Addressing non-ideal TX-FFE behavior of high-speed drivers through hierarchical waveform approximations

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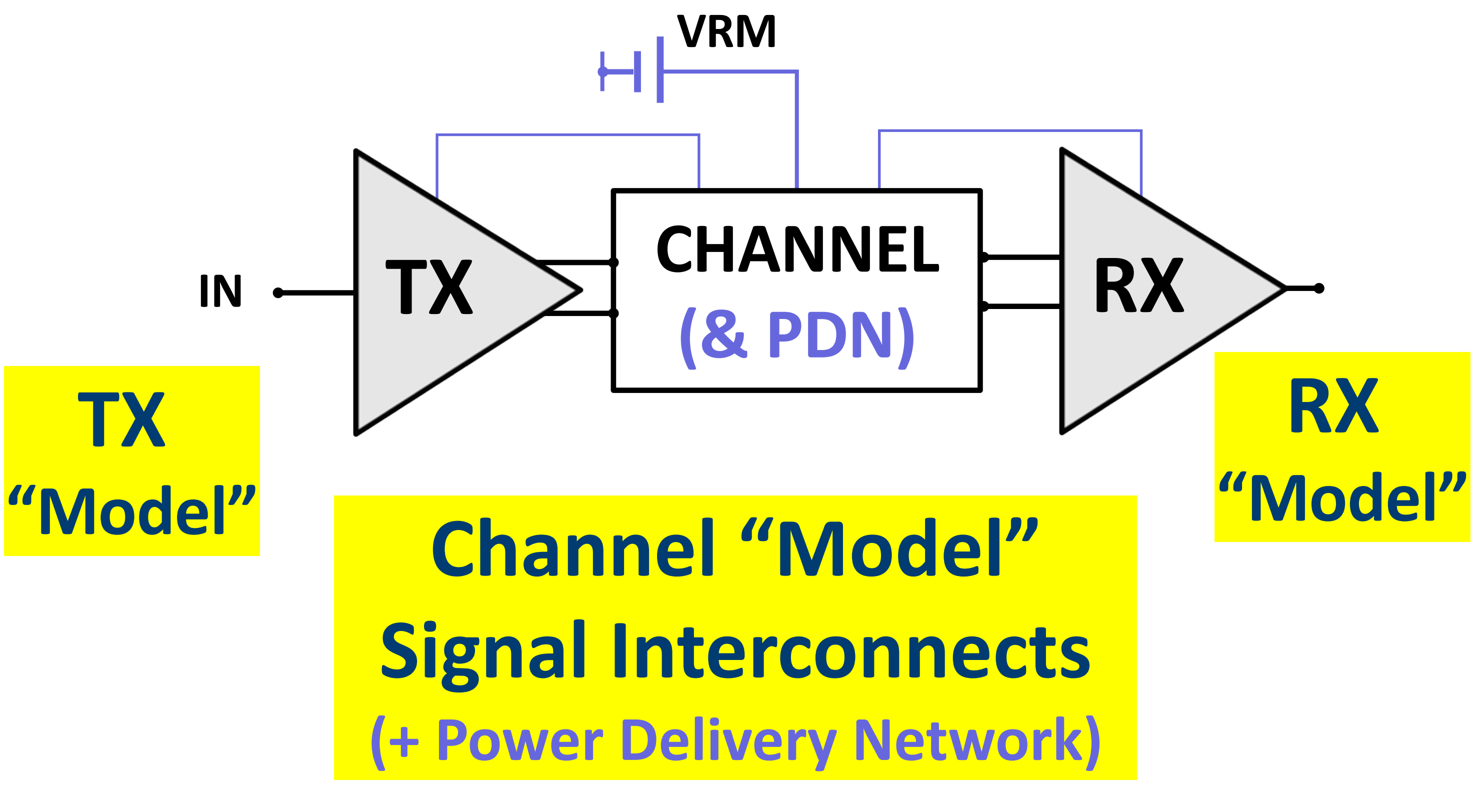
Signal Integrity Simulations

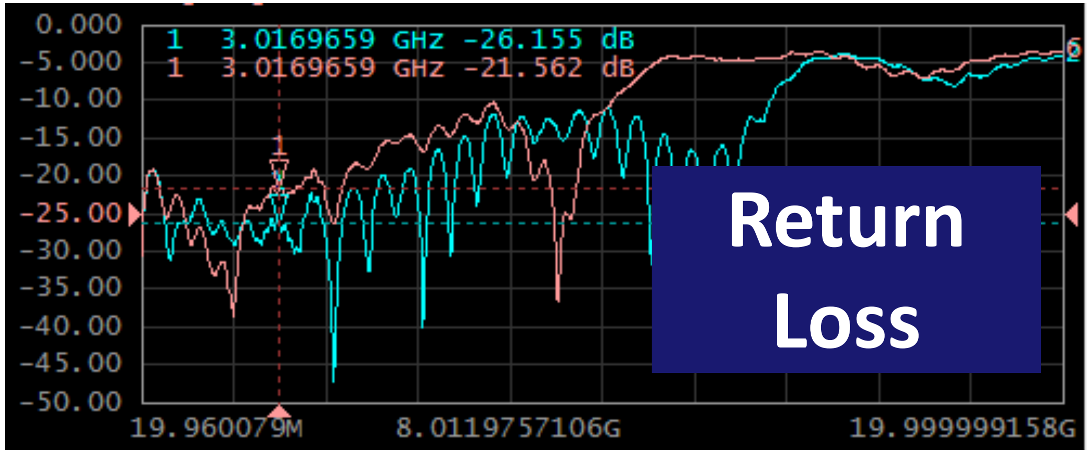


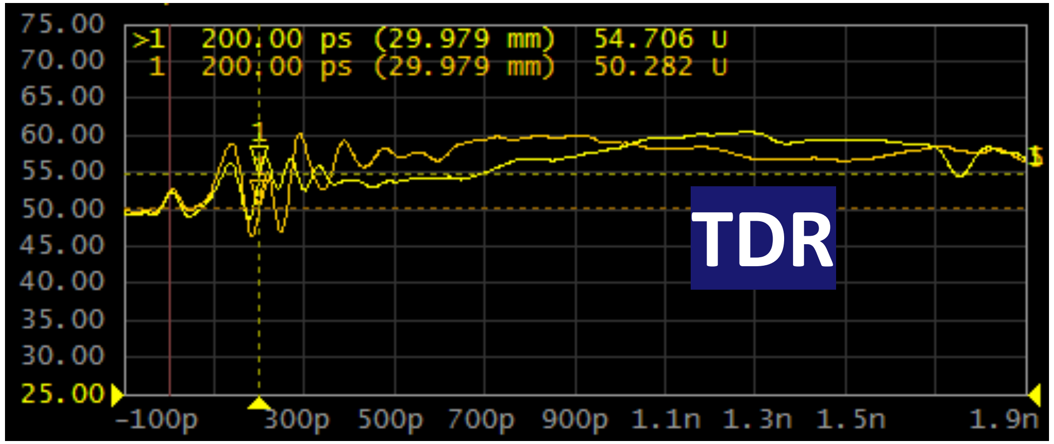
Types of "SI" Analyses:

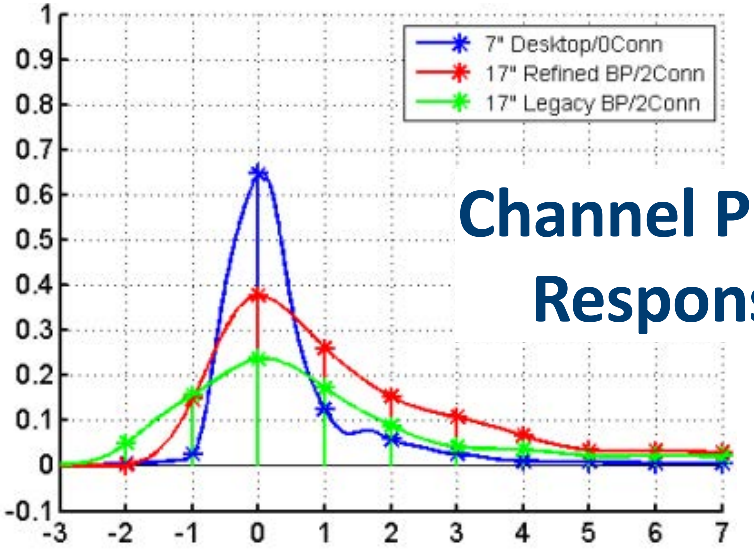
- S-Parameter
    - Insertion Loss
    - Return Loss
    - FEXT/NEXT
- TDR/TDT
- Eye-diagrams / .TRAN
    - Mask / BER
    - Optimal PHY/EQ Settings
    - SI/PI Co-Sim

Evaluation of Channel “Performance”

Frequency Domain *Time Domain*

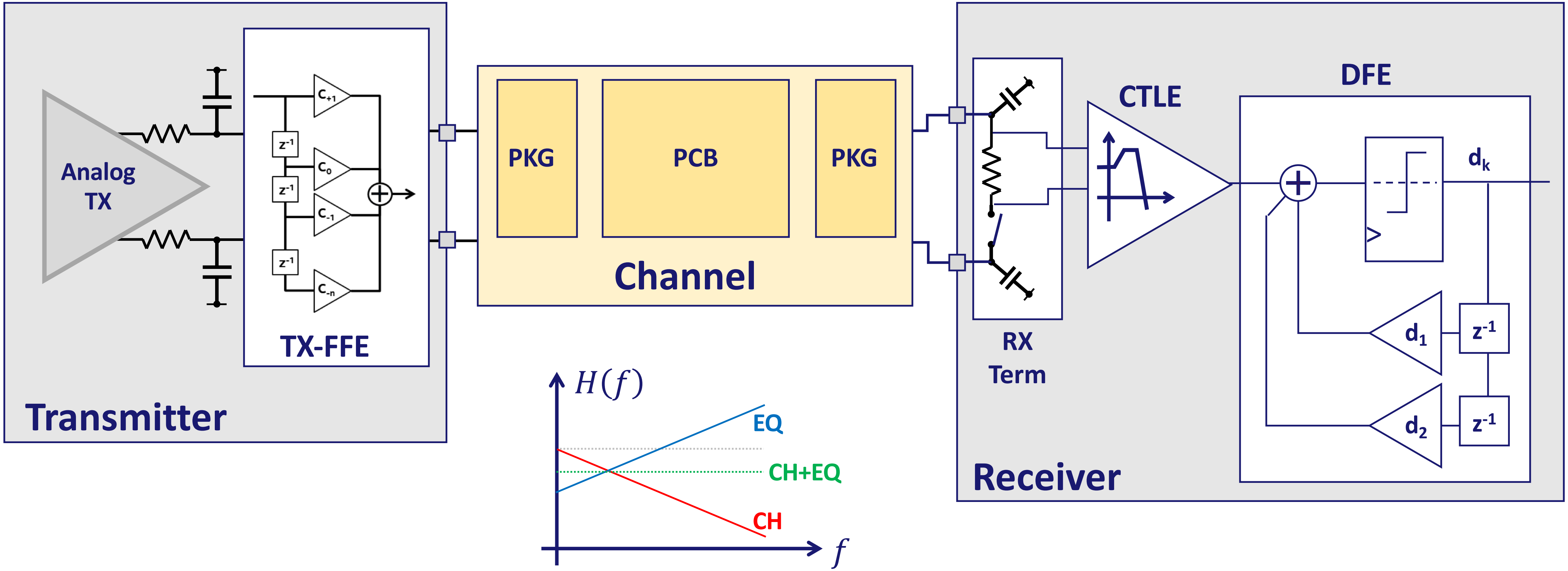






Channel Pulse Response

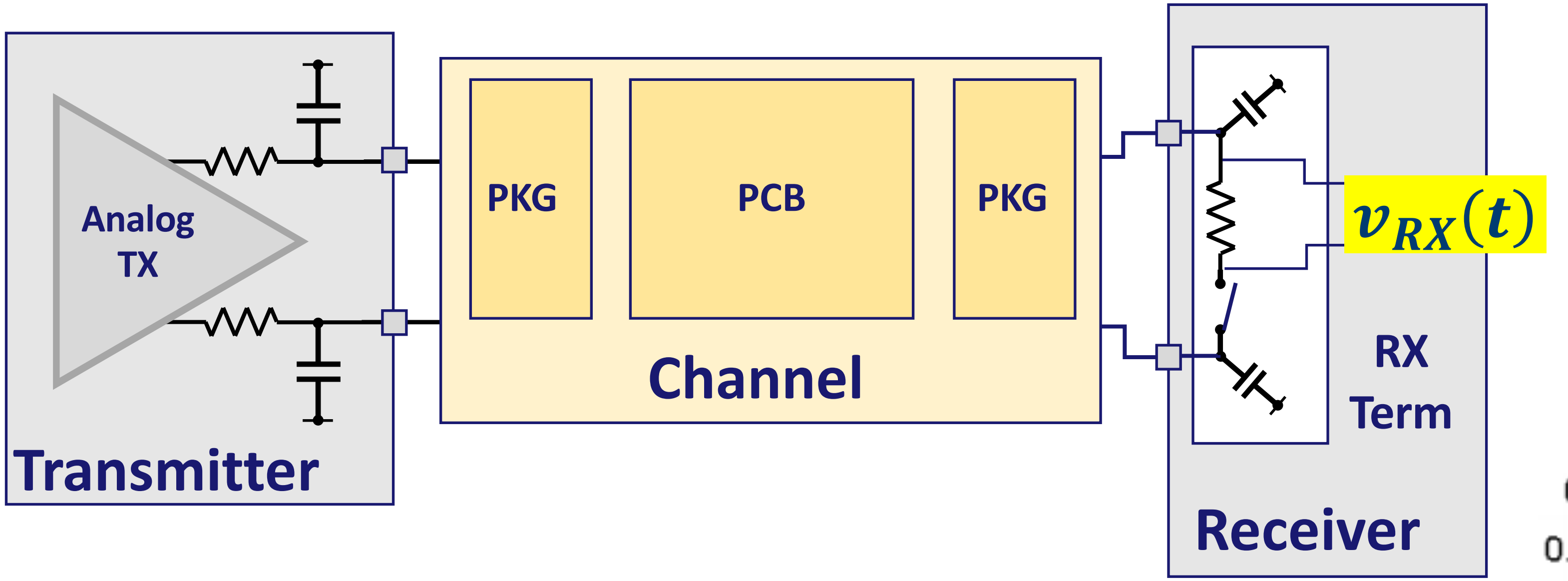
High-Speed Serial Links

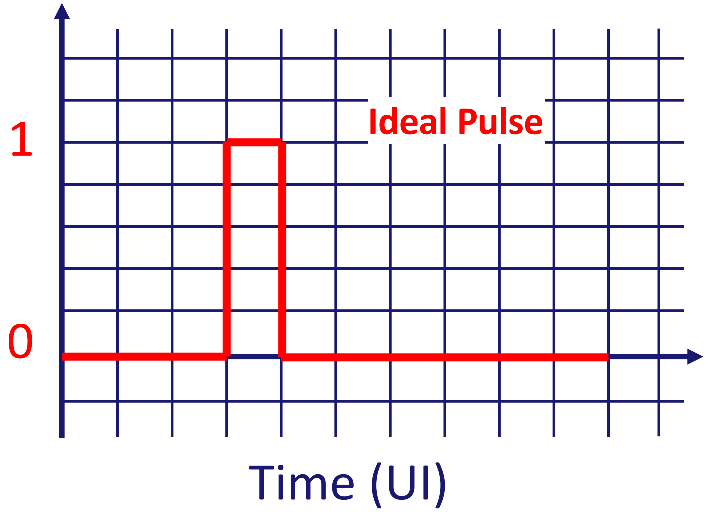


Very complex TX and RX topologies, with Equalizers,
in order to revert the low-pass filter behavior of the interconnections

High-Speed Serial Links

Reference: http://www.ece.tamu.edu/~spalermo/ecen720.html

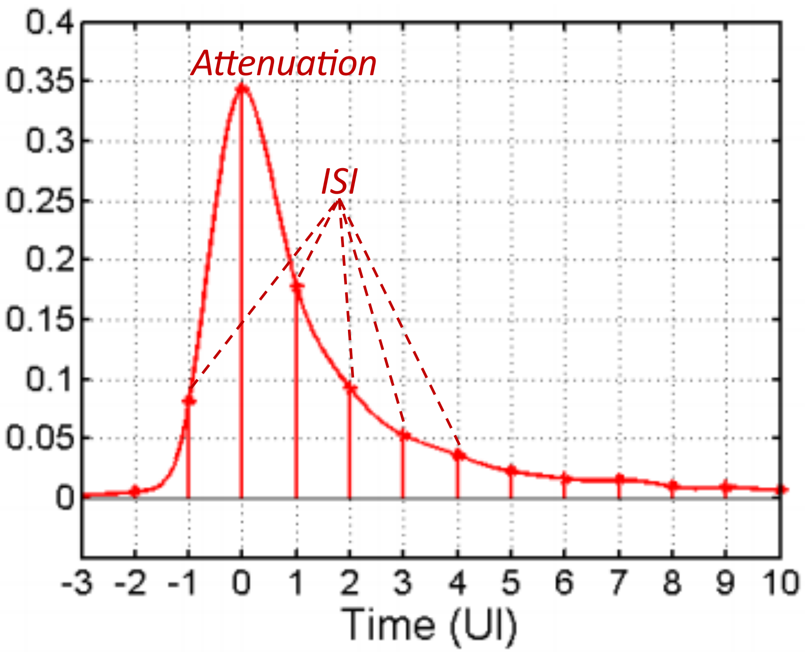




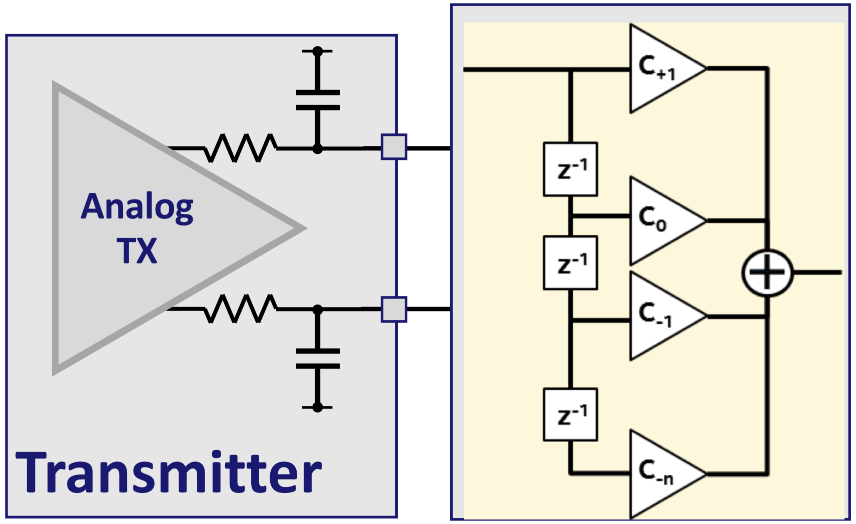
Non-equalized Pulse Response shows Attenuation + several UI of Channel memory (ISI)

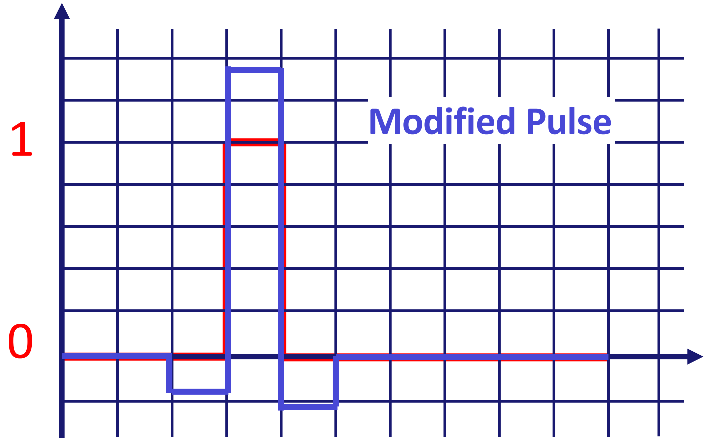
⇩

Eye-Diagram Closure



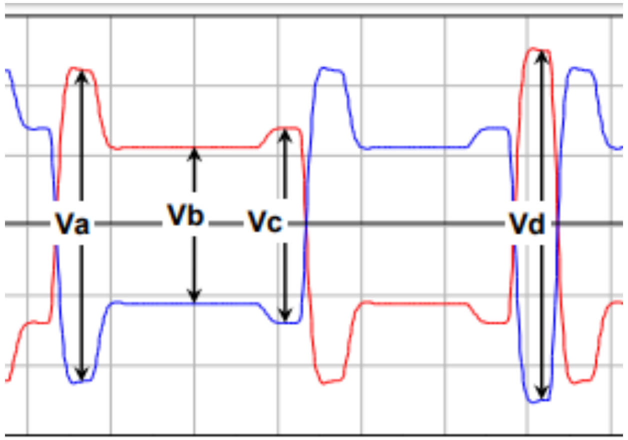
High-Speed Serial Links





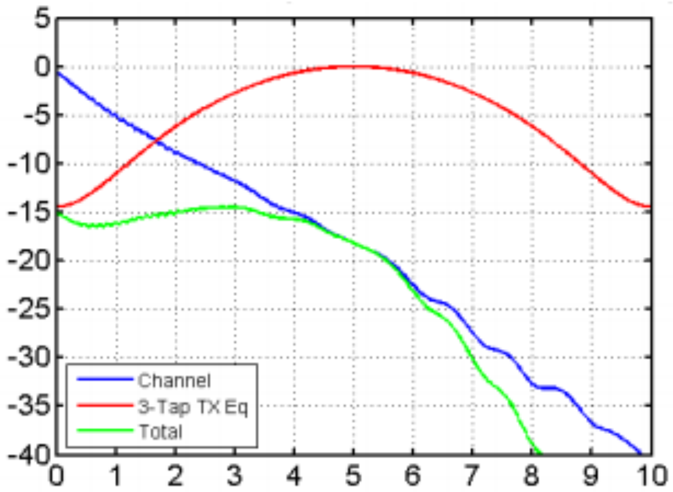
TX Feed Forward Equalizer

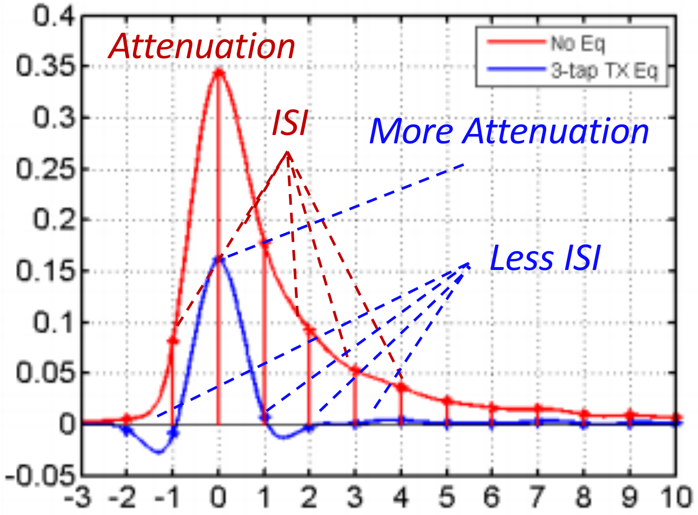
Intentional distortions on TX Signals depending on Bit-Pattern transitions



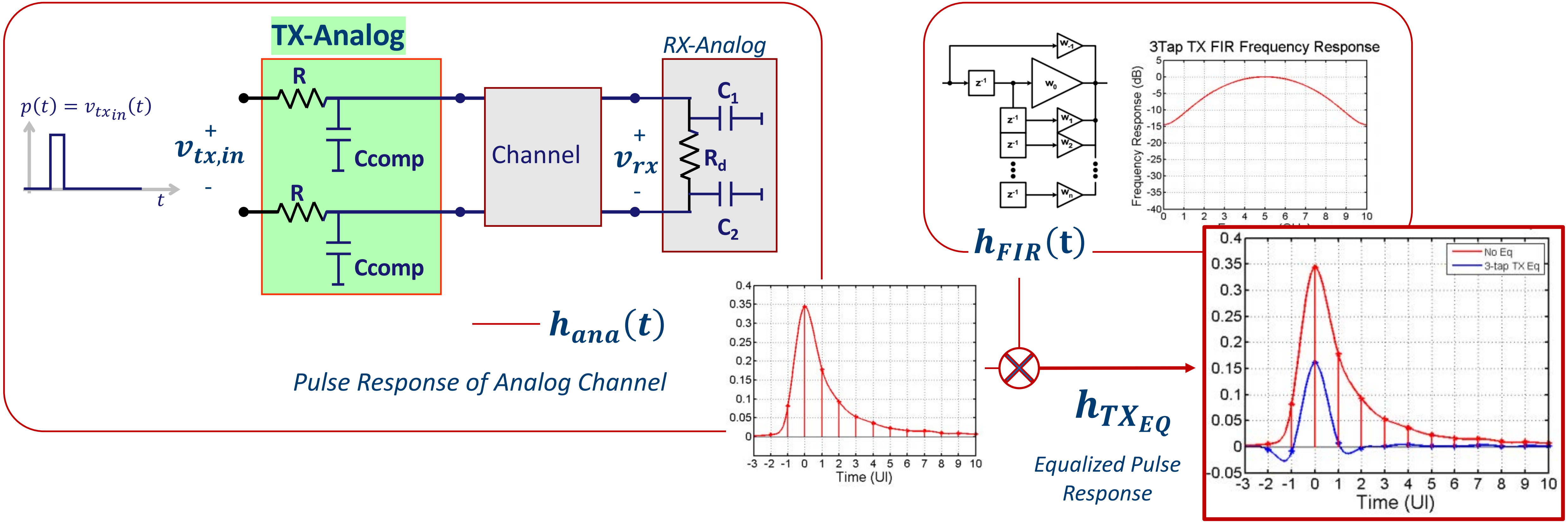
De-emphasis = $20 \log_{10} Vb/Va$
Preshoot = $20\log_{10} Vc/Vb$
Boost = $20\log_{10} Vd/Vb$

Reference: http://www.ece.tamu.edu/~spalermo/ecen720.html

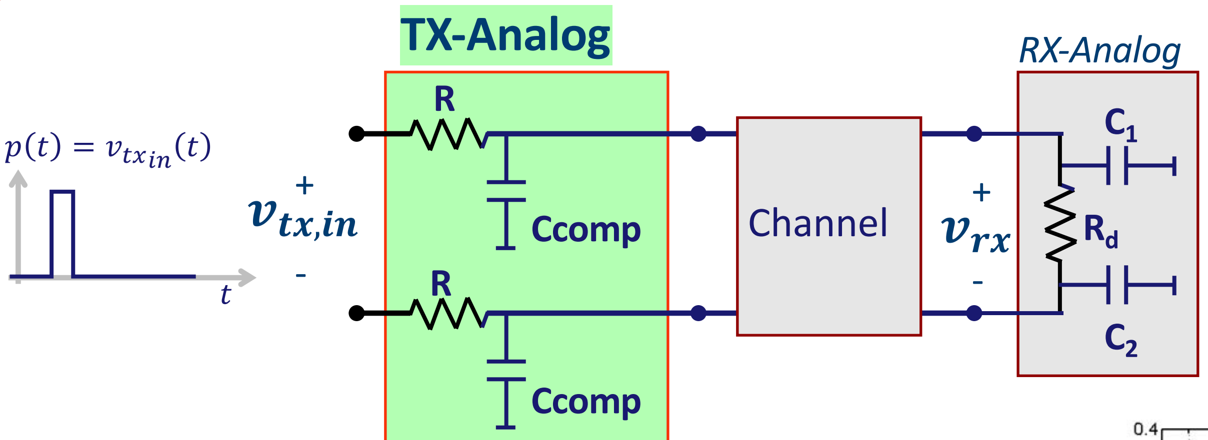




Standard simulation framework: IBIS-AMI



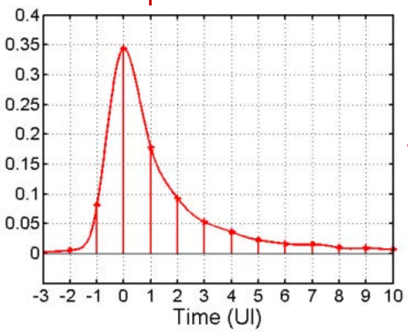
Standard simulation framework: IBIS-AMI



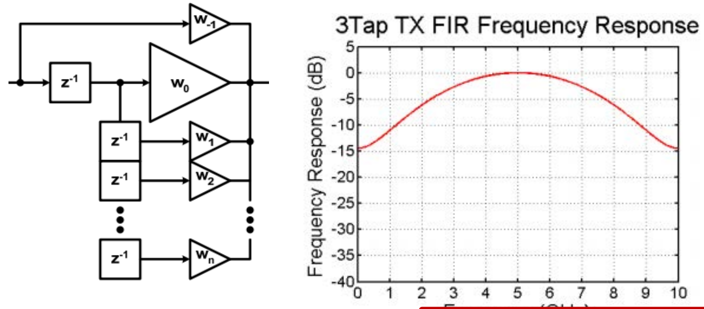
Only Differential signal!

$h_{ana}(t)$

Pulse Response of Analog Channel



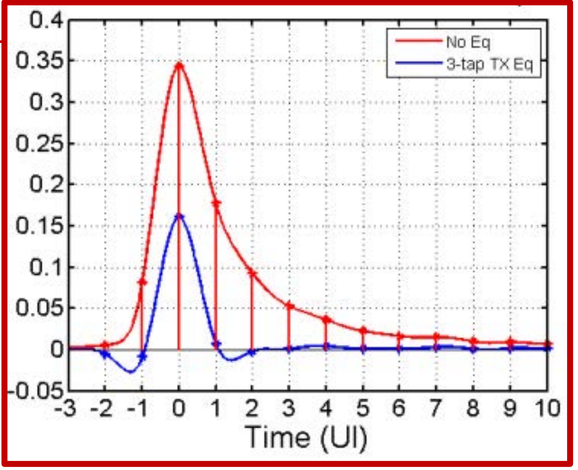
TX EQ = Ideal FIR filter



$h_{FIR}(t)$

$h_{TX_{EQ}}$

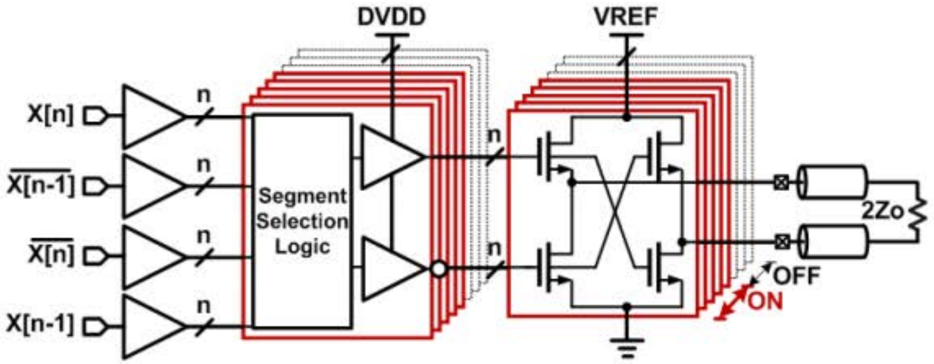
Equalized Pulse Response



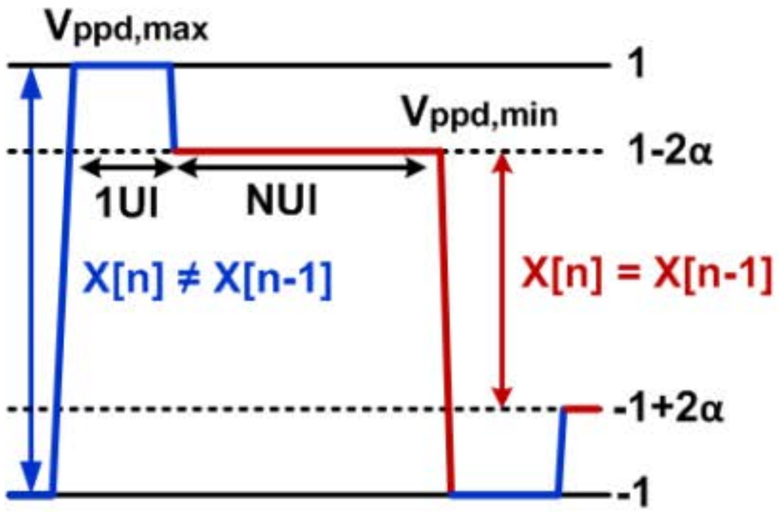
Pre-/De-Emphasis impementation

Segmented Implementation [2]

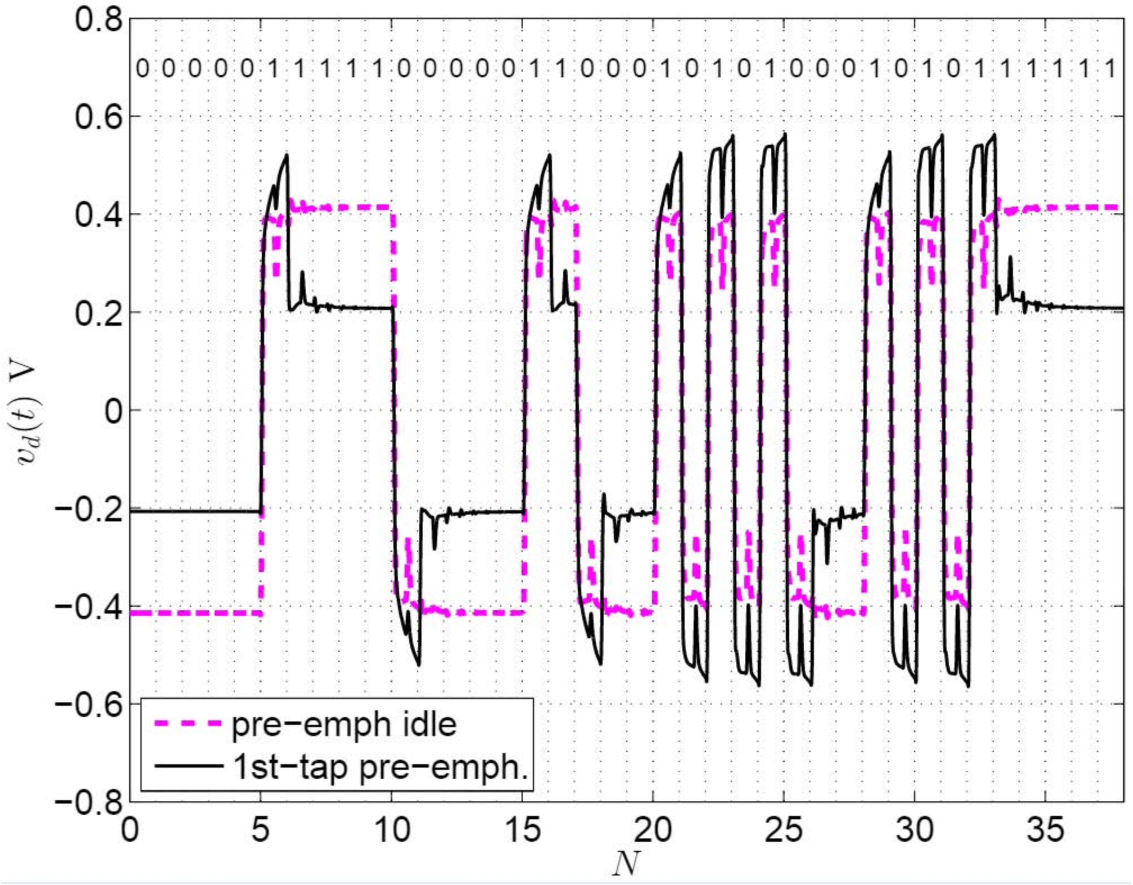
[2] R. Sredojevic, et al., JSSC 2011



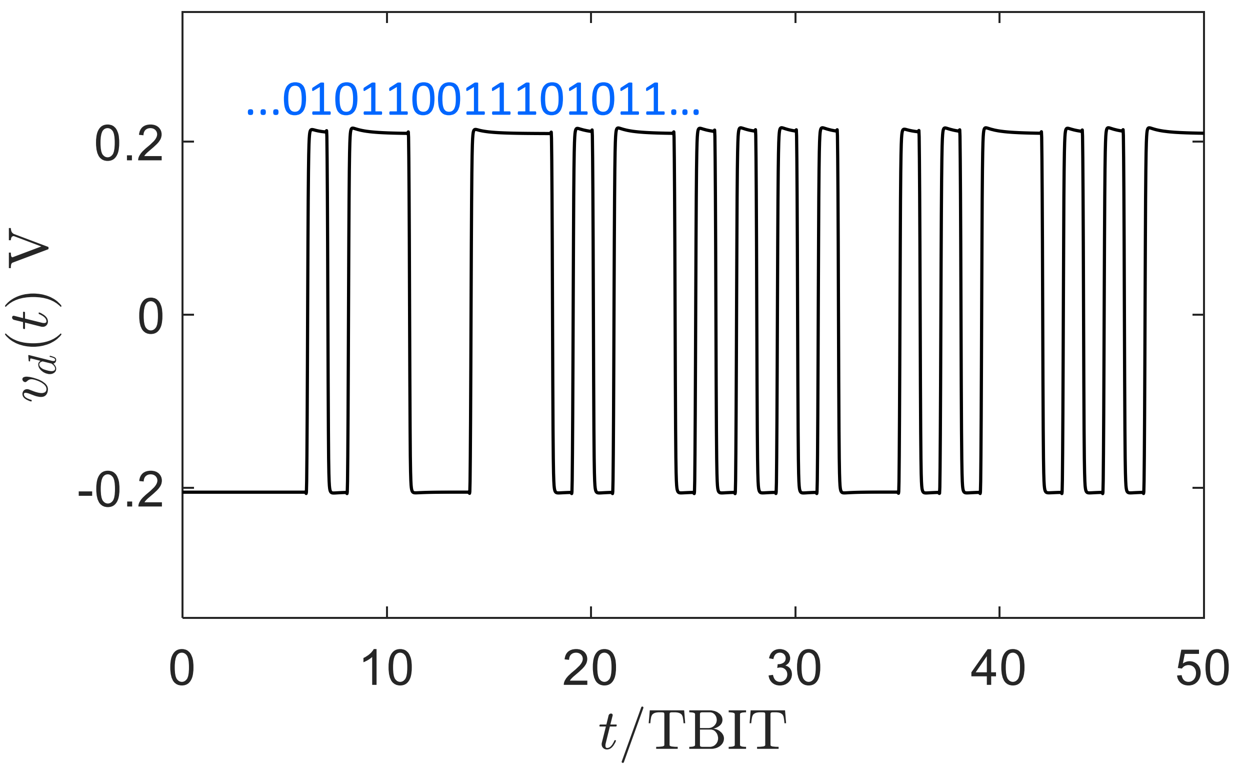
Example: 1 post-tap



Real Example: no TX-EQ vs TX-EQ



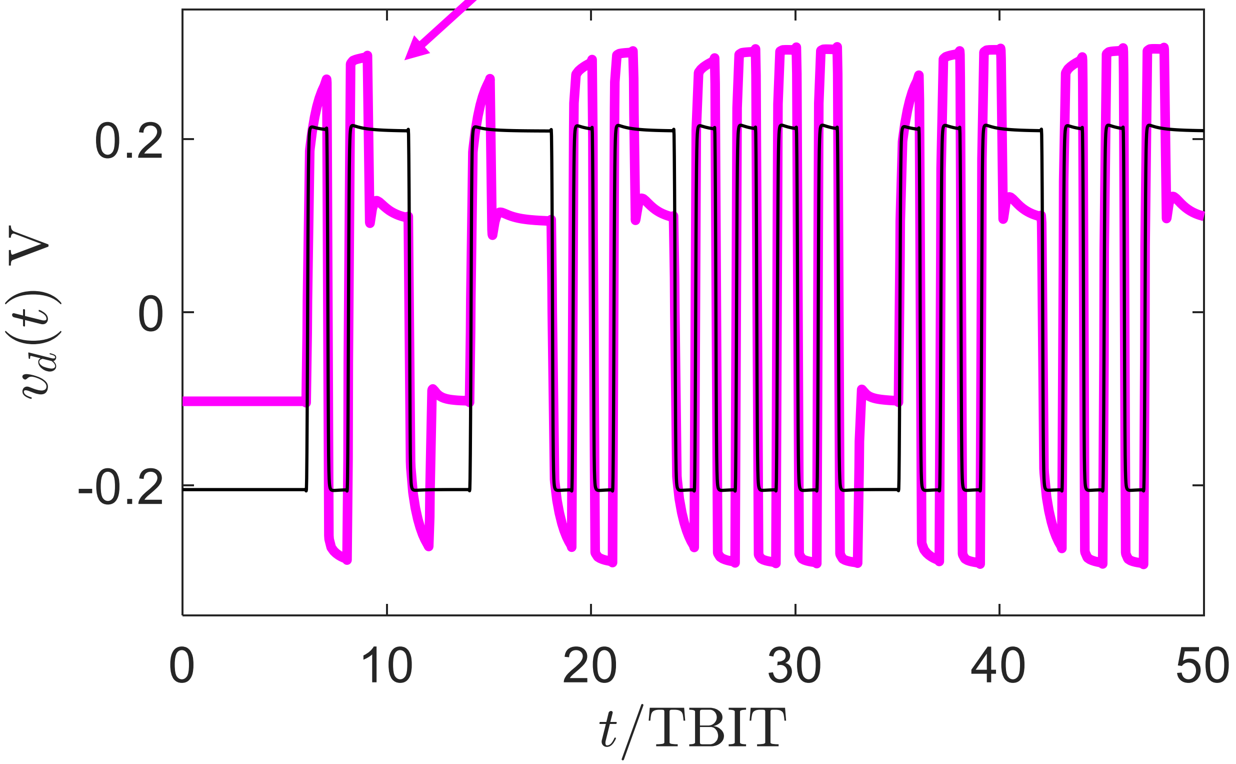
Switching pattern



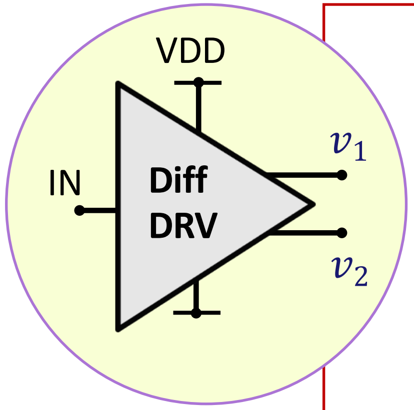
Switching pattern

Effect of pre-emphasis

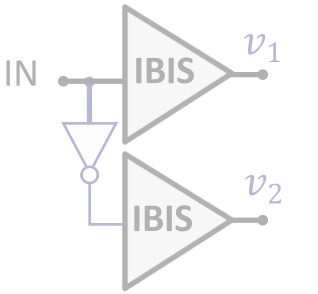
Note: slow transient!



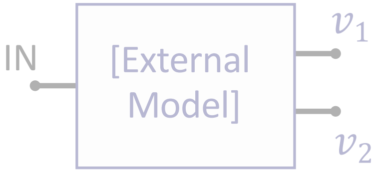
MPILOG Models



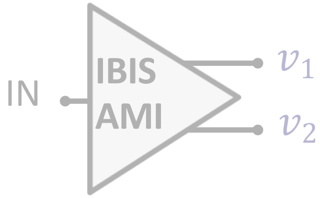
IBIS



Pseudo-Differential
(2x Single-Ended)

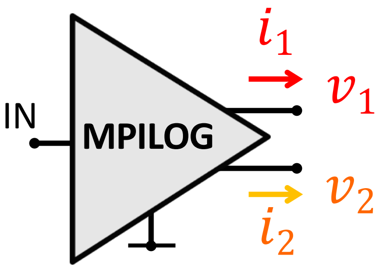


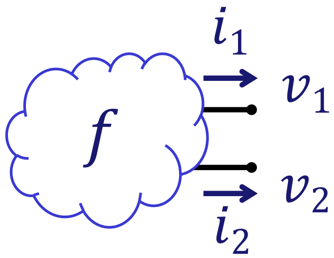
True-Differential



Support TX EQ

"MPILOG"
Framework



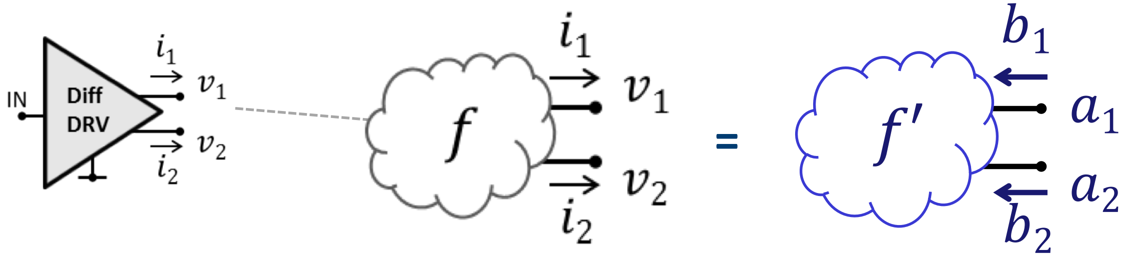


$$(i_1, i_2) = \boldsymbol{f}(v_1, v_2, IN, {}^{\partial}/_{\partial t})$$

- "Grey-box" macromodels
- Output currents i_1, i_2 reproduced with a "**mathematical function**" having output voltages v_1, v_2 as inputs *(true-differential)*

- Function $\boldsymbol{f}$ is a **parametric equation**, **fixed structure**
- Parameter Identification = **post-processing of suitable SPICE .TRAN**
- Function f is cast as SPICE/Verilog-A code

MPILOG Models



MPILOG, $v - i$ *MPILOG, scattering*

$$b_{1,2} = (v_{1,2} - Z_0 \cdot i_{1,2})/(2 \cdot \sqrt{Z_0})$$

$$a_{1,2} = (v_{1,2} + Z_0 \cdot i_{1,2})/(2 \cdot \sqrt{Z_0})$$

Scattering waves

MPILOG Macromodel Structure - Scattering Formulation

High-logic state ***Low-logic state***

$$\begin{cases} a_1 = w_{1H}(t) \cdot f_{1sH}(b_1, b_2) + w_{1L}(t) \cdot f_{1sL}(b_1, b_2) + f_{1d}(t, b_1, b_2, \partial/\partial t) \\ a_2 = w_{2H}(t) \cdot f_{2sH}(b_1, b_2) + w_{2L}(t) \cdot f_{2sL}(b_1, b_2) + f_{2d}(t, b_1, b_2, \partial/\partial t) \end{cases}$$

≈ "Pull-up" **NONLINEAR!**

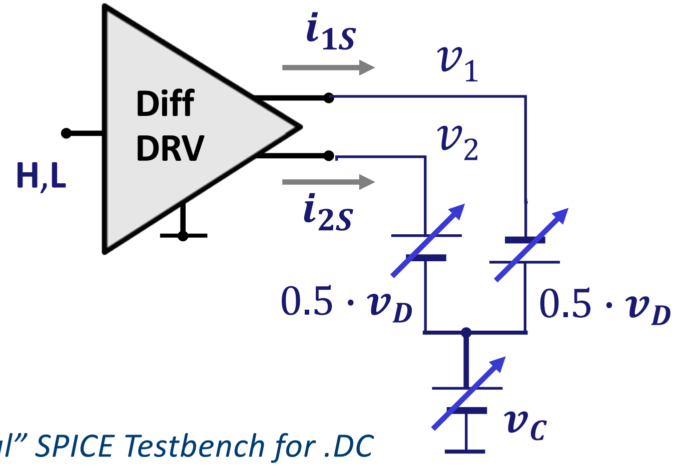
≈ "rising/falling/EQ"

≈ "Pull-down" **NONLINEAR!**

≈ "falling/rising/EQ"

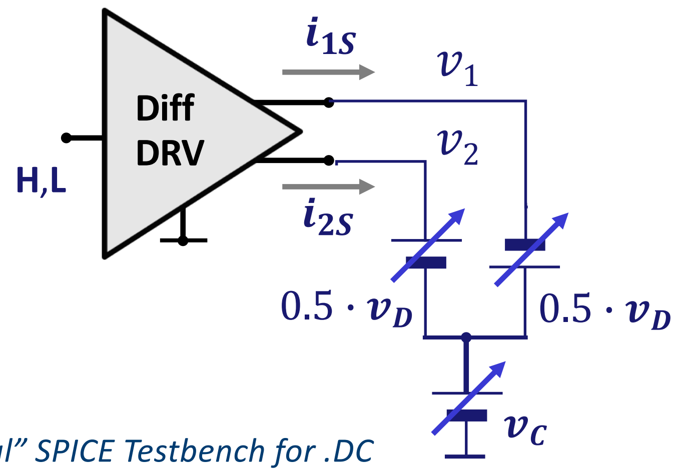
≈ "Ccomp", dynamic

Static Characteristics

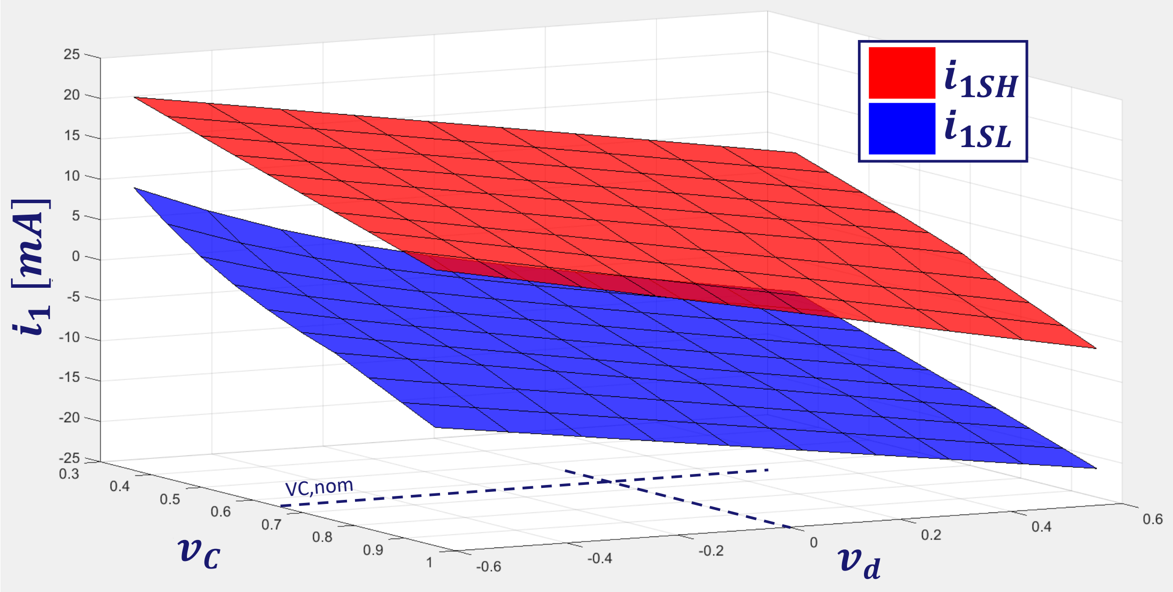


“Ideal” SPICE Testbench for .DC characterization

Static Characteristics



"Ideal" SPICE Testbench for .DC characterization



- Surfaces look quite "regular" → is it possible to *simplify* characterization?
- Parallel planes → linear → this justifies all assumptions of IBIS-AMI, superposition, etc…

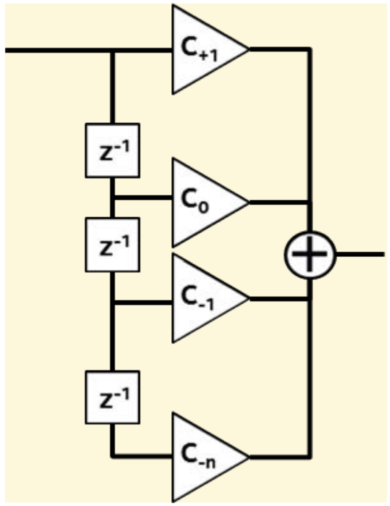
Weighting Functions: embedding pre-emphasis

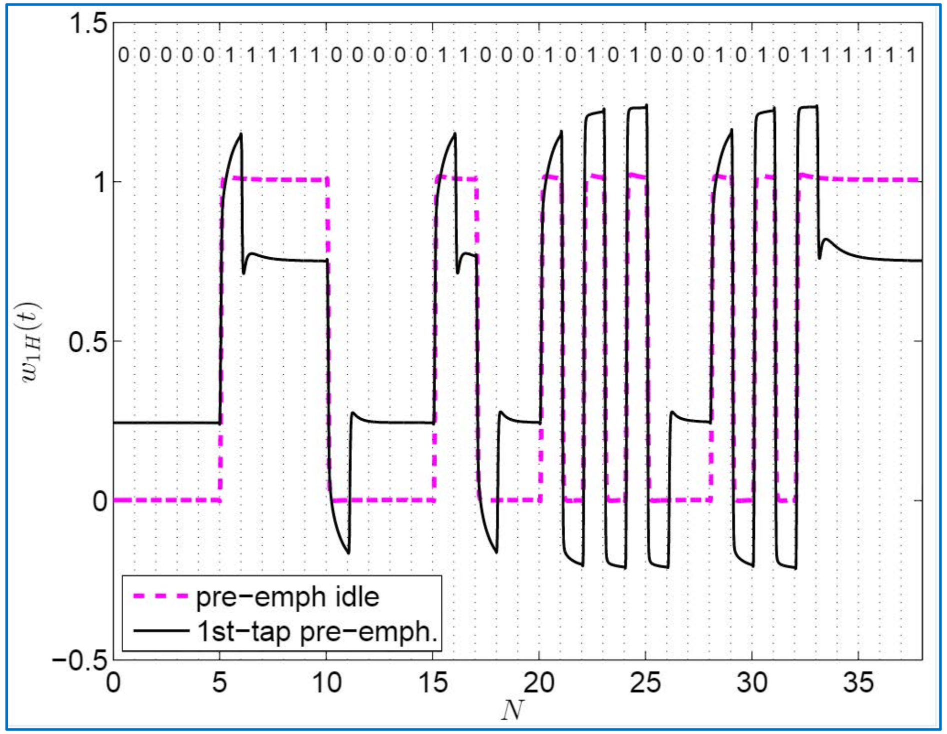
Unknown

$$\boxed{a_1} = w_{1H} \cdot f_{1SH}(b_{C,NOM}, b_{C,NOM}) + w_{1L} \cdot f_{1SL}(b_{C,NOM}, b_{C,NOM}) + f_{1d}(b_{C,NOM}, b_{C,NOM})$$

From HSPICE

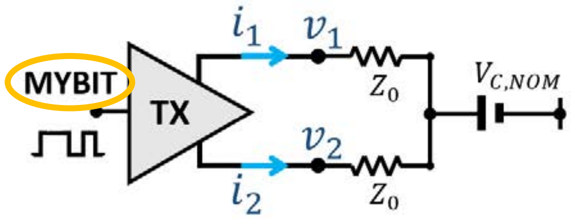
Known from static surface characterization





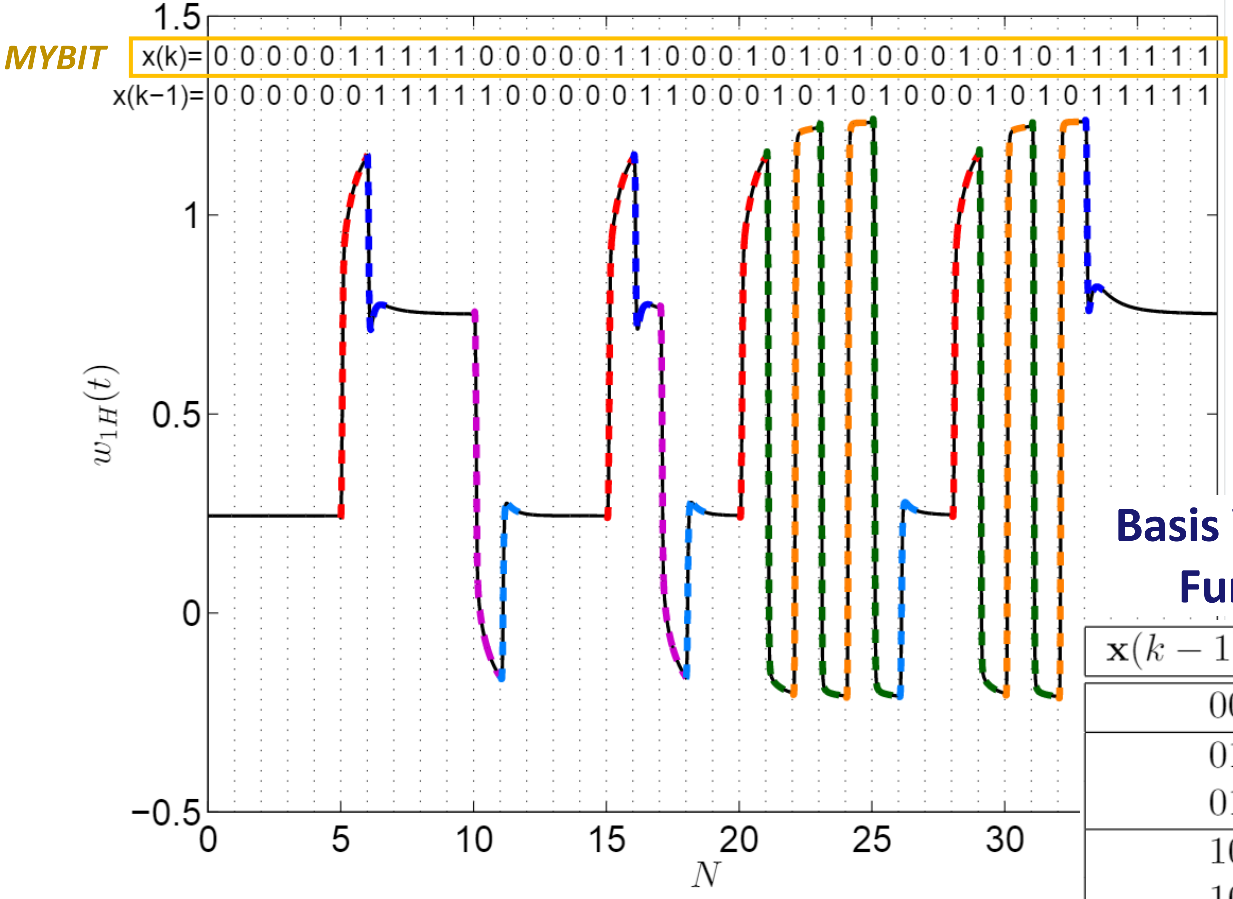
Pre-/De-emphasis effect is embedded in the weighting functions

Weighting Functions: embedding pre-emphasis



Electrical SPICE Testbench for Weighting-function Characterization

MYBIT is synthesized in order to **stress all possible TX state-transitions**.



Basis Weighting Functions

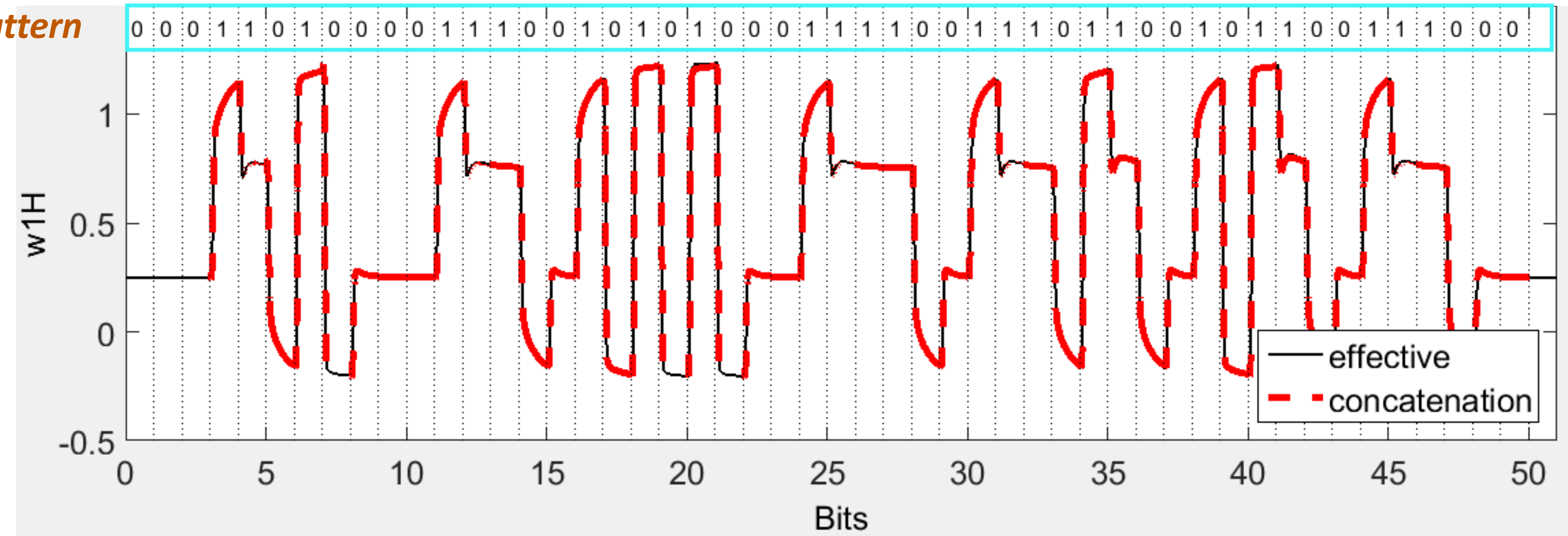
$\mathbf{x}(k-1)$		$\mathbf{x}(k)$
00	⟶	10
01	⟶	10
01	⟶	00
10	⟶	01
10	⟶	11
11	⟶	01

Example: 1 post-tap

Weighting Functions

For any **given bit-pattern**, the **global weighting functions** are calculated by **concatenation** of the **basis functions.**

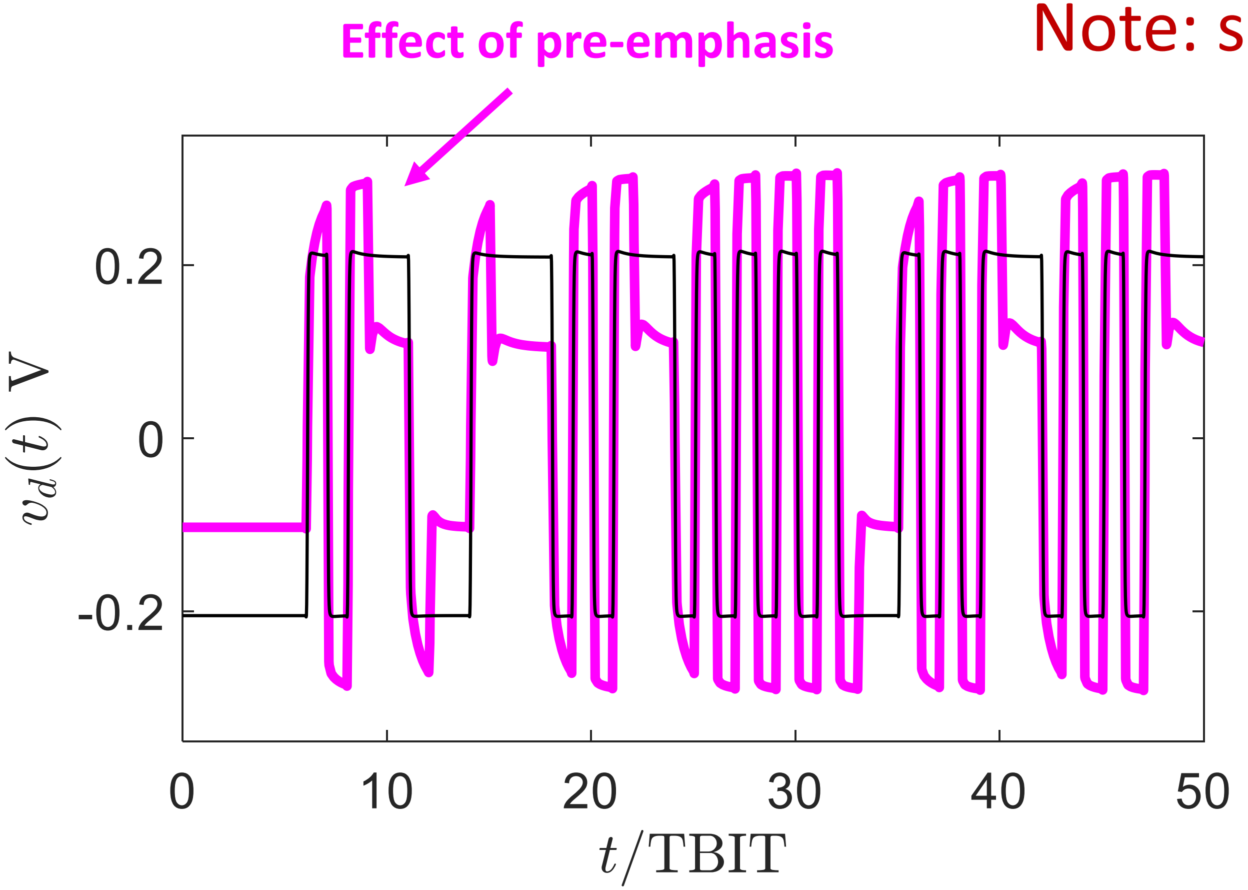
Generic Bit Pattern



Summary

- IBIS-AMI modeling
  - Ideal for drivers that behave almost linearly
  - Ideal for algorithmic parts
  - Pre/de-emphasis easily accounted for (algorithmically: ideal FIR)
  - Limited support for common-mode (may be very important)
- MpiLog modeling
  - General, can be applied to linear and nonlinear drivers
  - Can include Pre/de-emphasis, but may require many basis functions
  - Natively supports common mode (and power supply ports)
- Transistor-level modeling
  - Not an option, too slow

Switching pattern



Note: slow transient!

The slow transient is not a linear combination of shifted pulses!!

Algorithmic approach may fail: no FIR approx

The proposed model structure

Outputs: currents or reflected waves

Inputs: voltages or incident waves

$$\begin{pmatrix} y_1(t) \\ y_2(t) \end{pmatrix} = \begin{pmatrix} F_{11} & F_{12} \\ F_{21} & F_{22} \end{pmatrix} \begin{pmatrix} u_1(t) \\ u_2(t) \end{pmatrix} + \begin{pmatrix} \xi_1(t) \\ \xi_2(t) \end{pmatrix} + \begin{pmatrix} f_1\big(u_1(t), u_2(t)\big) \\ f_2\big(u_1(t), u_2(t)\big) \end{pmatrix}$$

Constant, linear approx of **static characteristics**

Switching waveforms: analog of weighting functions of MpiLog or pulse responses in IBIS-AMI

Dynamic submodel: linear, pole-zero model obtained by TD-VF as in MpiLog

Note 1: intrinsic multi-port formulation, common-mode embedded by construction

Note 2: pre/de-emphasis embedded in the switching waveforms

Hierarchical decomposition of switching waveforms

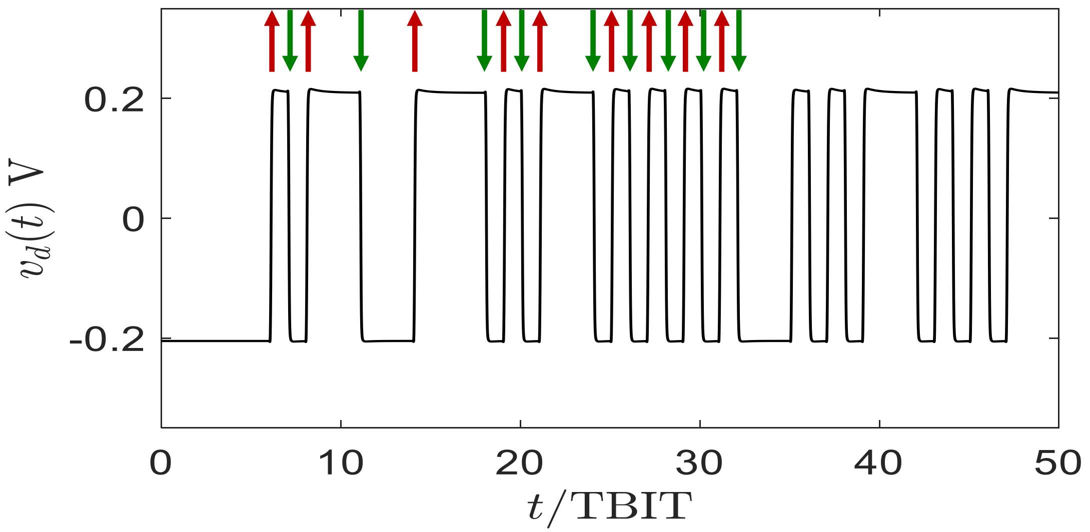
Initial rough approximation

Elementary switching waveforms, up or down

$$\xi_n(t) = \sum_{k\in\Omega_{n,u}^{(0)}} \varphi_{n,u}^{(0)}(t - kT_B) + \sum_{k\in\Omega_{n,d}^{(0)}} \varphi_{n,d}^{(0)}(t - kT_B)$$

Level (0)

Index sets corresponding to actual transitions



Hierarchical decomposition of switching waveforms

Initial rough approximation

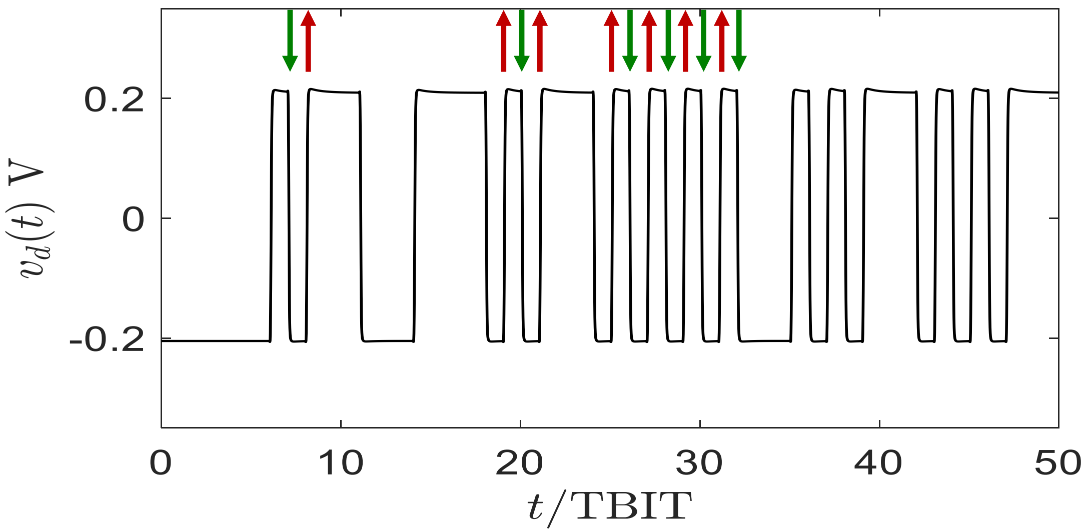
Add finer and finer details in a refinement loop

$$\xi_n(t) = \sum_{k\in\Omega_{n,u}^{(0)}} \varphi_{n,u}^{(0)}(t-kT_B) + \sum_{k\in\Omega_{n,d}^{(0)}} \varphi_{n,d}^{(0)}(t-kT_B)$$

$$+ \sum_{k\in\Omega_{n,u}^{(1)}} \varphi_{n,u}^{(1)}(t-kT_B) + \sum_{k\in\Omega_{n,d}^{(1)}} \varphi_{n,d}^{(1)}(t-kT_B)$$

Level (1)

Index sets, only «double» transitions



Hierarchical decomposition of switching waveforms

Initial rough approximation

Add finer and finer details in a refinement loop

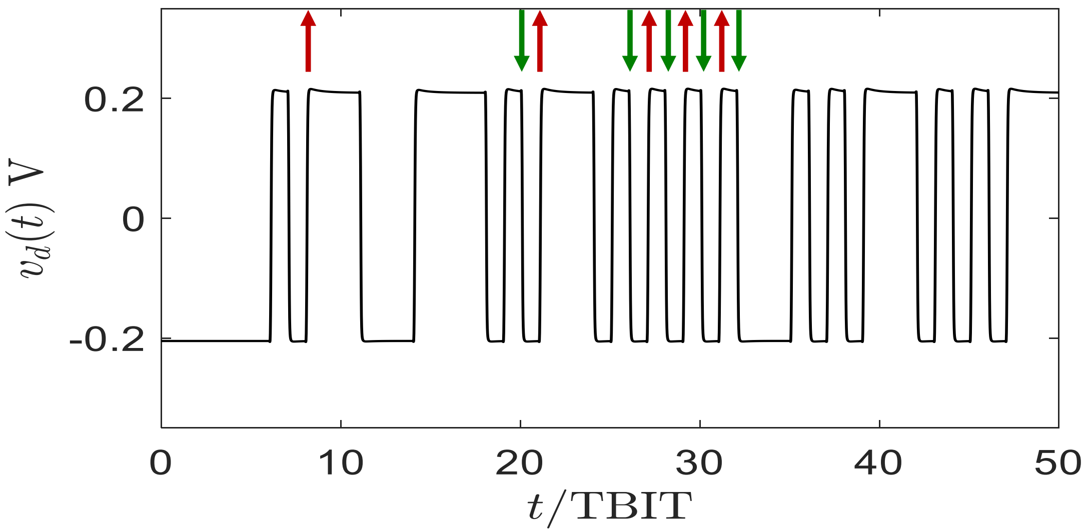
$$\xi_n(t) = \sum_{k\in\Omega_{n,u}^{(0)}} \varphi_{n,u}^{(0)}(t-kT_B) + \sum_{k\in\Omega_{n,d}^{(0)}} \varphi_{n,d}^{(0)}(t-kT_B)$$

$$+ \sum_{k\in\Omega_{n,u}^{(1)}} \varphi_{n,u}^{(1)}(t-kT_B) + \sum_{k\in\Omega_{n,d}^{(1)}} \varphi_{n,d}^{(1)}(t-kT_B)$$

$$+ \sum_{k\in\Omega_{n,u}^{(2)}} \varphi_{n,u}^{(2)}(t-kT_B) + \sum_{k\in\Omega_{n,d}^{(2)}} \varphi_{n,d}^{(2)}(t-kT_B)$$

Level (2)

Index sets, only «triple» transitions

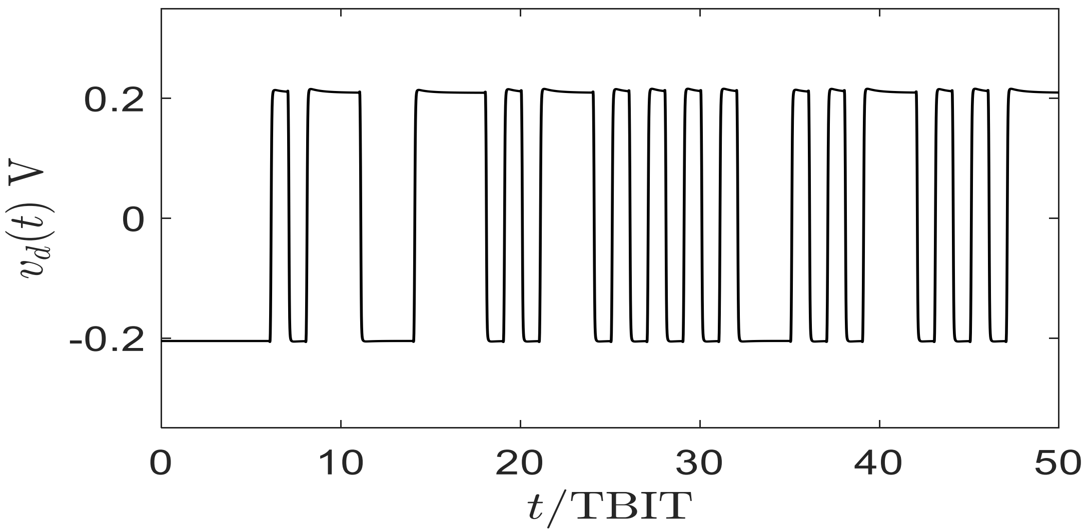


Hierarchical decomposition of switching waveforms

Initial rough approximation

Add finer and finer details in a refinement loop

$$\xi_n(t) = \sum_{k\in\Omega_{n,u}^{(0)}} \varphi_{n,u}^{(0)}(t-kT_B) + \sum_{k\in\Omega_{n,d}^{(0)}} \varphi_{n,d}^{(0)}(t-kT_B)$$
$$+ \sum_{k\in\Omega_{n,u}^{(1)}} \varphi_{n,u}^{(1)}(t-kT_B) + \sum_{k\in\Omega_{n,d}^{(1)}} \varphi_{n,d}^{(1)}(t-kT_B)$$
$$+ \sum_{k\in\Omega_{n,u}^{(2)}} \varphi_{n,u}^{(2)}(t-kT_B) + \sum_{k\in\Omega_{n,d}^{(2)}} \varphi_{n,d}^{(2)}(t-kT_B)$$
$$+ \cdots$$



Note: similar to JPEG compression and Wavelet transforms

Hierarchical decomposition of switching waveforms

Initial rough approximation

Add finer and finer details in a refinement loop

Pulse responses of the TX block, including pre/de-emphasis

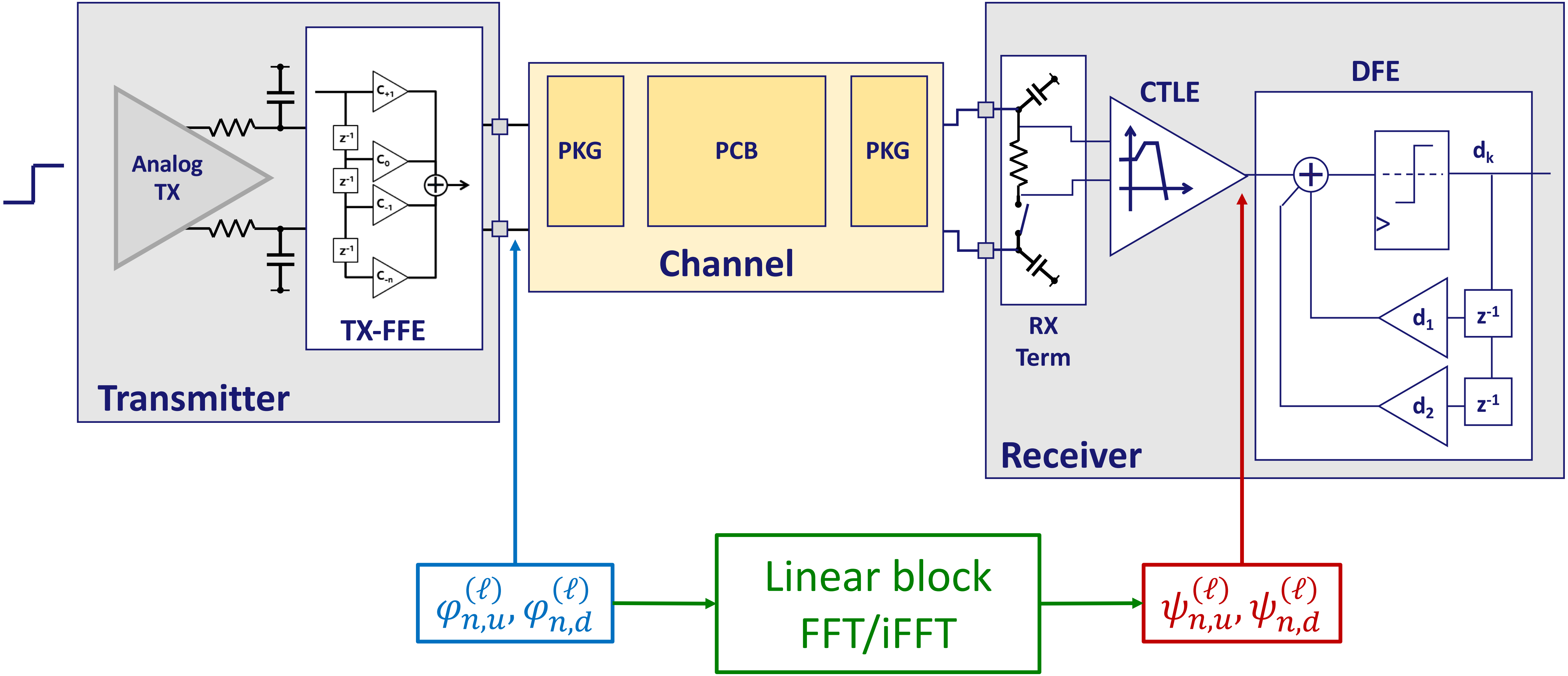
$$\xi_n(t) = \sum_{\ell=0}^{L} \left\{ \sum_{k \in \Omega_{n,u}^{(\ell)}} \varphi_{n,u}^{(\ell)}(t - kT_B) + \sum_{k \in \Omega_{n,d}^{(\ell)}} \varphi_{n,d}^{(\ell)}(t - kT_B) \right\}$$

Superposition of «levels»

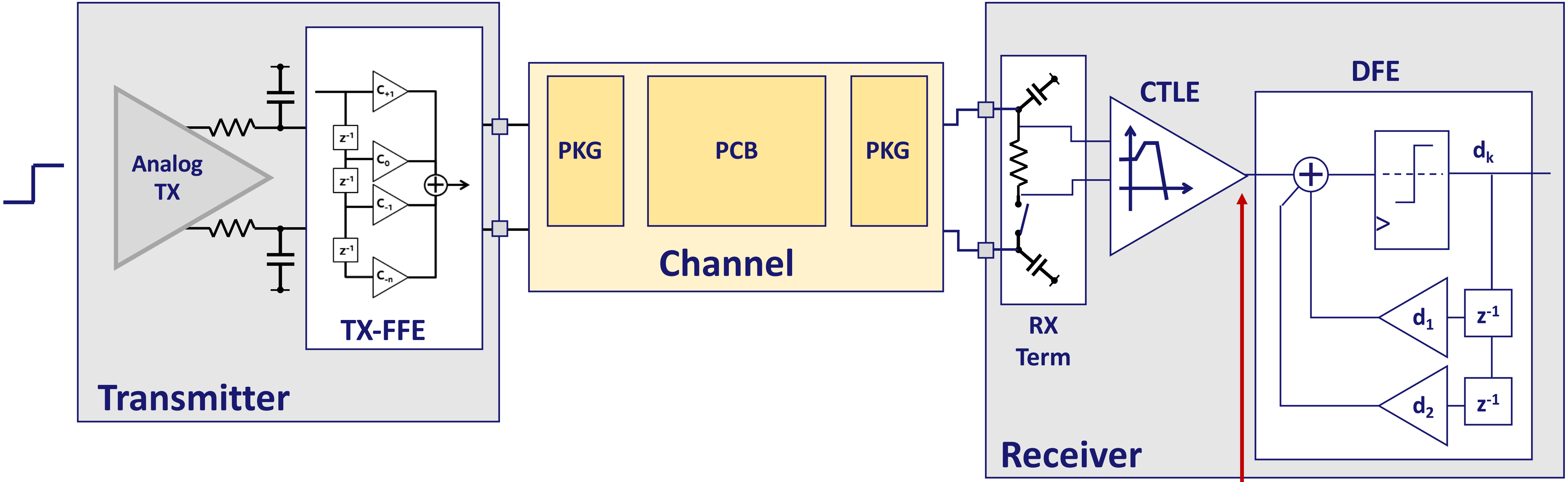
Sparse index sets

Note: similar to JPEG compression and Wavelet transforms

From TX to full channel responses



Full channel response hierarchical decomposition



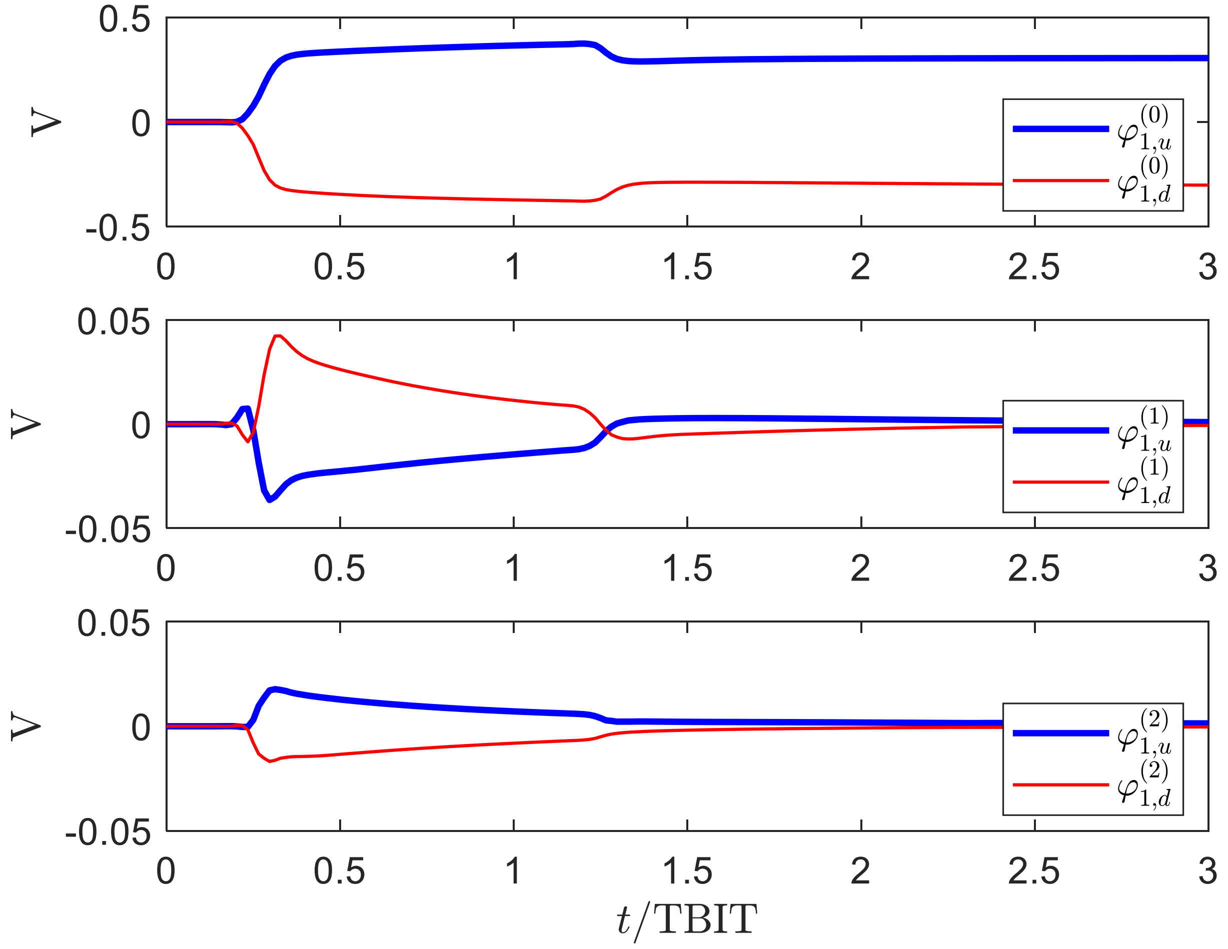
$$y_n(t) = \sum_{\ell=0}^{L} \left\{ \sum_{k \in \Omega_{n,u}^{(\ell)}} \psi_{n,u}^{(\ell)}(t - kT_B) + \sum_{k \in \Omega_{n,d}^{(\ell)}} \psi_{n,d}^{(\ell)}(t - kT_B) \right\}$$

Basis functions φ (no channel)

$\ell = 0$ — "01…" or "10…" transitions

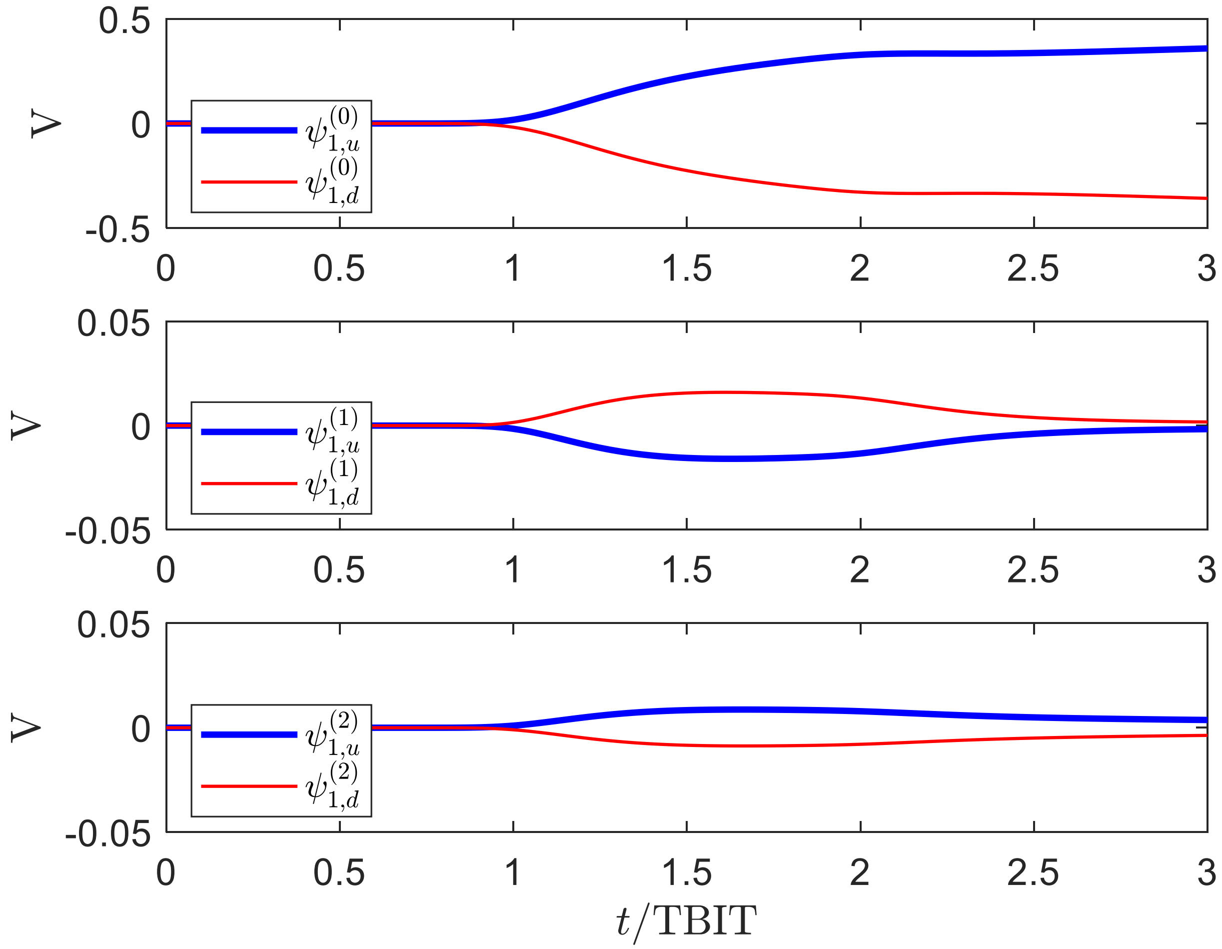
$\ell = 1$ — "010" or "101"

$\ell = 2$ — "0101" or "1010"



Basis functions: ψ (with channel)

$\ell = 0$



"01…" or "10…" transitions

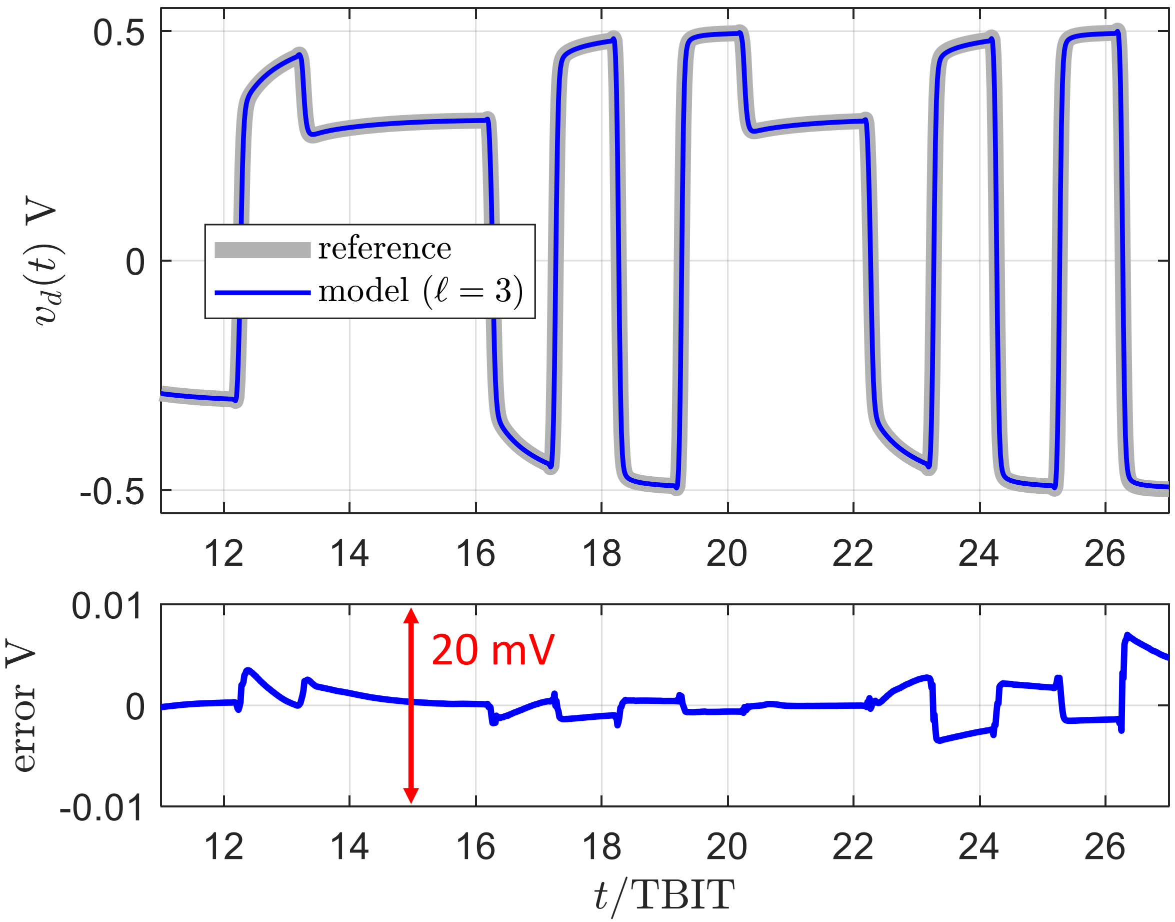
$\ell = 1$

"010" or "101"

$\ell = 2$

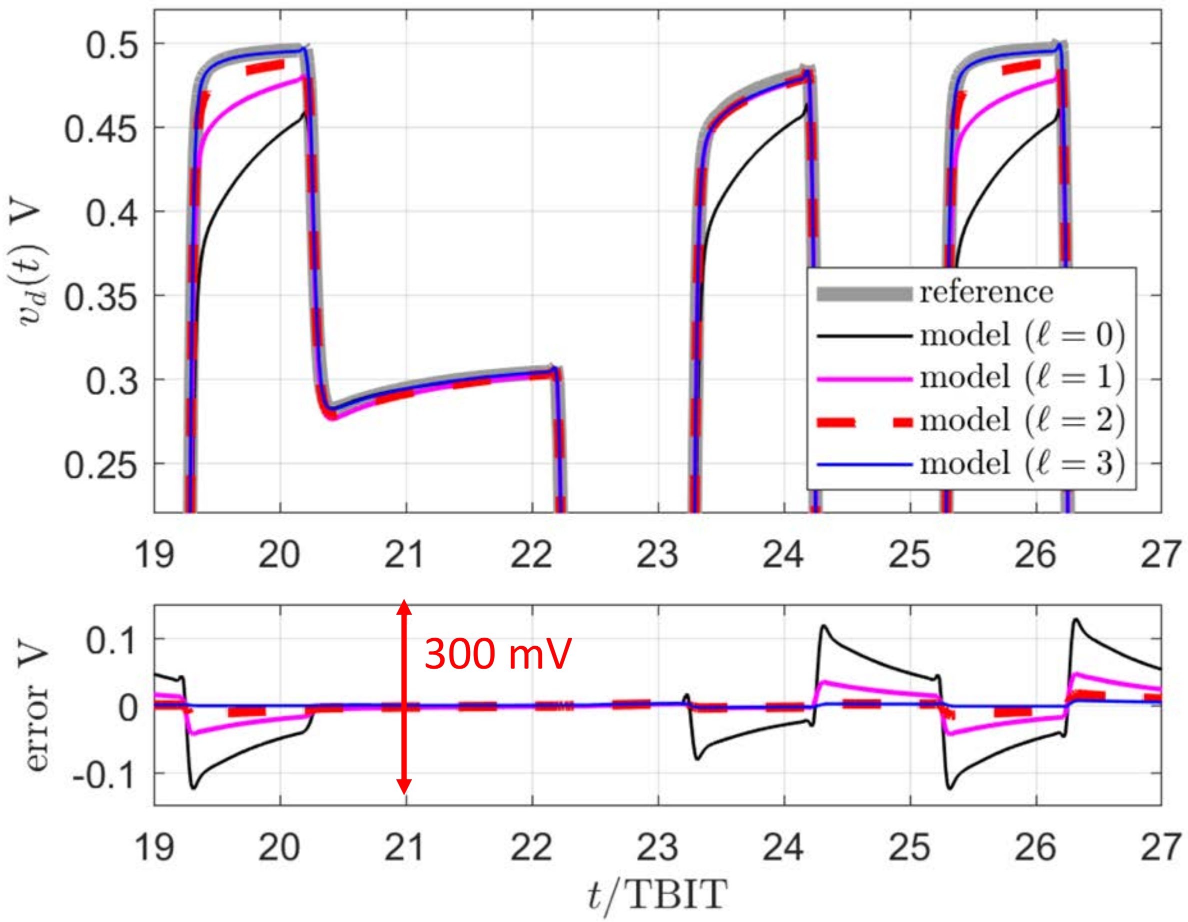
"0101" or "1010"

Results: model validation



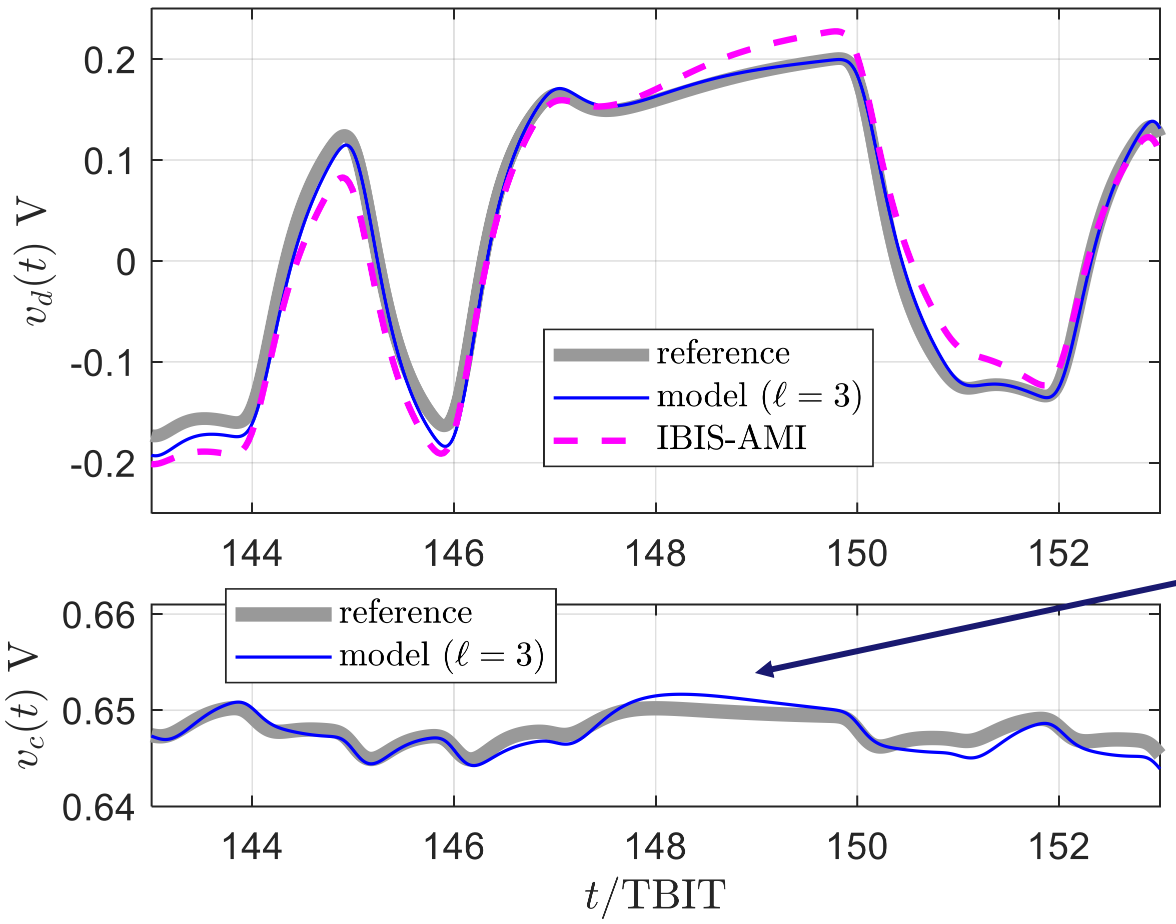
- **Relative error < 1%**
- **Excellent accuracy**

Results: model validation



Big improvement with *increasing hierarchical level*

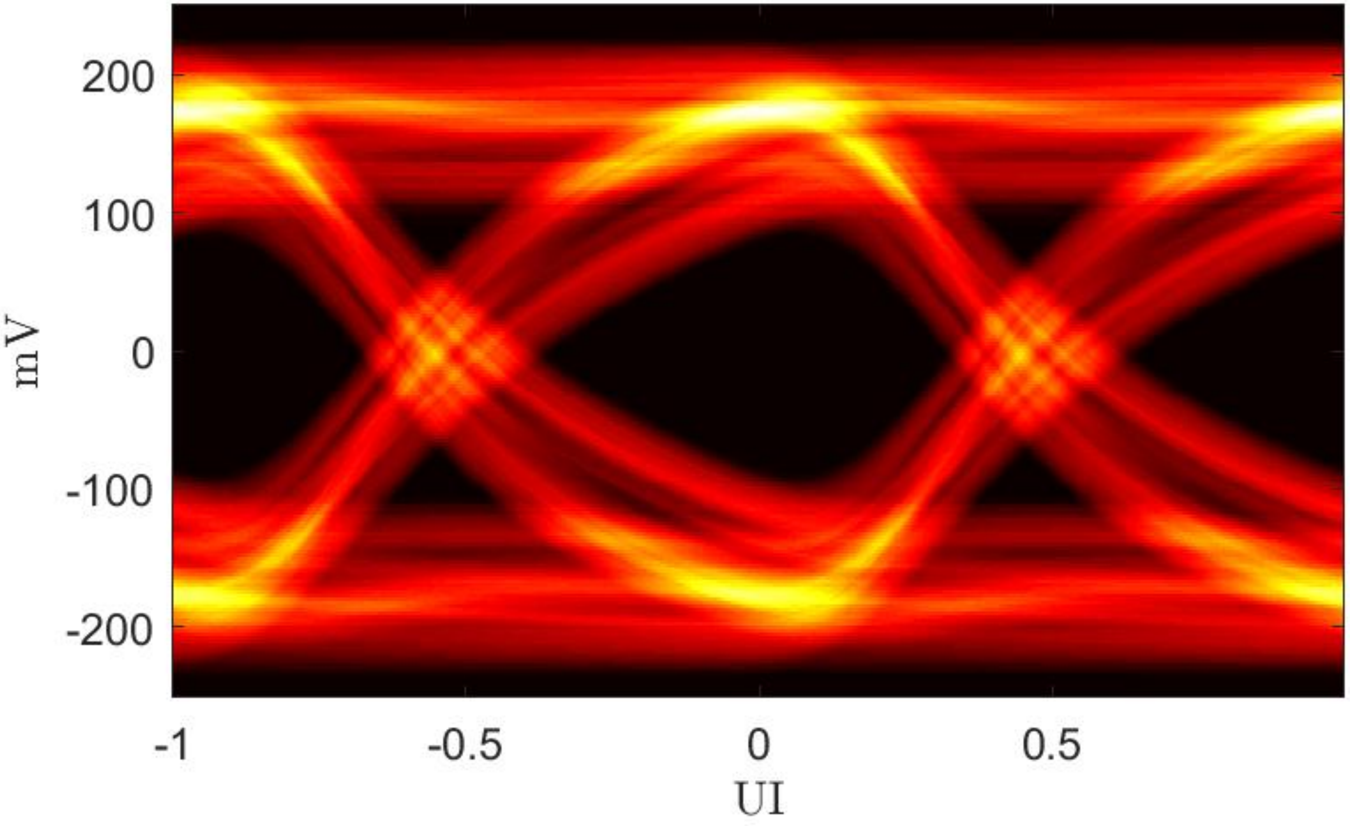
Results: application to a real data link



Residual nonlinearity error

Results: eye pattern

Received voltage, 1e6 PRBS-31 pattern



- **1e6 PRBS-31 pattern**
- **CPU time <30 s**
  (Matlab, *not optim.*)

Conclusions

- Novel model structure for differential drivers with pre-emphasis
  - Includes common-mode
  - Includes analog effects of TX-FFE HW implementation (slow transients)
  - Based on hierarchical decomposition of switching signals
  - Tradeoff between accuracy and complexity
  - Fully linear
- Proposed enhancement of IBIS-AMI framework
  - Proposed model fits naturally into IBIS-AMI framework
  - Enables fast waveform simulation and eye diagram construction