4**	**-6.1%**	13.2
	St. Dev.	1.36	-2.9%	2.29	63.6%	**1.41**	**0.7%**	1.40
	Worst	16.6	-2.4%	16.4	-3.5%	**16.7**	**-1.8%**	17.0
Extraction time (hrs)		□34.27		8.57		**8.57**		N/A
Simulation time (hrs)		2.43		2.51		**2.64**		598.54

Use same PLL behavioral model (ours)

Conclusions

- Use accurate behavioral model to perform fast MC analysis for process variation (BMCS)
- Our modified sensitivity analysis saves considerable regression cost for complicated curve fitting
- Handle any distribution of device parameter variation
- Include detailed output waveforms and behavior shift, not some statistical numbers only (well observability)
- Reduce the simulation time for MC analysis from several days to several hours
- Retain high accuracy

Thanks for your attention !!!