POLITECNICO DI TORINO

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Compact Multivariate Surface Approximations for Power-aware I/O models

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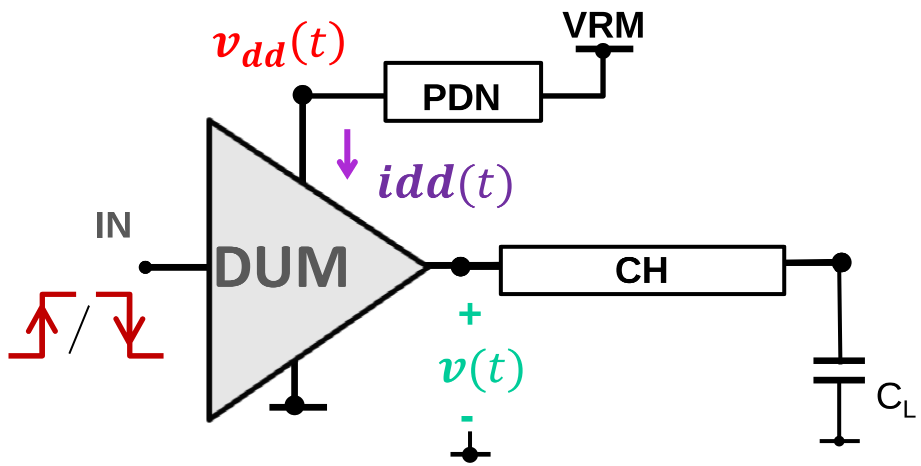
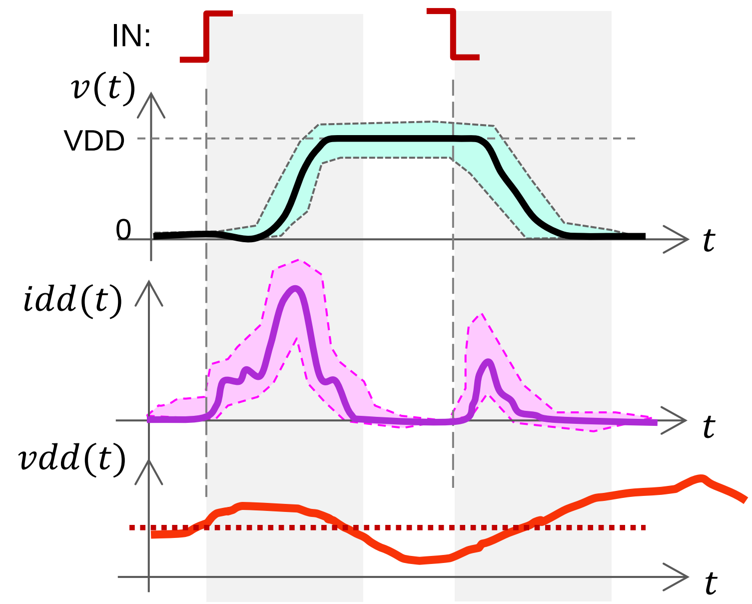
Agenda

1. **Macromodels for SI&PI: Requirements**
2. **Open Issues**
3. **Enhanced Mpilog & Multivariate Surface Approximations**
4. **Possible Proposal for IBIS**
5. **Conclusions**

Requirements for SI&PI co-simulation





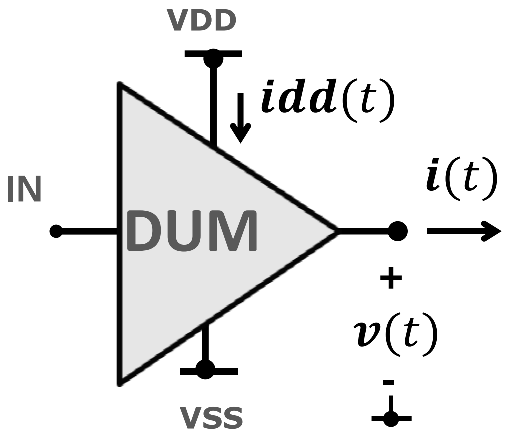
Accuracy at Output Port ($v(t), i(t)$)
+ Supply-Current Profile ($i_{dd}(t)$)
+ Supply-Voltage Noise ($v_{dd}(t)$)
+ Supply-Noise Effects ($f(\Delta v_{dd})$)

= **I/O-buffer model for SI&PI**

Targets:

$$\begin{cases} v(t), i(t) \\ v_{dd}(t), i_{dd}(t) \\ \Delta t, \Delta v_{out}, \Delta i_{dd} = f(\Delta v_{dd}) \end{cases}$$

Power-awareness in IBIS v5.0

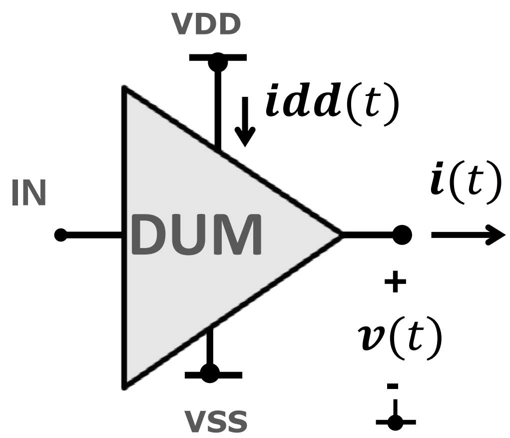


$$i(t) = w_H(t)\cdot \overset{\textbf{Pull-Up}}{I_{PU}(v)} + w_L(t)\cdot \overset{\textbf{Pull-Down}}{I_{PD}(v)} - \overset{\textbf{“Dynamic”}}{C_{COMP}\frac{\partial v}{\partial t}}$$

Up/Down Events

IBIS v3.2 @ nominal VDD

Power-awareness in IBIS v5.0



Pull-Up *Pull-Down* *“Dynamic”*

$$i(t) = w_H(t) \cdot I_{PU}(v) + w_L(t) \cdot I_{PD}(v) - C_{COMP}\frac{\partial v}{\partial t}$$

Up/Down Events

IBIS v3.2 **@ nominal VDD**

IBIS v5.0

$$i(t) = w_H(t) \cdot \boxed{K_{SSOPU}(\Delta v_{dd})} \cdot I_{PU}(v)$$
$$+ w_L(t) \cdot \boxed{K_{SSOPD}(\Delta v_{ss})} \cdot I_{PD}(v)$$
$$- C_{COMP}\, \partial v / \partial t$$

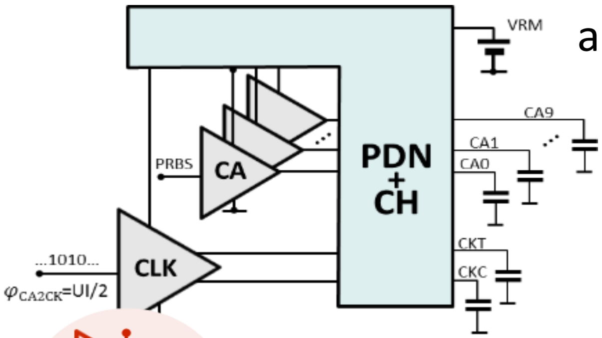
$$i_{dd}(t) = \boxed{w_H(t) \cdot K_{SSOPU}(\Delta v_{dd}) \cdot I_{PU}(v)}$$
$$+ \boxed{\partial i_{dd}(t)}$$

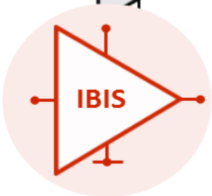
KSSO_PU/PD introduce **approximations** of supply/ground noise on output static characteristics

Supply-current is explicitly modeled, and corresponds to **pull-up** and **crowbar / pre-driver** contributions

The Problem…

CA-bus (10x CA I/Os and 1x CLK Driver)

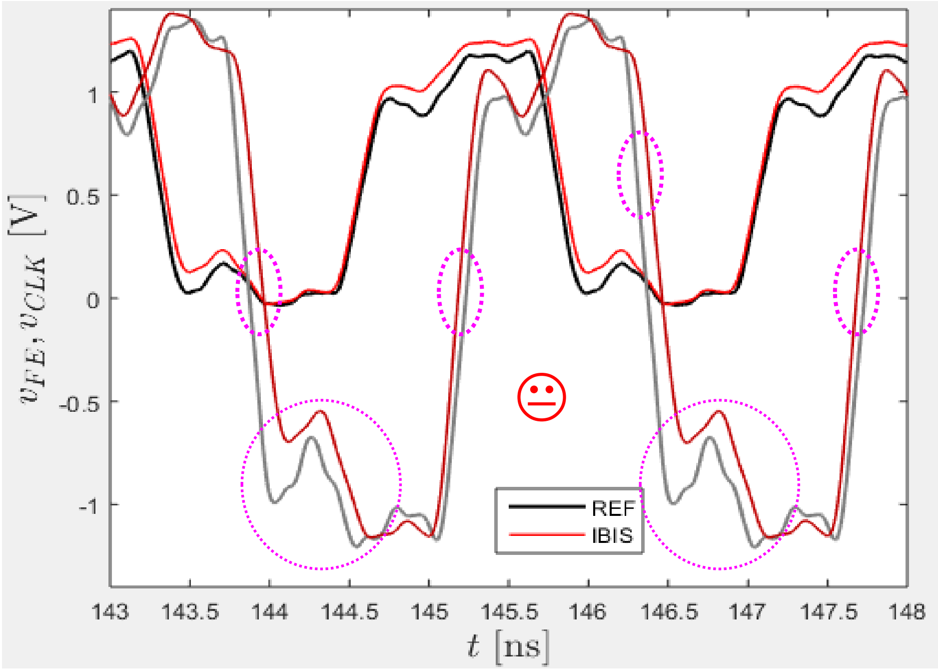




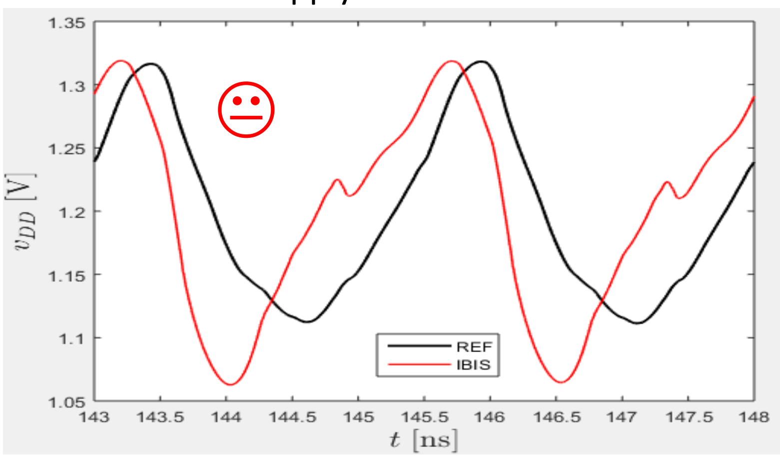
Reference (XTOR-level)

vs **IBIS v5.0** 😐

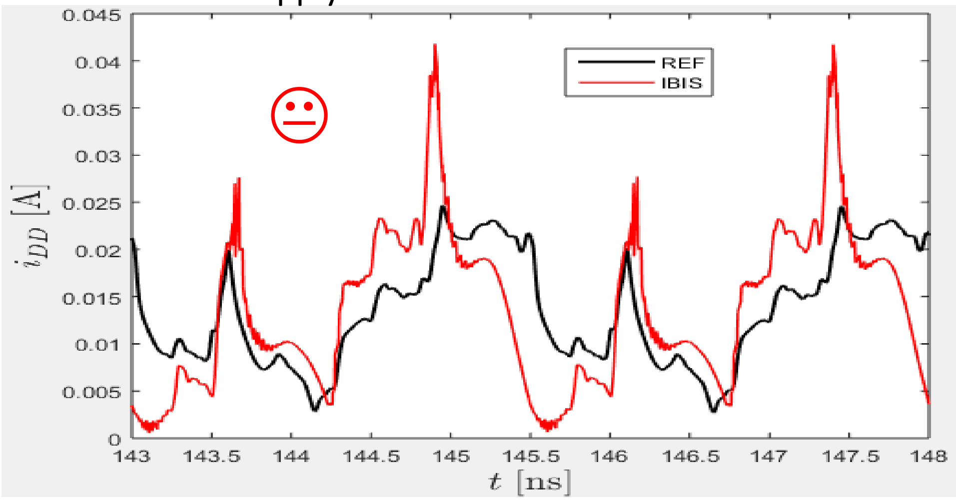
CLK/DATA Far-End Signals



Supply-Noise



Supply-Current



Open Issues

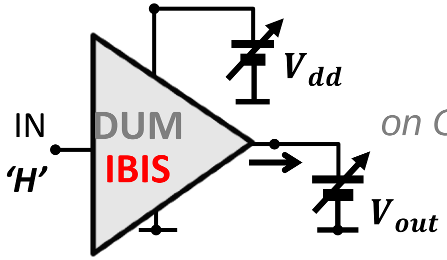
(i) Static Characteristics & VDD

(ii) Rising/Falling Waveforms & VDD

(iii) Supply-Current & VDD

(iv) Power-supply port modeling

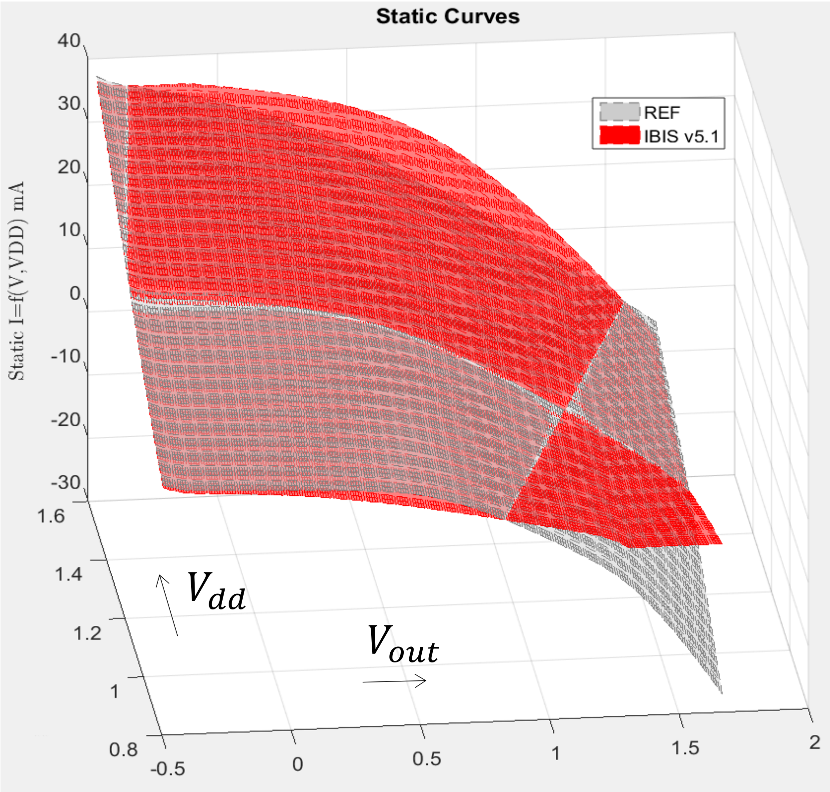
(i) Static Characteristics & VDD

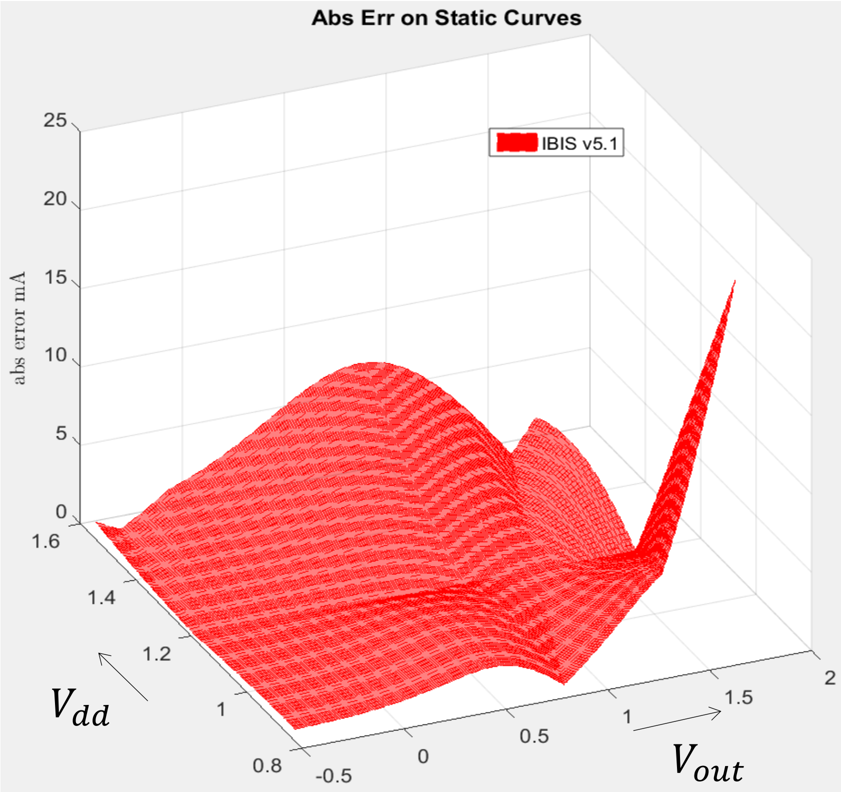


Nested .DC sweep on Output and Supply ports

$$i(t) = w_H(t) \cdot K_{SSOPU}(\Delta v_{dd}) \cdot I_{PU}(v) + w_L(t) \cdot K_{SSOPD}(\Delta v_{ss}) \cdot I_{PD}(v) \ \ldots$$

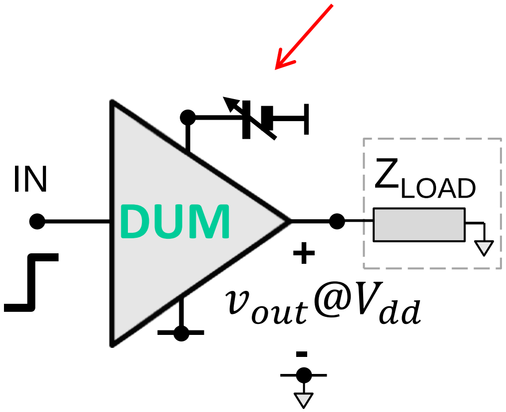
Possible approximation inaccuracy ?



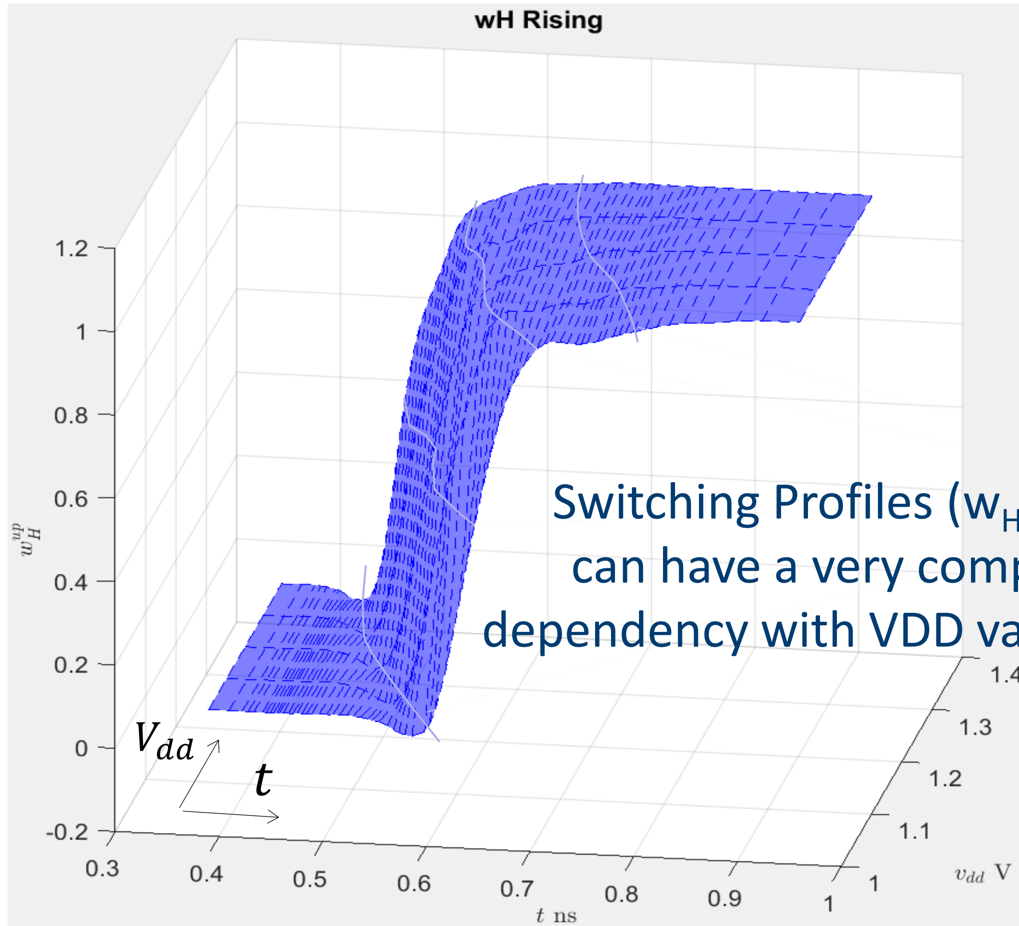


(ii) Rising/Falling Waveforms & VDD

$$V_{dd} \in [80\%, \dots, 100\%, \dots, 120\%] \times V_{DD,NOM}$$



$$i(t) = w_H(t) \cdot K_{SSOPU}(\Delta v_{dd}) \cdot I_{PU}(v)$$
$$+ w_L(t) \cdot K_{SSOPD}(\Delta v_{ss}) \cdot I_{PD}(v) \ \dots$$

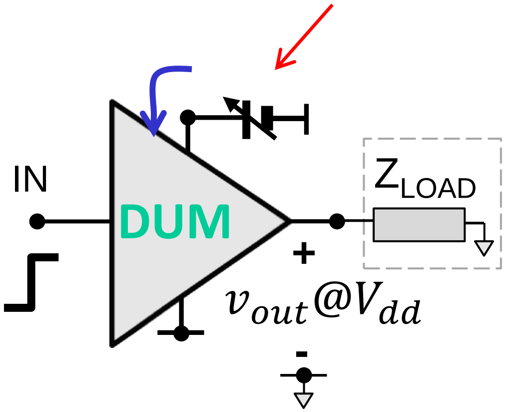


Switching Profiles (w_H, w_L) can have a very complex dependency with VDD variations

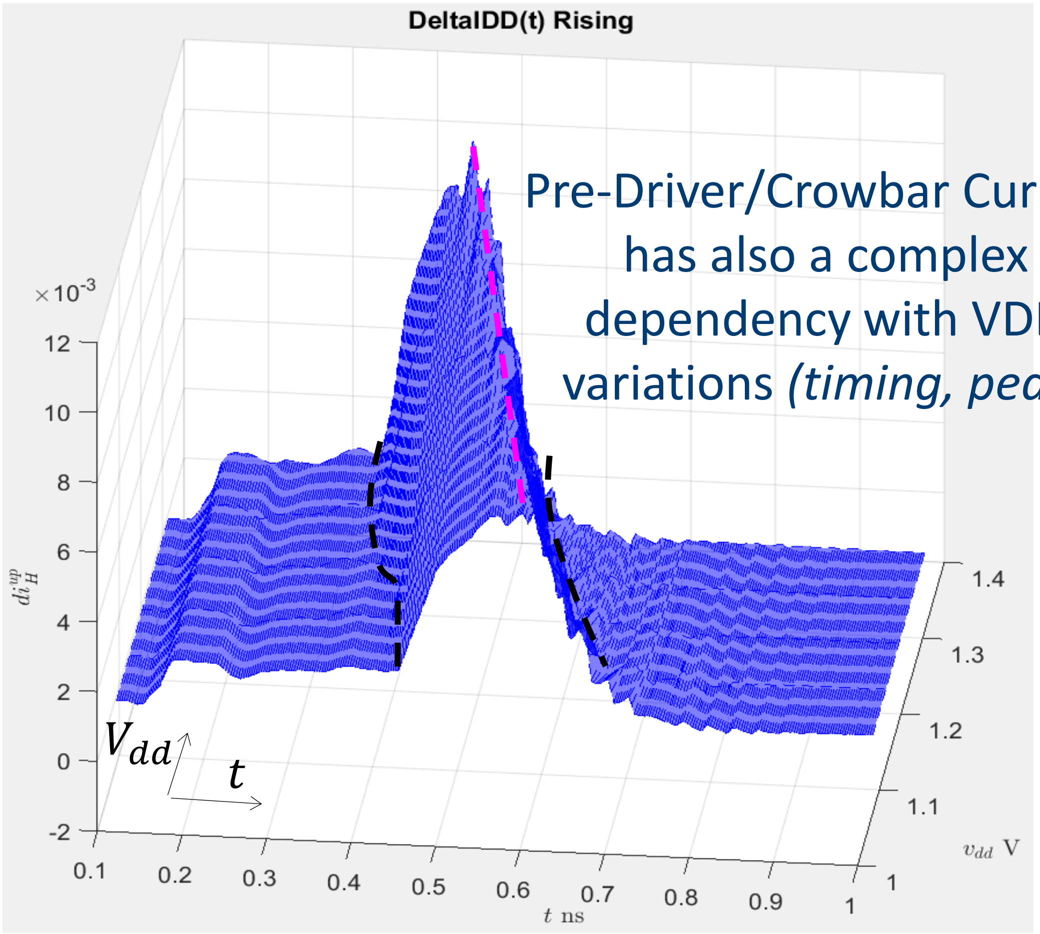
IBIS v5.0 model structure may be limited in representing this behavior

(iii) Supply-Current & VDD

$$V_{dd} \in [80\%, \dots, 100\%, \dots, 120\%] \times V_{DD,NOM}$$

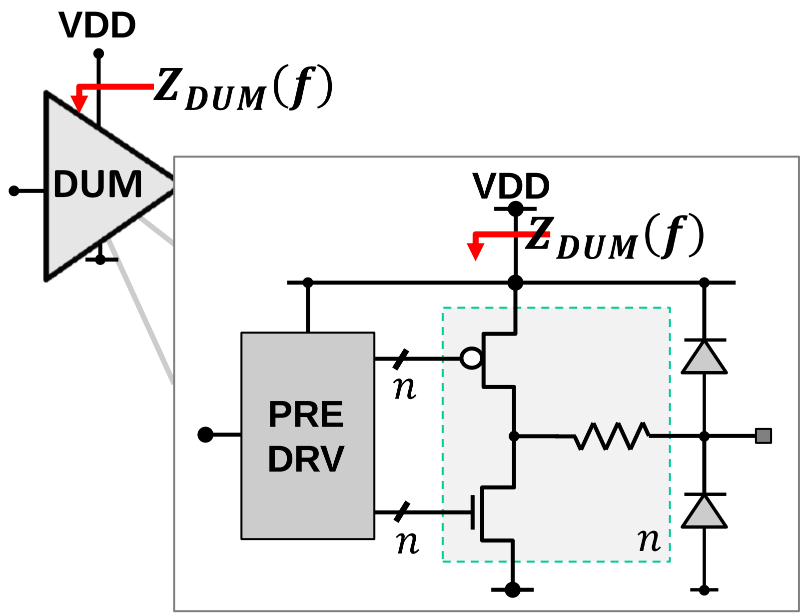


$$i_{dd}(t) = w_H(t) \cdot K_{SSOPU}(\Delta v_{dd}) \cdot I_{PU}(v) + \partial i_{dd}(t)$$

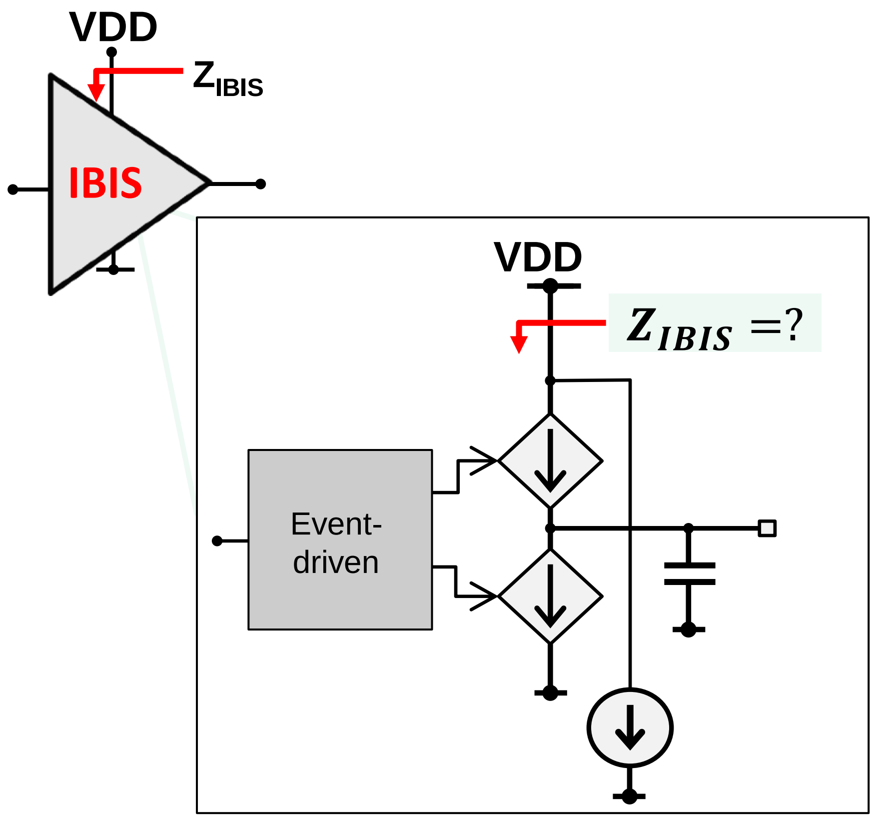


IBIS v5.0 model structure may be limited in representing this behavior

(iv) Power-supply port modeling



$\neq$



How to correctly model
I/O-Buffer "supply-port impedance"?

$$i_{dd}(t) = w_H(t) \cdot K_{SSOPU}(\Delta v_{dd}) \cdot I_{PU}(v) + \partial i_{dd}(t)$$

Our Contributions

[1] C. Siviero, S. Grivet-Talocia, G Signorini, I. S. Stievano, ''***Behavioral Macromodeling of High-Speed Drivers via Compressed Tensor Representations***'', IEEE MTT-S International Conference on Numerical Electromagnetic and Multiphysics Modeling and Optimization for RF, Microwave and Terahertz Applications (NEMO2015), Ottawa (Canada), Aug. 2015.

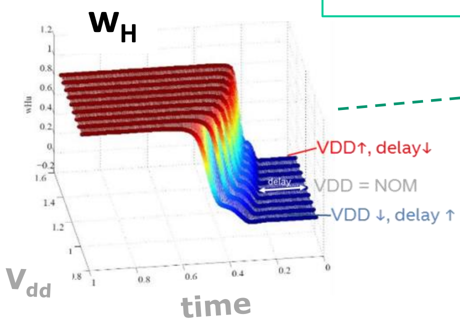
[2] G. Signorini, C. Siviero, I.S. Stievano, S. Grivet-Talocia, M. Mirmark ''***IBIS + Mpilog: Current and Future Developments on I/O-Buffer Modeling***'', IBIS Summit @ SPI2016, May 2016.

[3] G. Signorini, C. Siviero, S. Grivet-Talocia, I.S. Stievano, ''***Macromodeling of I/O Buffers via Compressed Tensor Representations and Rational Approximations***'', IEEE Transactions on Components, Packaging and Manufacturing Technology, Oct. 2016.

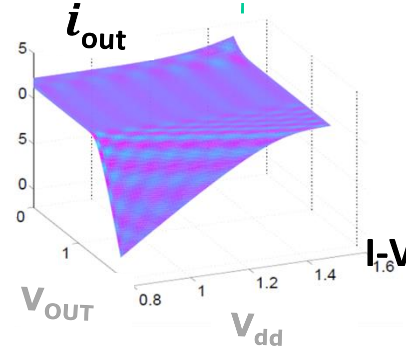
Enhanced Mpilog Models: R&D work

$$
\begin{aligned}
i(t) = {} & w_H(t, v_{dd}) \cdot [I_{PU}(v, v_{dd}) + f_H(v, v_{dd}; d/dt)] \\
& + w_L(t, v_{dd}) \cdot [I_{PD}(v, v_{dd}) + f_L(v, v_{dd}; d/dt)]
\end{aligned}
$$

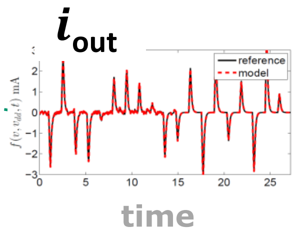
$$
\begin{aligned}
i_{dd}(t) = {} & w_H(t, v_{dd}) \cdot \left[I_{PU,S}(v, v_{dd}) + f_{H,S}(v, v_{dd}; d/dt)\right] \\
& + w_L(t, v_{dd}) \cdot \left[I_{PD,S}(v, v_{dd}) + f_{L,S}(v, v_{dd}; d/dt)\right] \\
& + \partial i(t, v_{dd})
\end{aligned}
$$



Multivariate Switching Characteristics @ (ii) & (iii)



Multivariate I-V Characteristics @ (i)



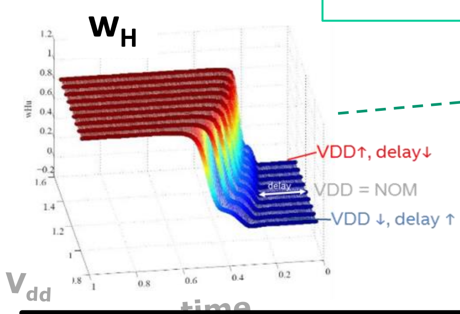
Multiple-Input Single-Output (MISO) Rational Approx. via Time-Domain Vector-Fitting @ (iv)

- Explicit dependency with VDD in model sub-components
- Mathematical structure ⇒ **re-cast** as **Verilog-A** or **SPICE** circuit

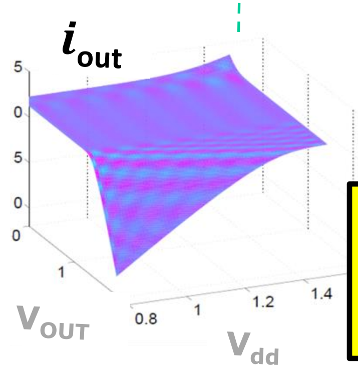
Enhanced Mpilog Models: R&D work

$$
\begin{aligned}
i(t) = {} & w_H(t, v_{dd}) \cdot [I_{PU}(v, v_{dd}) + f_H(v, v_{dd}; d/dt)] \\
& + w_L(t, v_{dd}) \cdot [I_{PD}(v, v_{dd}) + f_L(v, v_{dd}; d/dt)]
\end{aligned}
$$

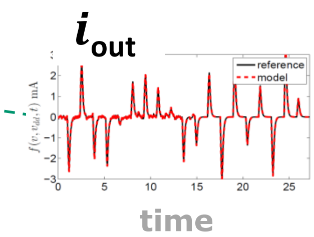
$$
\begin{aligned}
i_{dd}(t) = {} & w_H(t, v_{dd}) \cdot \left[I_{PU,S}(v, v_{dd}) + f_{H,S}(v, v_{dd}; d/dt)\right] \\
& + w_L(t, v_{dd}) \cdot \left[I_{PD,S}(v, v_{dd}) + f_{L,S}(v, v_{dd}; d/dt)\right] \\
& + \partial i(t, v_{dd})
\end{aligned}
$$



Multivariate Switching Characteristics @ (ii) & (iii)



Multivariate I-V Characteristics @ (i)



Multiple-Input Single-Output (MISO) Rational Approx. via Time-Domain Vector-Fitting @ (iv) **[3,4]**

- Explicit dependency with VDD in model sub-components

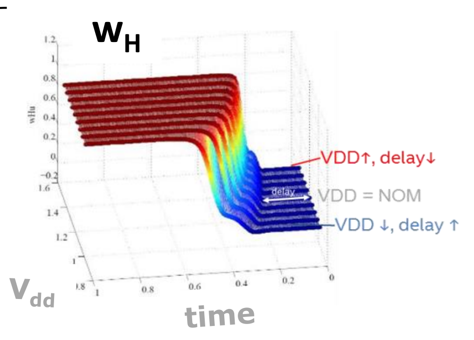
- Mathematical structure ⇒ **re-cast** as **Verilog-A** or **SPICE** circuit

[4] S. Grivet-Talocia, B. Gustavsen, “Passive Macromodeling - Theory and Applications," John Wiley & Sons, 2016..

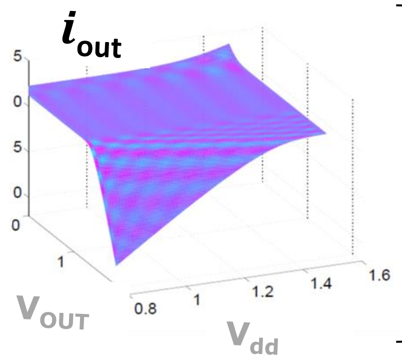
Compact Multivariate Surface Approximations (i)

- Basis function approximation and fitting techniques (e.g., Sigmoids or Gaussians, global or local polynomials) not always successful 😐
- Alternative solution is needed…

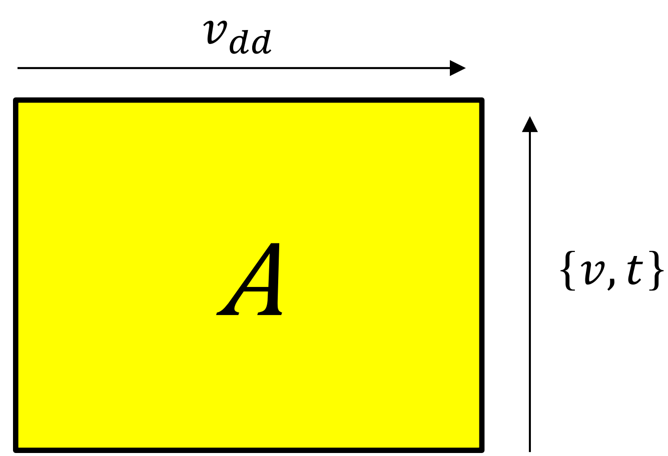
Collected TRAN/DC data casted into a rectangular matrix A



$y = G(t, v_{dd})$



$y = F(v, v_{dd})$

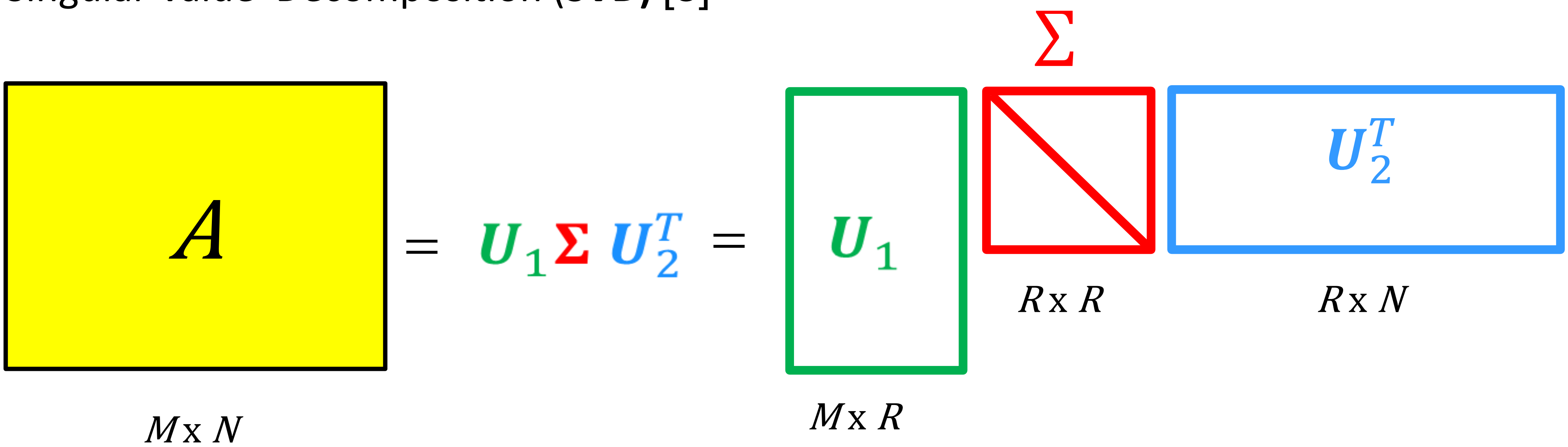


M x N

TASK : Find an accurate & compact model that can be easily incorporated into SPICE

Compact Multivariate Surface Approximations (ii)

Singular Value Decomposition (**SVD)** [5]



$$R = \mathrm{rank}(A)\ ,\ \ R \leq \min(M,N)$$

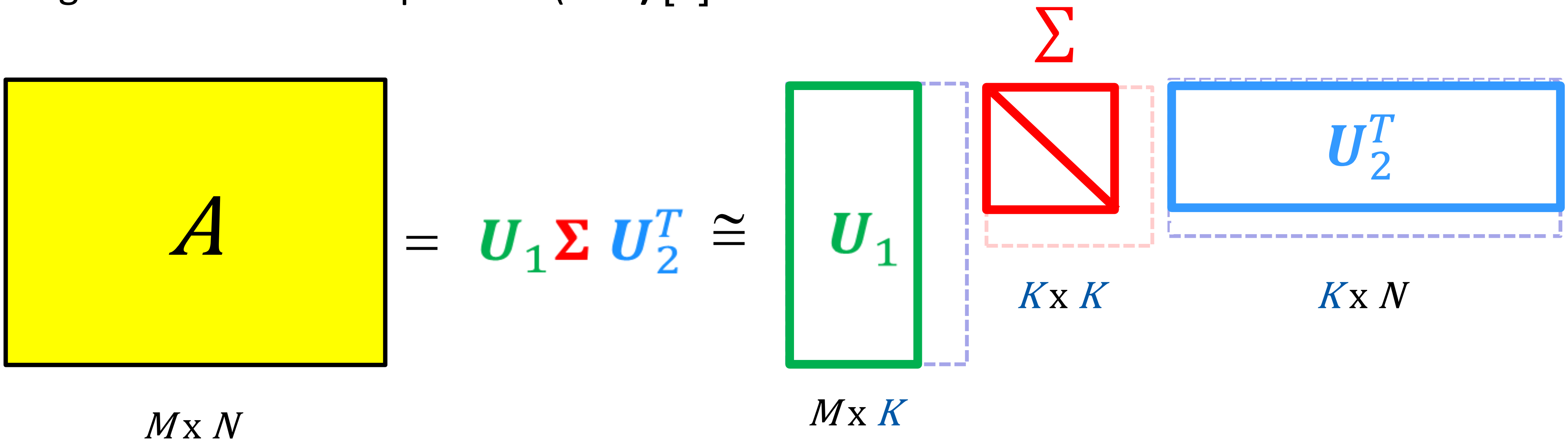
$$\Sigma = \mathrm{diag}\{\sigma_1, \sigma_2, \ldots, \sigma_R\}$$

$\sigma_1 > \sigma_2 > \ldots > \sigma_R$ singular values

[5] G. H. Golub, C. F. Van Loan, “Matrix Computation,”, The Johns Hopkins University Press, 3rd edition 1996.

Compact Multivariate Surface Approximations (iii)

Singular Value Decomposition (**SVD)** [5]



$R = \mathrm{rank}(A)$, $R \leq \min(M,N)$

$\Sigma = \mathrm{diag}\{\sigma_1, \sigma_2, \ldots, \sigma_K\}$ **Truncation up to the K-th largest singular value**

→ Addresses compactness & analytical description

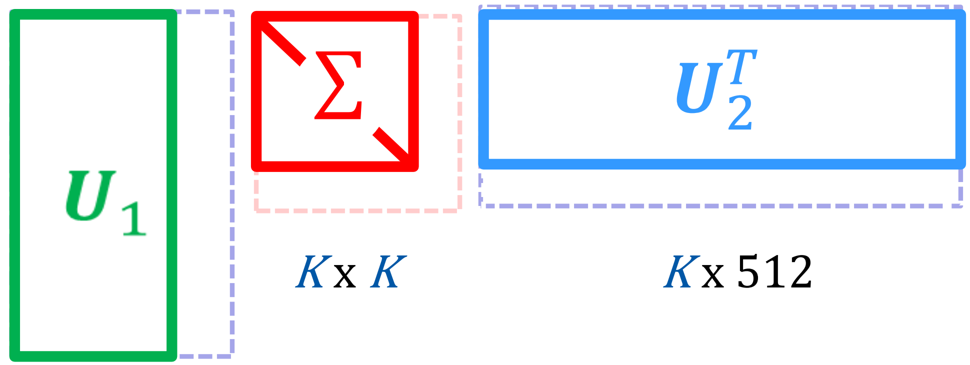
[5] G. H. Golub, C. F. Van Loan, “Matrix Computation,”, The Johns Hopkins University Press, 3rd edition 1996.

SVD & Image Compression (i)

Original matrix collects grayscale pixel intensity values, each ranging from 0 to 255 (1 byte)

512 x 512
$R = 512$

$= \boldsymbol{U}_1 \boldsymbol{\Sigma} \boldsymbol{U}_2^T \cong$



K x K

K x 512

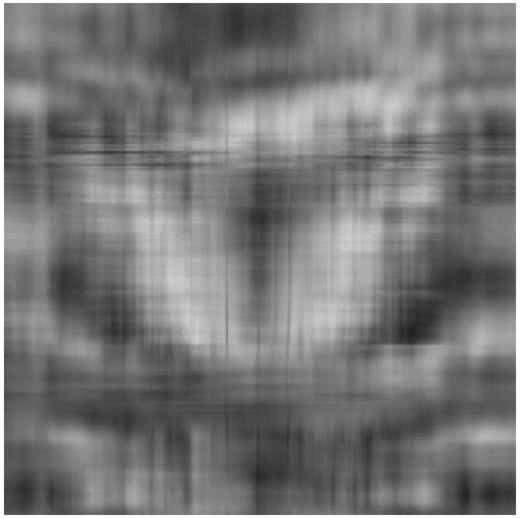
512 x K

Complexity Factor: $\mathrm{CF} = (\#\mathrm{SVD}) / (\#\mathrm{original}) = (2\cdot(512\cdot K) + K) / (512)^2$

Image size compression occurs when $\mathrm{CF} < 1 \rightarrow K \leq 255$

SVD & Image Compression (ii)

$K = 5$
$\mathrm{CF} \cong 2\%$



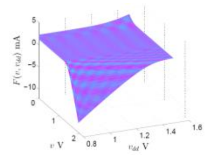
$K = 20$
$\mathrm{CF} \cong 8\%$

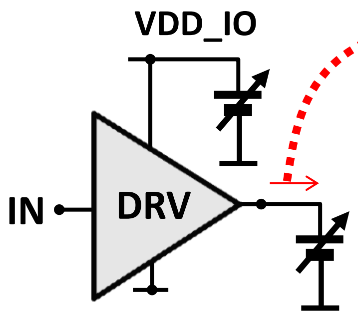
$K = 50$
$\mathrm{CF} \cong 20\%$

$K = 100$
$\mathrm{CF} \cong 40\%$

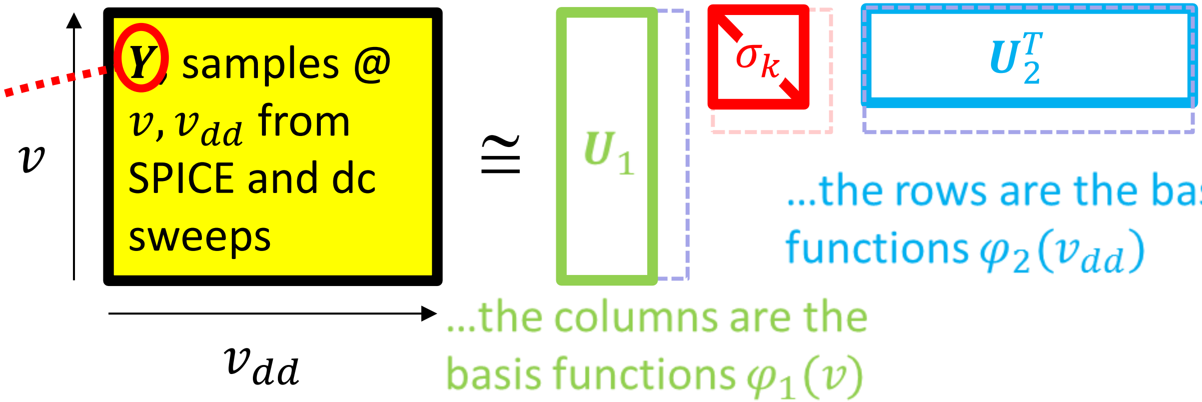
Static characterization and modeling (i)

$$y = F(v, v_{dd})$$





Static characterization Testbench



...the rows are the basis functions $\varphi_2(v_{dd})$

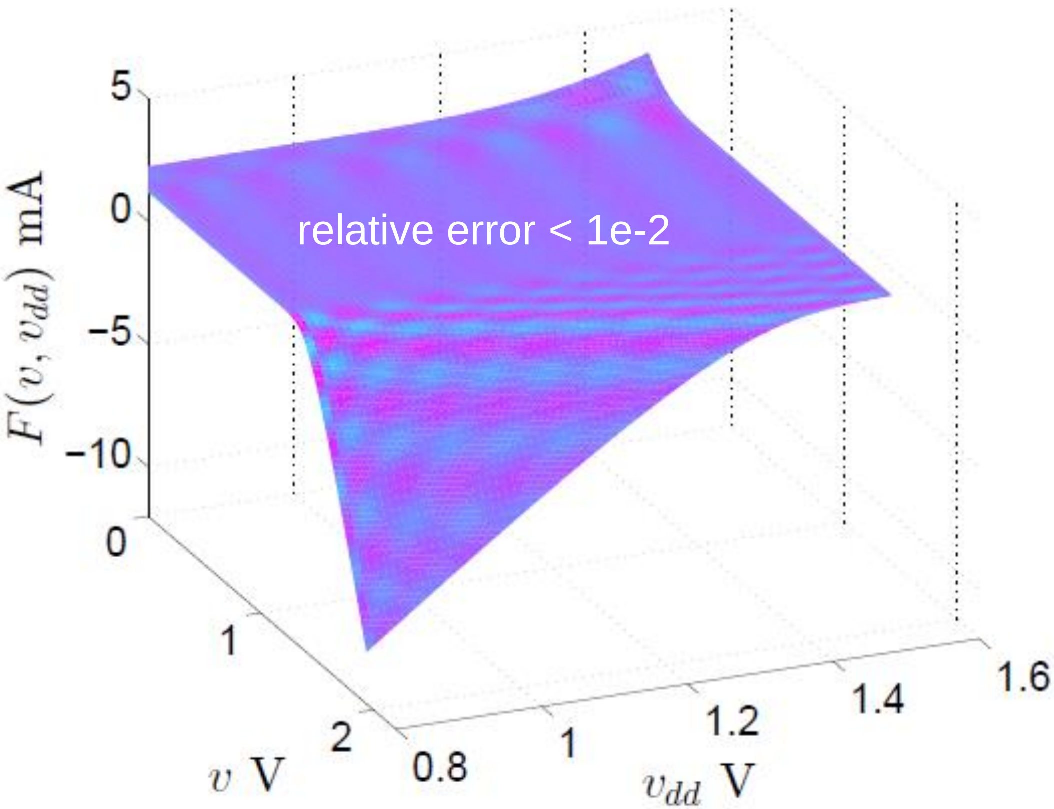
...the columns are the basis functions $\varphi_1(v)$

Truncation process :

maximum compactness meeting target accuracy

Static characterization and modeling (ii)

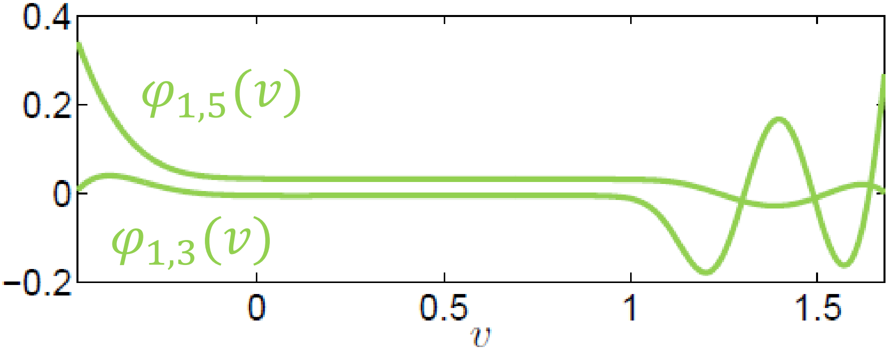
$$y = F(v, v_{dd}) = \sum_{i=1}^{K} \sigma_i \varphi_{1,i}(v) \varphi_{2,i}(v_{dd})$$

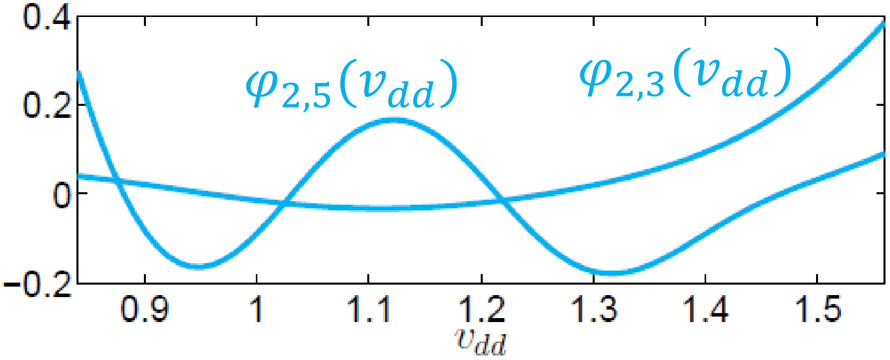


- Tunable accuracy
- Compact representation : expansion order $\boldsymbol{K = 9}$, $\mathbf{CF \cong 30\%}$

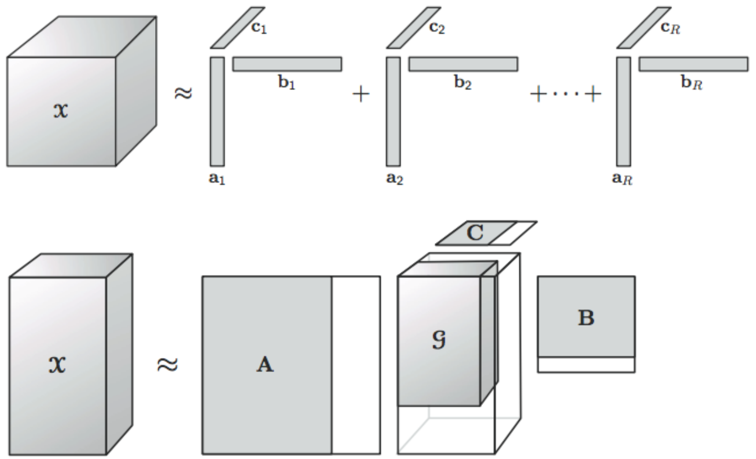
Static characterization and modeling (iii)

$$y = F(v, v_{dd}) = \sum_{i=1}^{K} \sigma_i \varphi_{1,i}(v) \varphi_{2,i}(v_{dd})$$





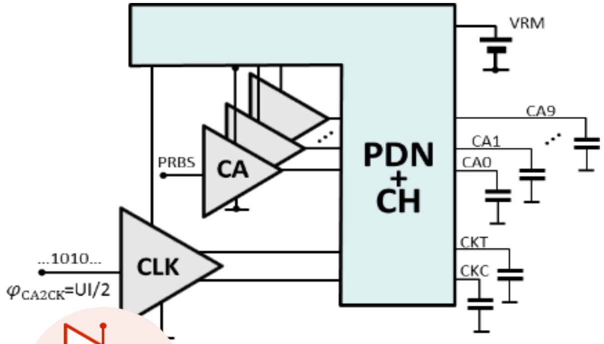
- Readily implemented in SPICE with voltage controlled sources or Verilog-A modules
- High order generalization to the tensor case available [6]

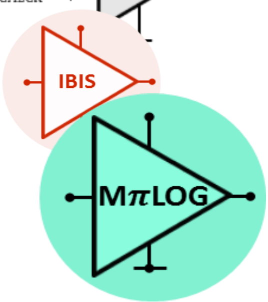


[6] T. G. Kolda and B. W. Bader, “Tensor Decompositions and Applications”, SIAM Review, Vol. 51, No. 3, 2009, pp. 455–500

Validation

CA-bus (10x CA I/Os and 1x CLK Driver)



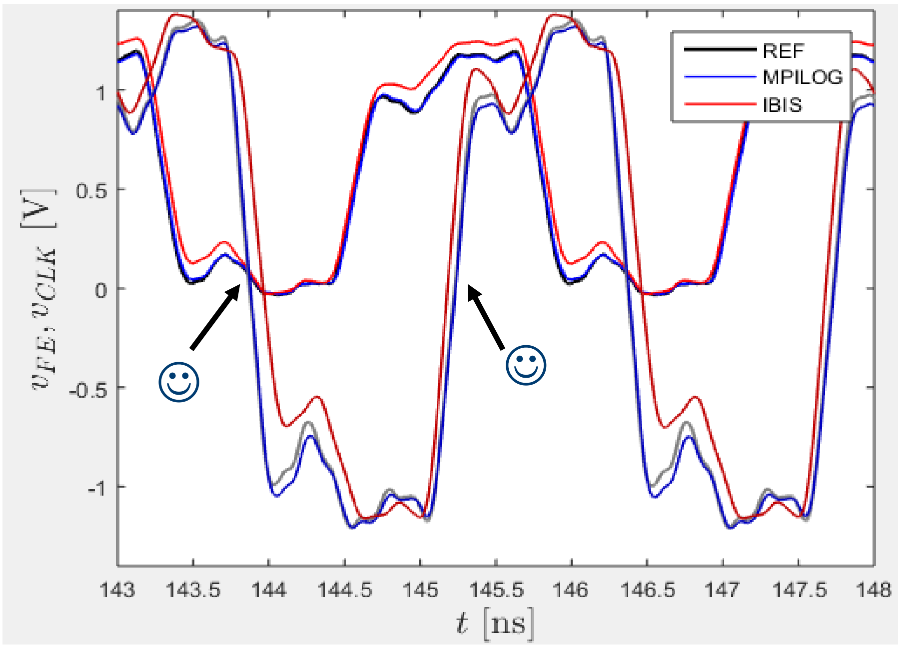


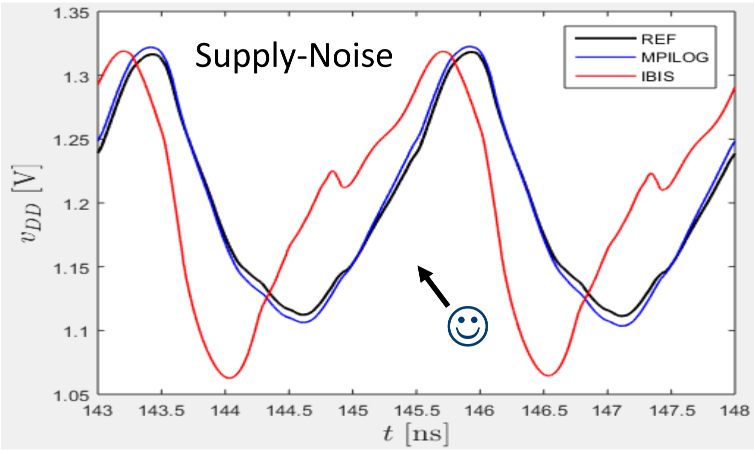
Reference (XTOR-level)

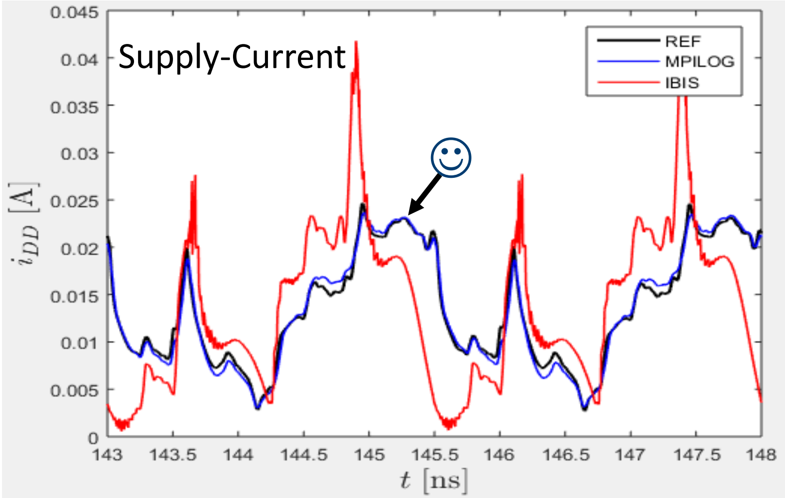
vs **IBIS v5.1** 😐

vs **MPILOG** ☺

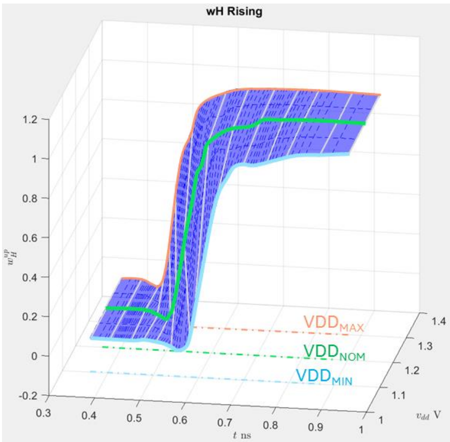
CLK/DATA Far-End Signals







3-curve approx. of 3D-Surfaces in IBIS



How to include 3-curve approx. data in an IBIS file?

```
[Model] DDR_PAD
| variable            typ    min    max
[Temperature Range]   25     -30    125
[Voltage Range]       1.2    1.1    1.3
[Rising Waveform]
| Time              v(typ)  v(min) v(max)
  0
  25ps
  ...
  1.21ns
  1.22ns
```

IBIS v5.1:

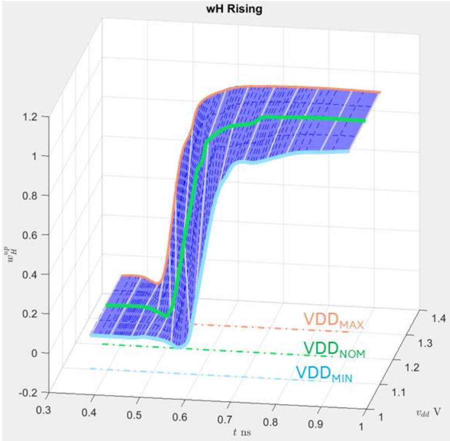
Process: TT	Process: SS	Process: FF
VDD: TYP	VDD: MIN	VDD: MAX
Temp: Typ	Temp: Max	Temp: Min

For all IBIS table …

PU/PD
Rising/Falling V-t
Rising/Falling I-t

1 [Model],
3 PVT Corners

3-curve approx. of 3D-Surfaces in IBIS



How to include 3-curve approx. data in an IBIS file?

```
[Model] DDR_PAD
| variable             typ    min    max
[Temperature Range]    25     -30    125
[Voltage Range]        1.2    1.1    1.3
[Rising Waveform]
| Time               v(typ) v(min) v(max)
  0
  25ps
  …
  1.21ns
  1.22ns
```

For all IBIS table …
PU/PD
Rising/Falling V-t
Rising/Falling I-t

~~IBIS v5.1:~~

~~Process: TT~~	~~Process: SS~~	~~Process: FF~~
~~VDD: TYP~~	~~VDD: MIN~~	~~VDD: MAX~~
~~Temp: Typ~~	~~Temp: Max~~	~~Temp: Min~~

~~1 [Model],~~
~~3 PVT Corners~~

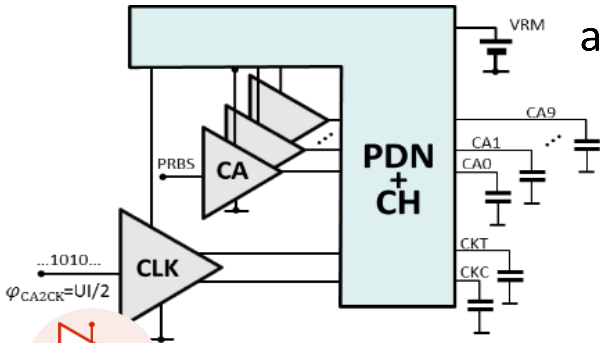
“enhanced” IBIS

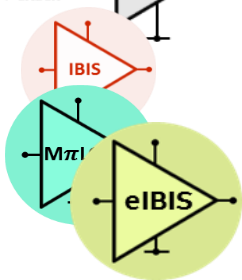
Process: TT	Process: TT	Process: TT
VDD: TYP	VDD: MIN	VDD: MAX
Temp: 25	Temp: 25	Temp: 25

1 [Model],
1 PT Corner (e.g., TT/25C)
Accuracy @SI&PI
(capture VDD-effects)

Validation

CA-bus (10x CA I/Os and 1x CLK Driver)



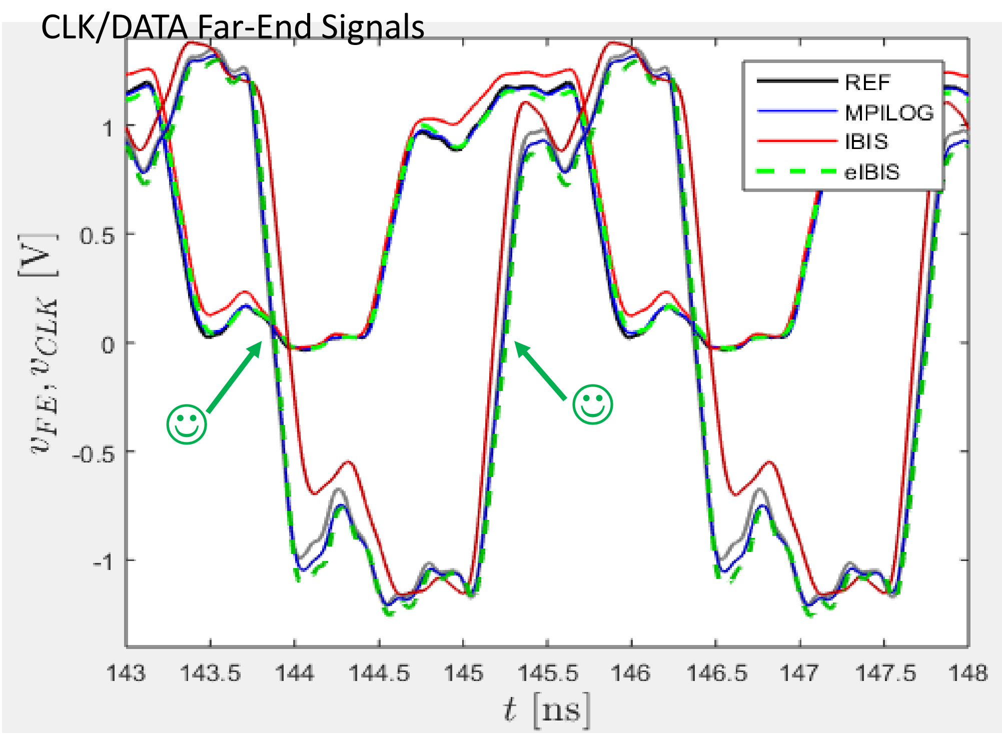


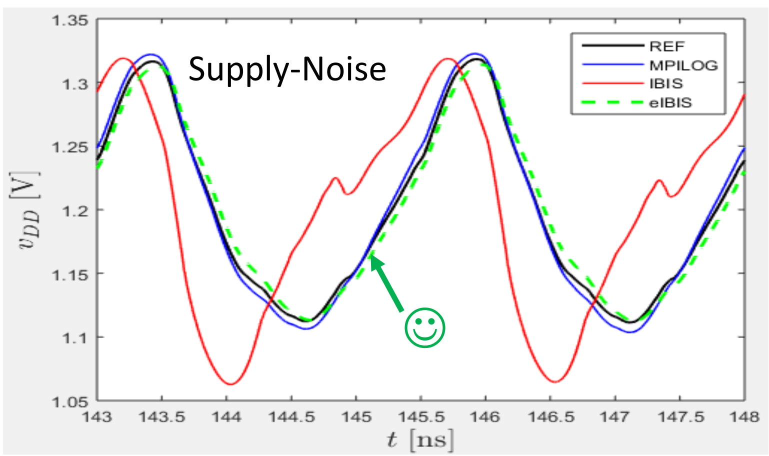
Reference (XTOR-level)

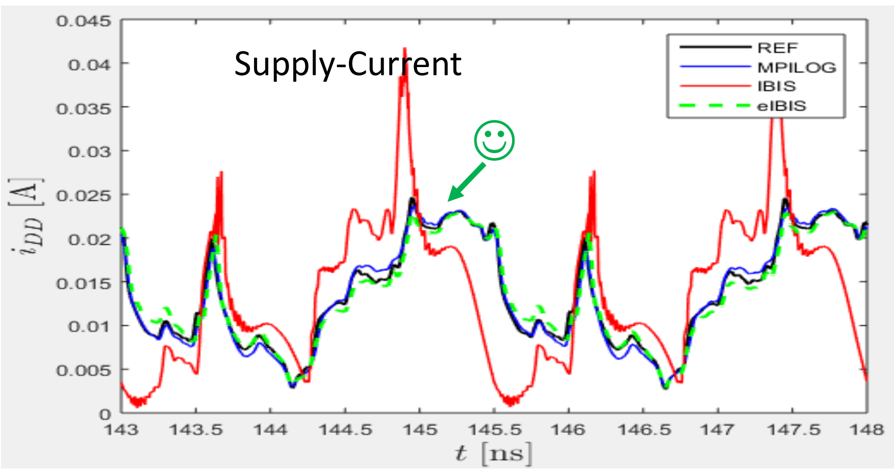
vs **IBIS v5.1** 😐

vs **MPILOG** ☺

vs **e-IBIS** ☺







Conclusions

Enhanced Mpilog models to accurately reproduce currents and voltages at **output** and **supply ports** :

- ✓ Compact Multivariate Surface Approximations **SVD + truncation-process** for I-V and switching characteristics
- ✓ Multiple-Input Rational Approx. & **TD-VF** identification for Dynamic Characteristics

Flexible and **modular** approach using **Mpilog** + implementations possible in **SPICE/Verilog-A**

Identification of **potential limitations** of IBIS models power-awareness and proposal on **possible IBIS enhancements**

Validation tests highlight **excellent accuracy** in **SI/PI co-simulations**

Q&A