Equalizer Modeling for IBIS-AMI

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Introduction to High-Definition Multimedia Interface (HDMI)

Version	Year	Transmission bandwidth
HDMI 2.0	2013	6 Gbps/channel X 3 channels
HDMI 2.1	2018	12 Gbps/channel X 4 channels

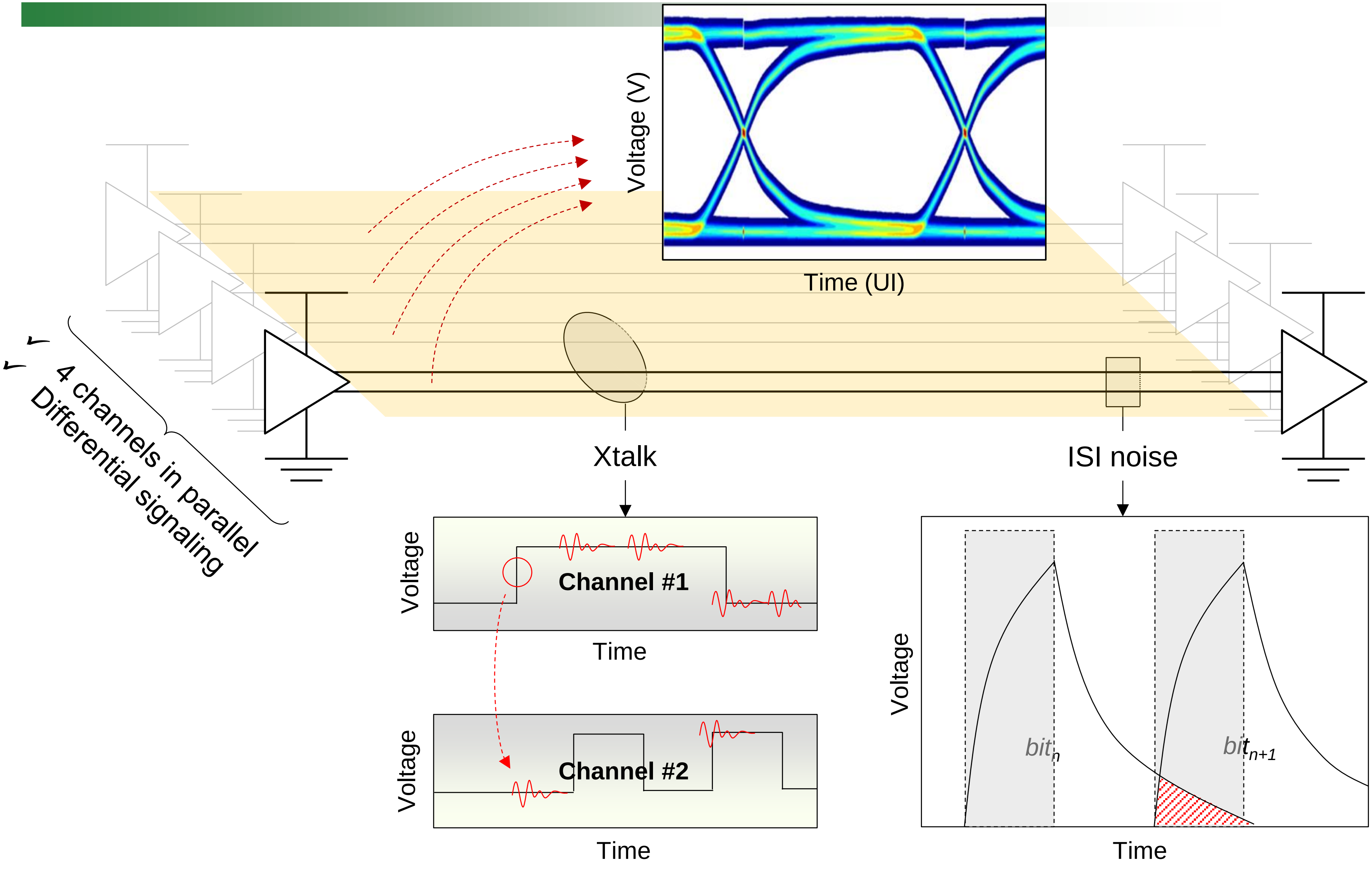
HDMI
HIGH-DEFINITION MULTIMEDIA INTERFACE

Digital image

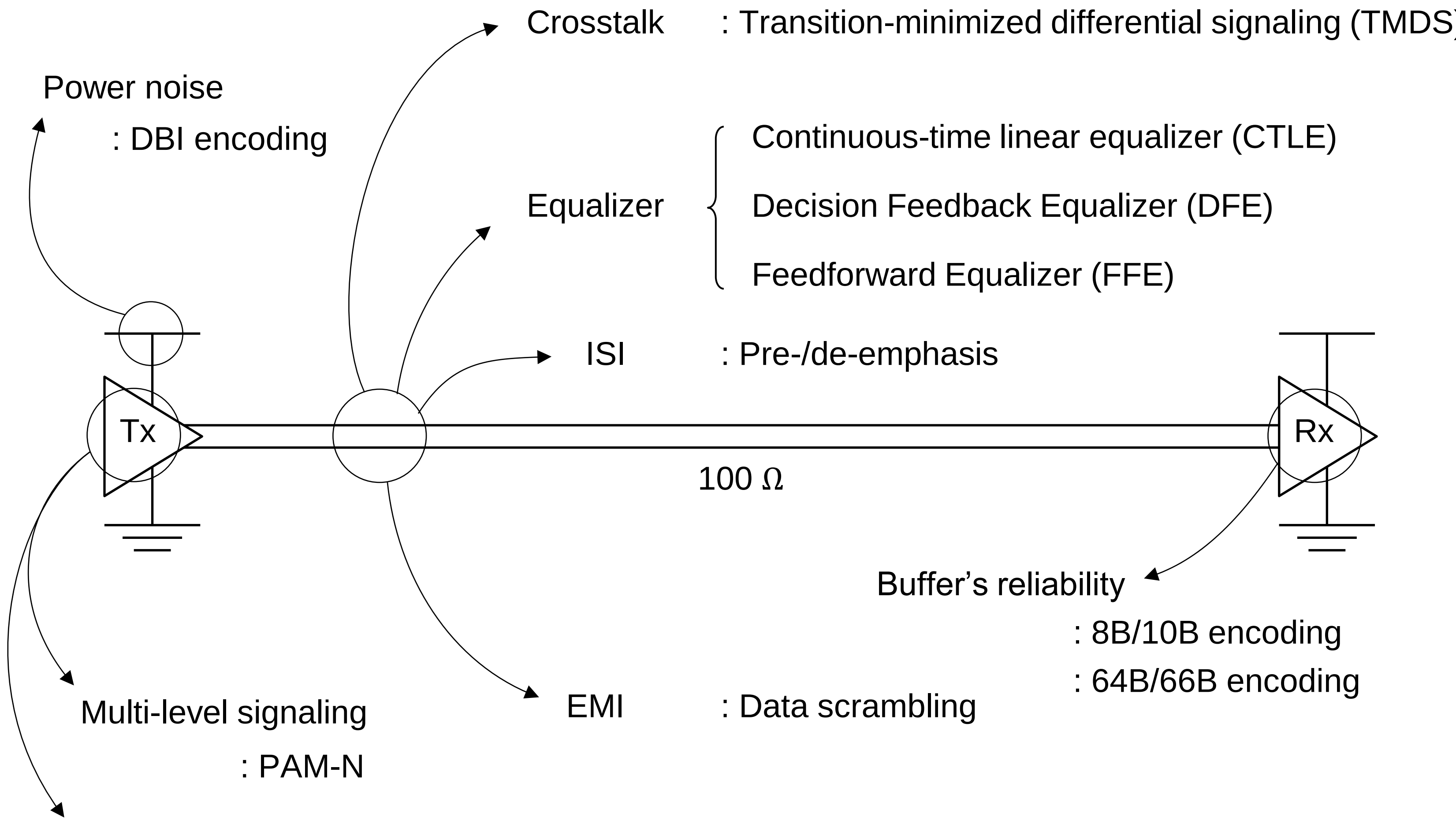
- HDMI is provided for transmitting digital television audiovisual signals from DVD players, set-top boxes and other audiovisual sources to television sets, projectors and other video displays

Ref] *"HDMI Licensing, LLC Releases HDMI Specification Version 1.4" HDMI.org. HDMI Licensing, LLC. Retrieved August 25, 2017.*

Signal Integrity (SI) Issues on HDMI Channels and eye diagram



What is the Signal Integrity at System-level ?



Signal level

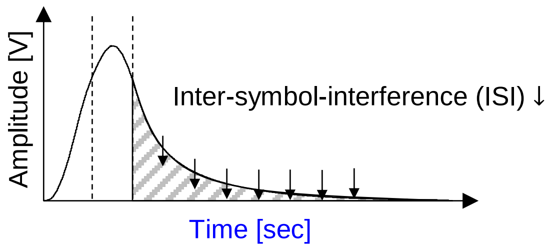
Data level

Error-correction code: BCH, RS code

Introduction to an Equalizer

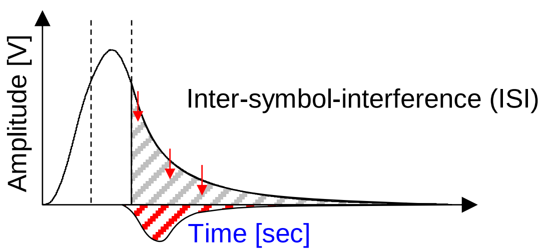
- Definition: A component makes the channel have the same performance

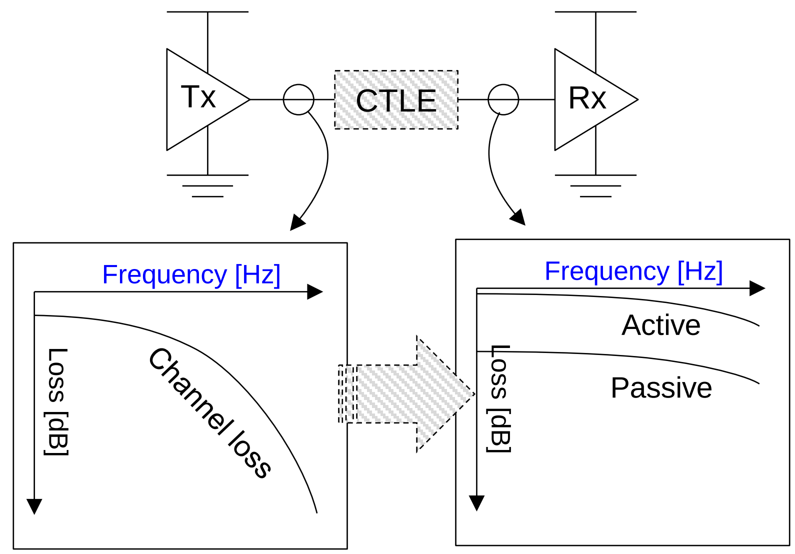
··· in **time** domain	··· in **frequency** domain
✓ **Feedback equalizer** • Decision feedback equalizer (DFE) • Feedforward equalizer (FFE)	✓ **Continuous time linear equalizer (CTLE)** • Active equalizer • Passive equalizer



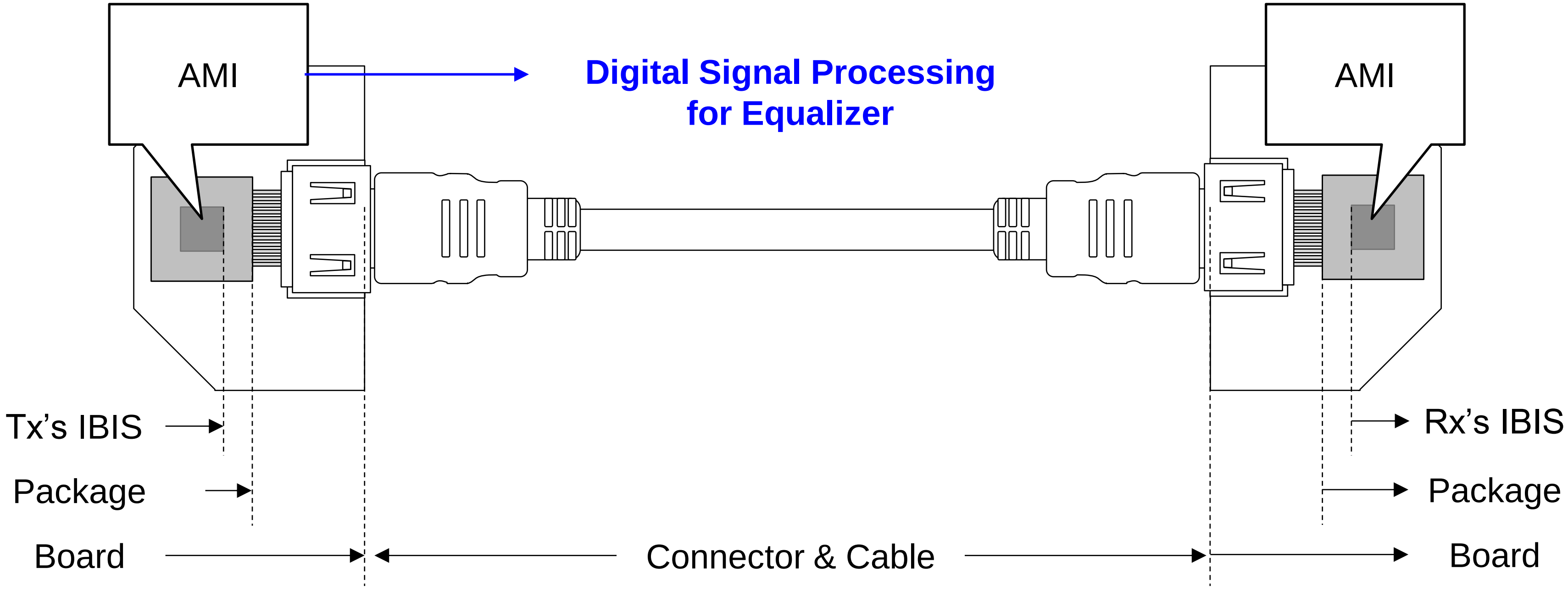
✓ **Emphasis**

- Pre-emphasis
- De-emphasis



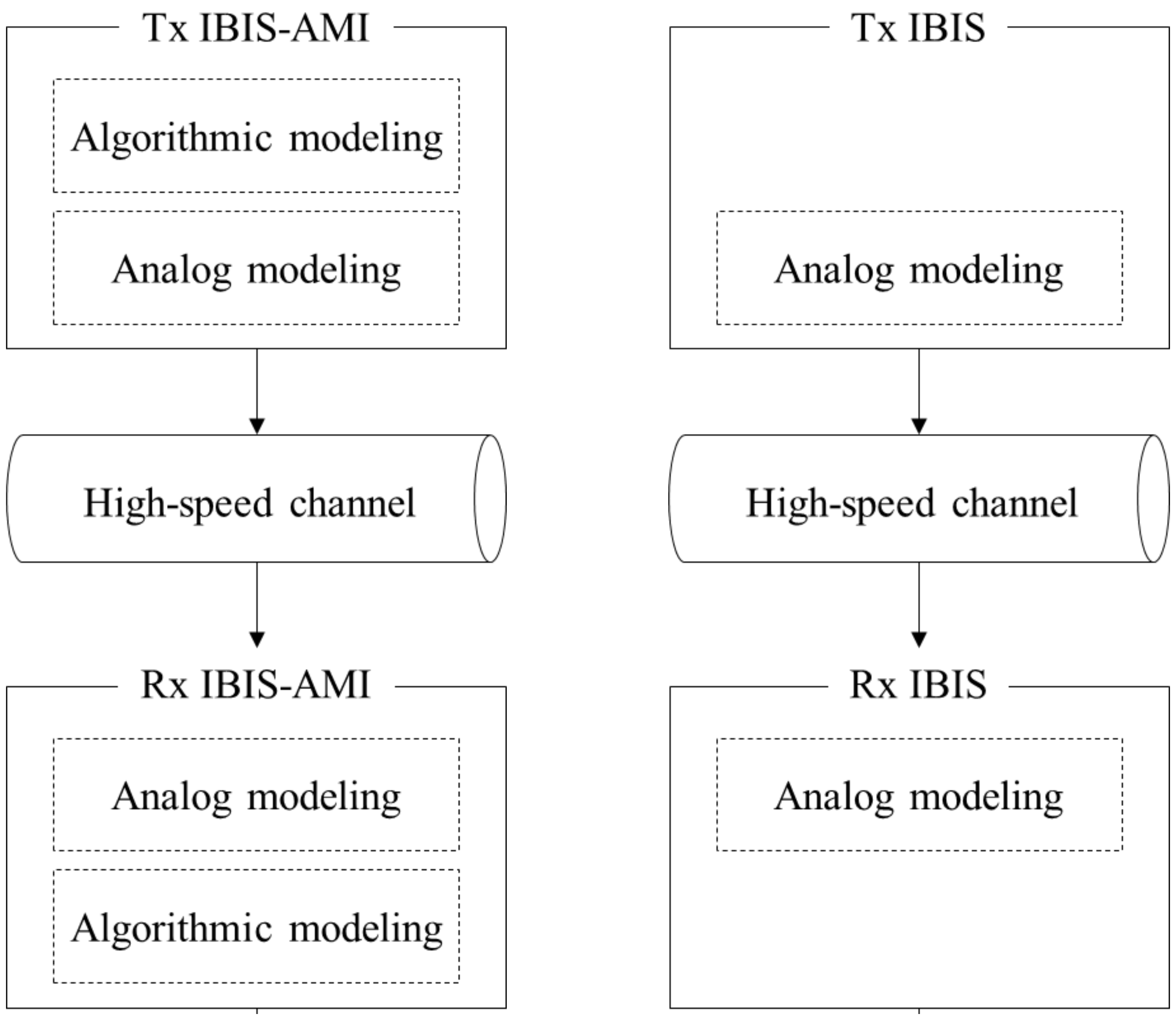


IBIS Algorithmic Modeling Interface (IBIS-AMI)



- IBIS-AMI provides not only the analog model but also the digital signal processing (DSP) for the equalizer

Comparison between IBIS and IBIS-AMI



Equations for the Frequency-domain Equalizer: CTLE

- The received waveform when S21 is given:

$$r(t) = \mathcal{F}^{-1}[\mathcal{F}\{p(t)\} \times \mathrm{S}_{21}(f)]$$

- The insertion loss (S_{21}) of the equalized channel by a CTLE:

$$\mathrm{S}_{21,\mathrm{eq\_ch}}(f) = \left[\left\{S_{21,ch}(f)\right\}_{S\to T} \times \left\{S_{21,eq}(f)\right\}_{S\to T}\right]_{T\to S}$$

- the received pulse for the equalized channel by the CTLE:

$$r_{eq\_CTLE}(t) = \mathcal{F}^{-1}\left[\mathcal{F}\{p(t)\} \times \mathrm{S}_{21,\mathrm{eq\_ch}}(f)\right]$$

Equations for the Time-domain Equalizers

- A **DFE** can be expressed with the following equation:

$$r_{e,i}(t) = r_i(t) \times \{1 - e_i\}$$

, where $r_{e,i}$ (t) is the i-th interval of the equalized SBR

- If $p(t)$ denotes the pulse to be transmitted, the behavior of the **pre-emphasis** is expressed with following equations:

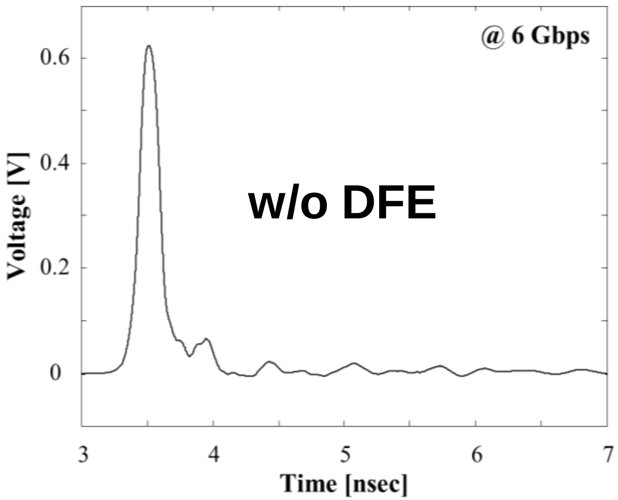
$$p_{pre}(t) = p(t) + \alpha \times p(\beta t)$$

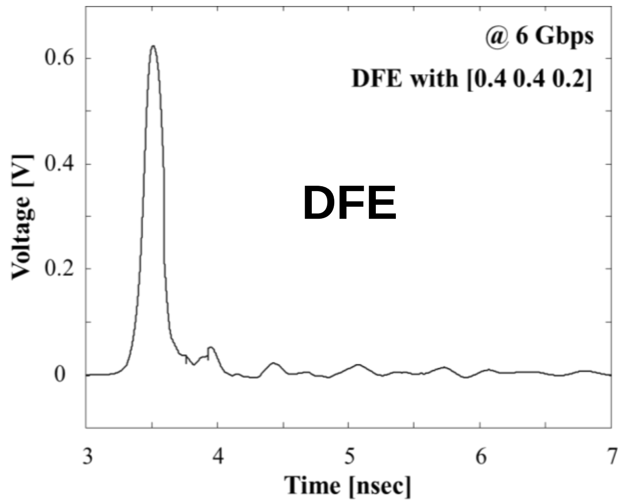
, where α, β denote the weight factor for the amplitude and time

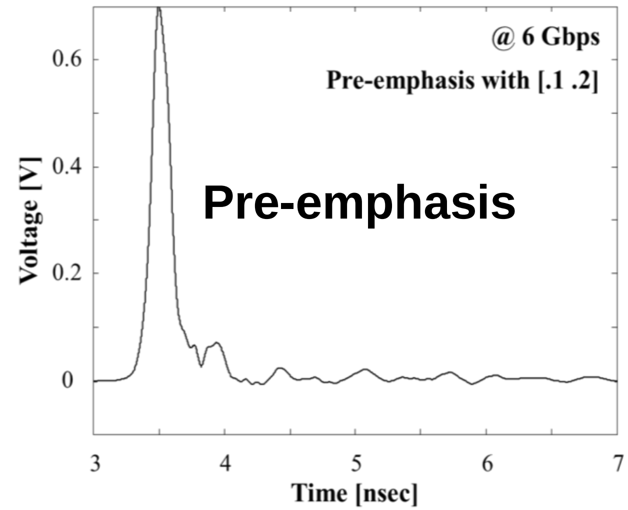
- A **de-emphasis** behavior can be expressed in form of following equation:

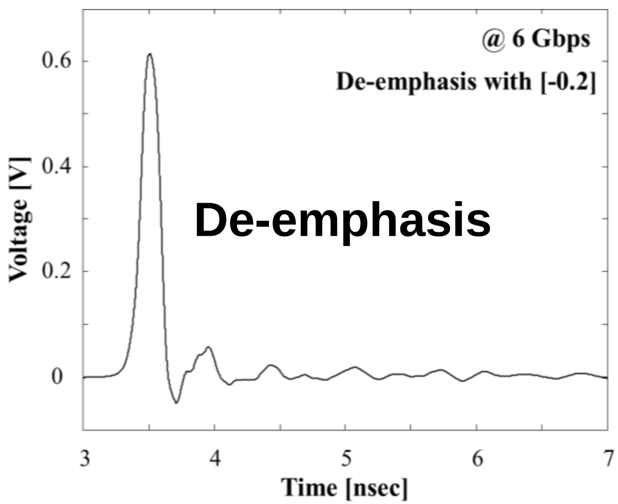
$$p_{de}(t) = p(t) - \alpha \times p(\beta t - T)$$

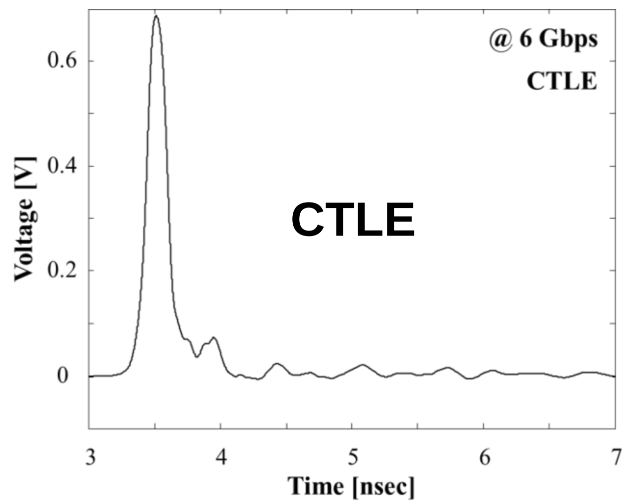
Equalized Single Bit Responses



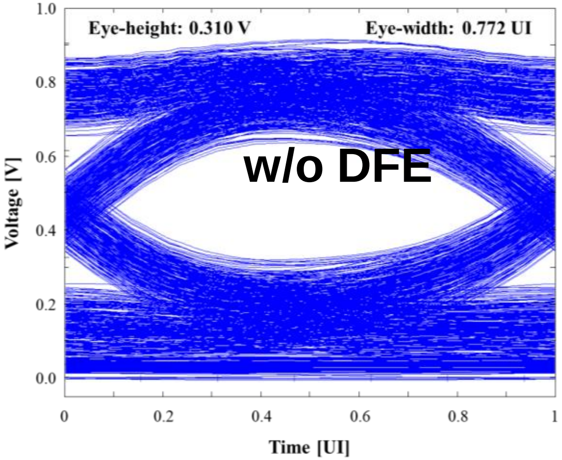


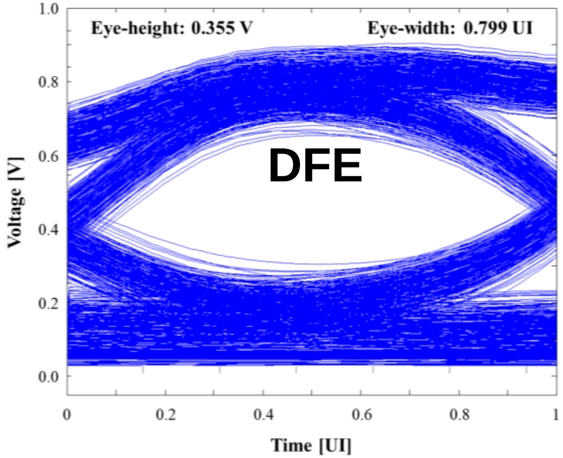


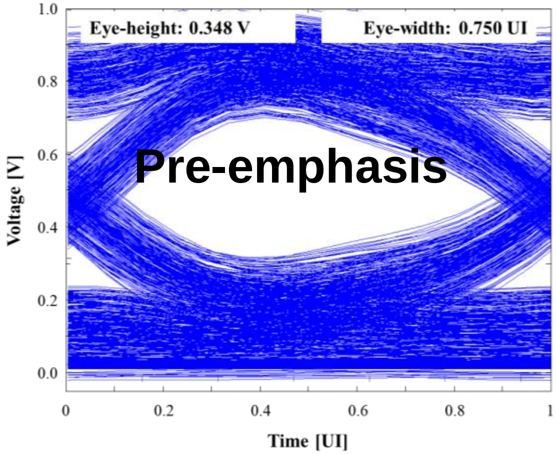


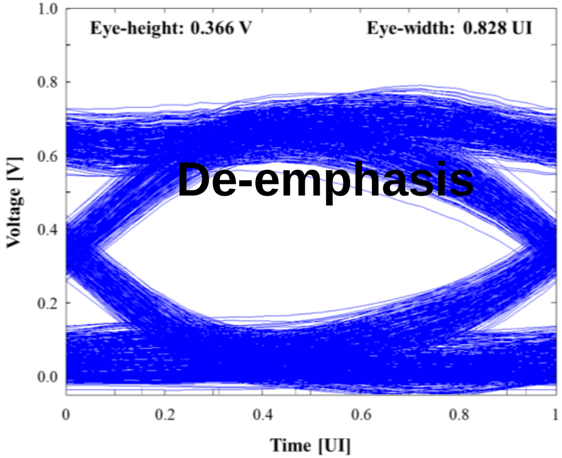


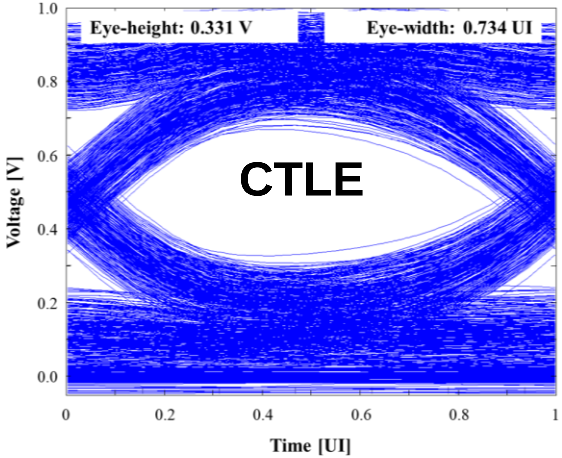
Transient Simulation with Equalizers



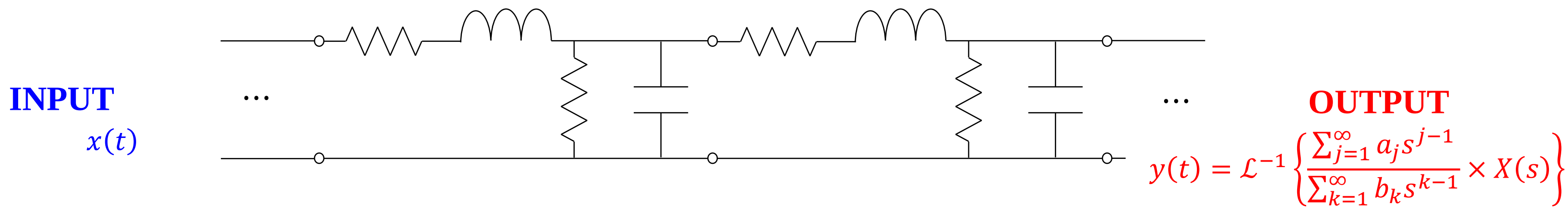




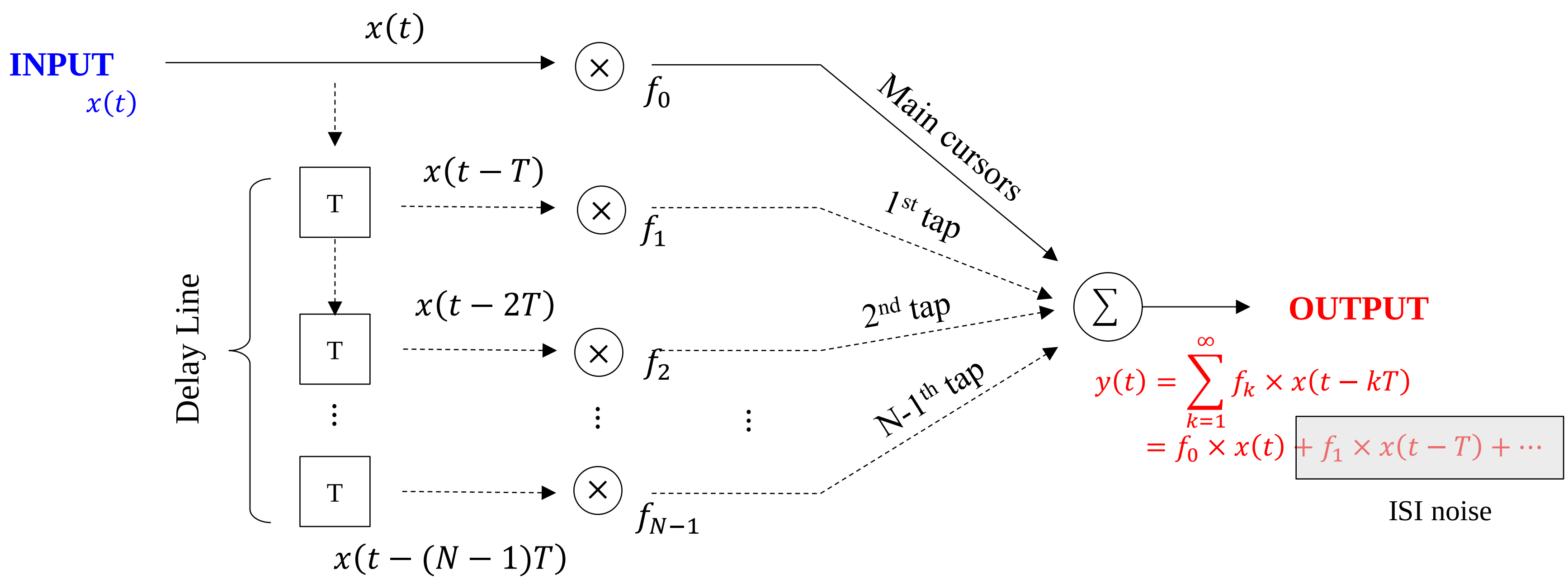




Channels' Another Expression: Finite Impulse Response (FIR) Filter

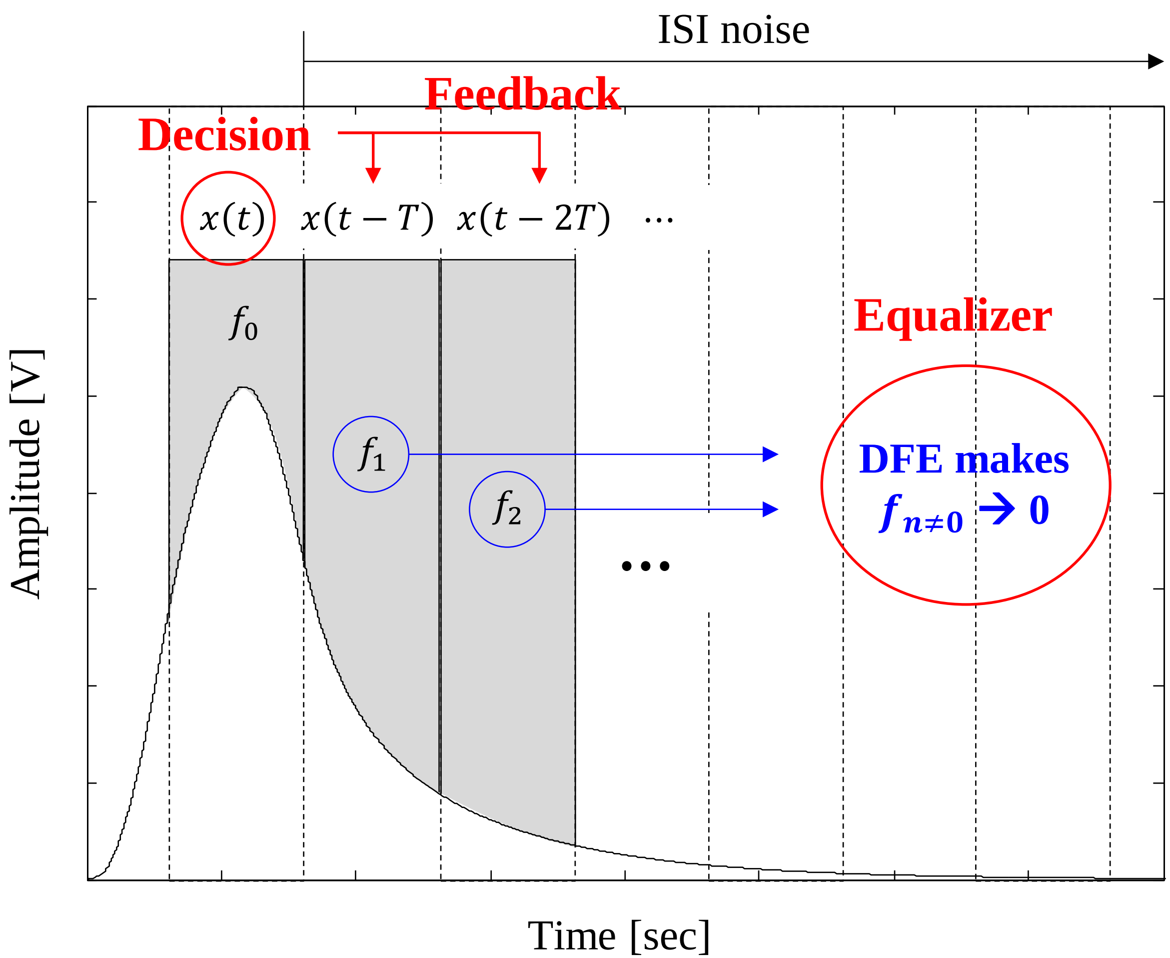


< RLCG model >



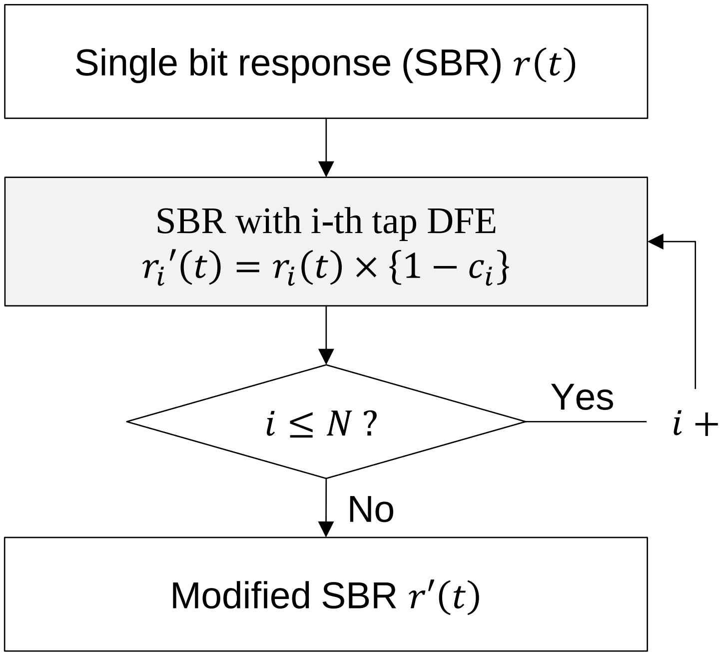
< FIR filter >

FIR Filter Expression and DFE in Time Domain

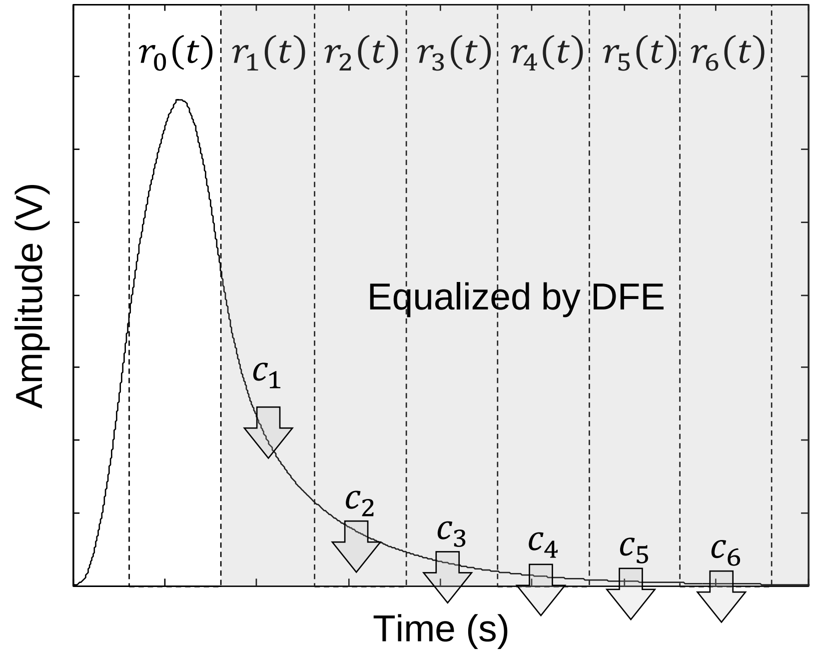


- DFE equalizes the ISI noise for the next bits

Behavior Model for DFE



< Behavior model >



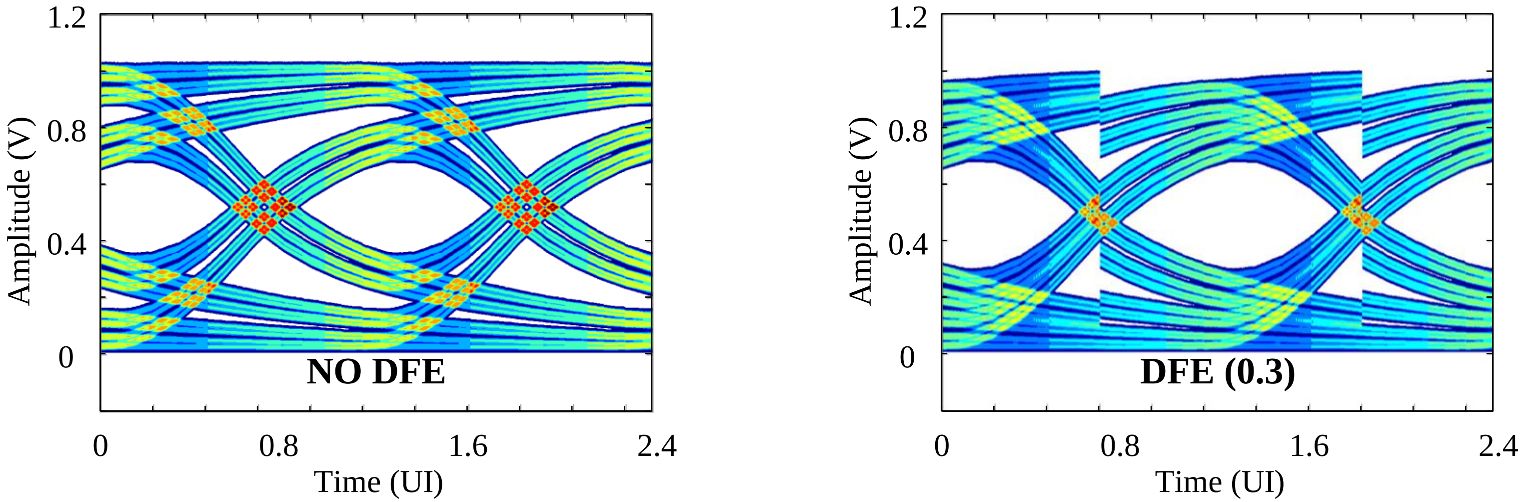
< Equalized SBR >

- Equalizing ISI noise

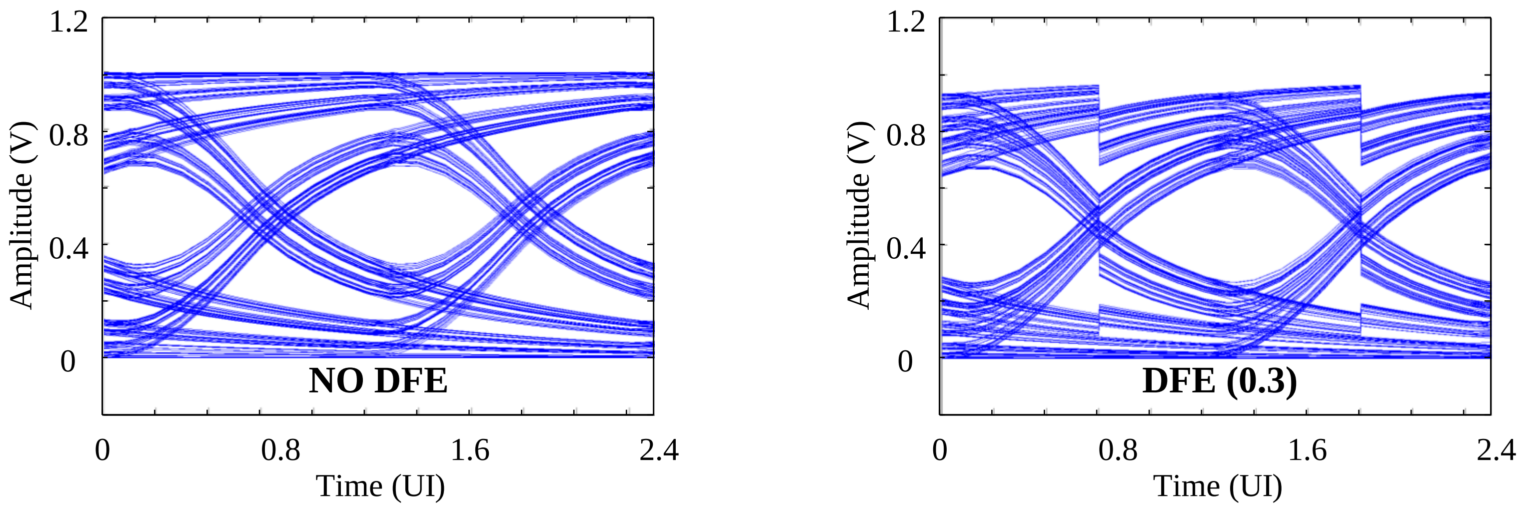
$$r_i'(t) = r_i(t) \times \{1 - c_i\} = r_i(t) - c_i \times r_i(t)$$

When $\vec{C} = \vec{\mathbf{0}}$, the DFE would be disabled

Experimental Verification for N-tap DFE



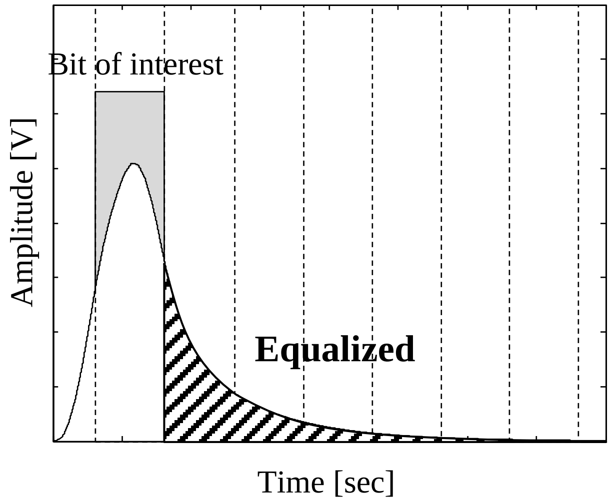
< Statistical eye diagram >

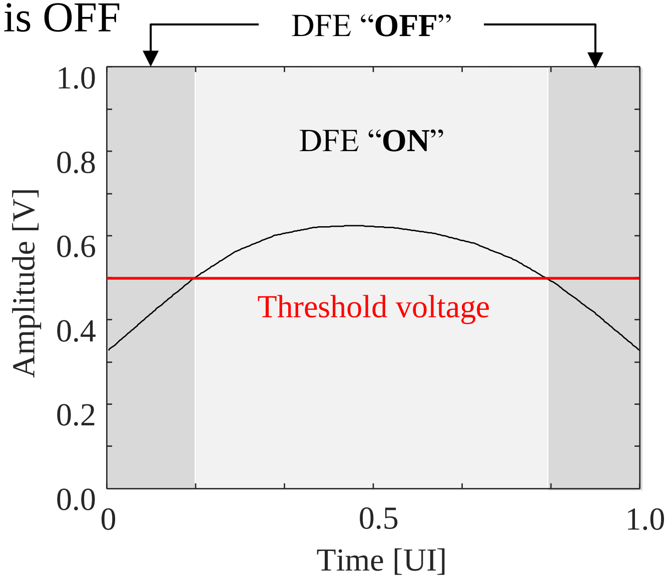


< Transient simulation >

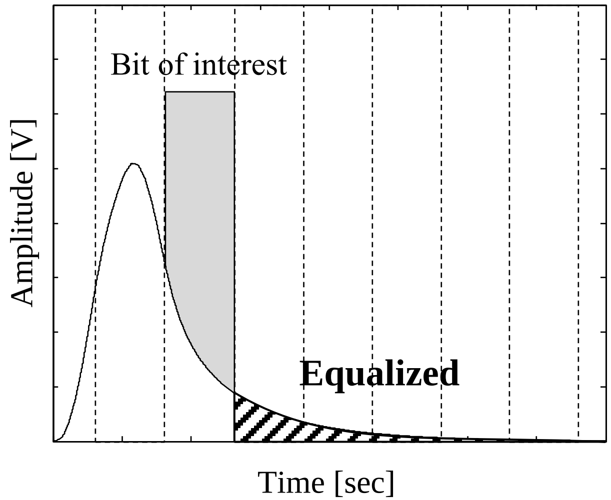
DFE's Wrong Cases Depending on Threshold Voltage

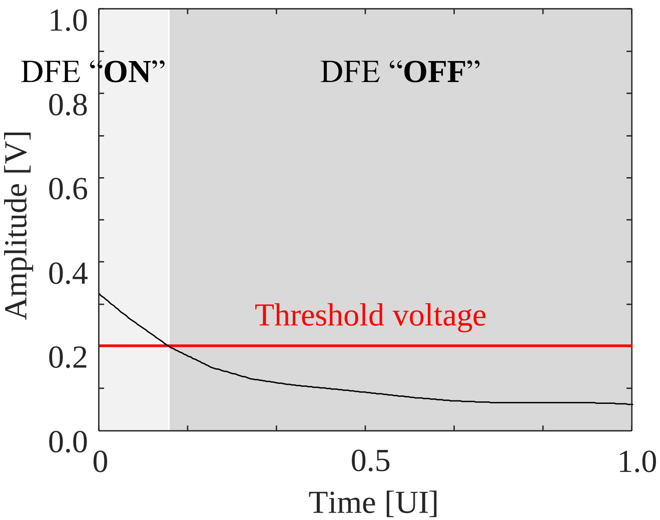
- Case #1: Although the received bit 1, the DFE is OFF



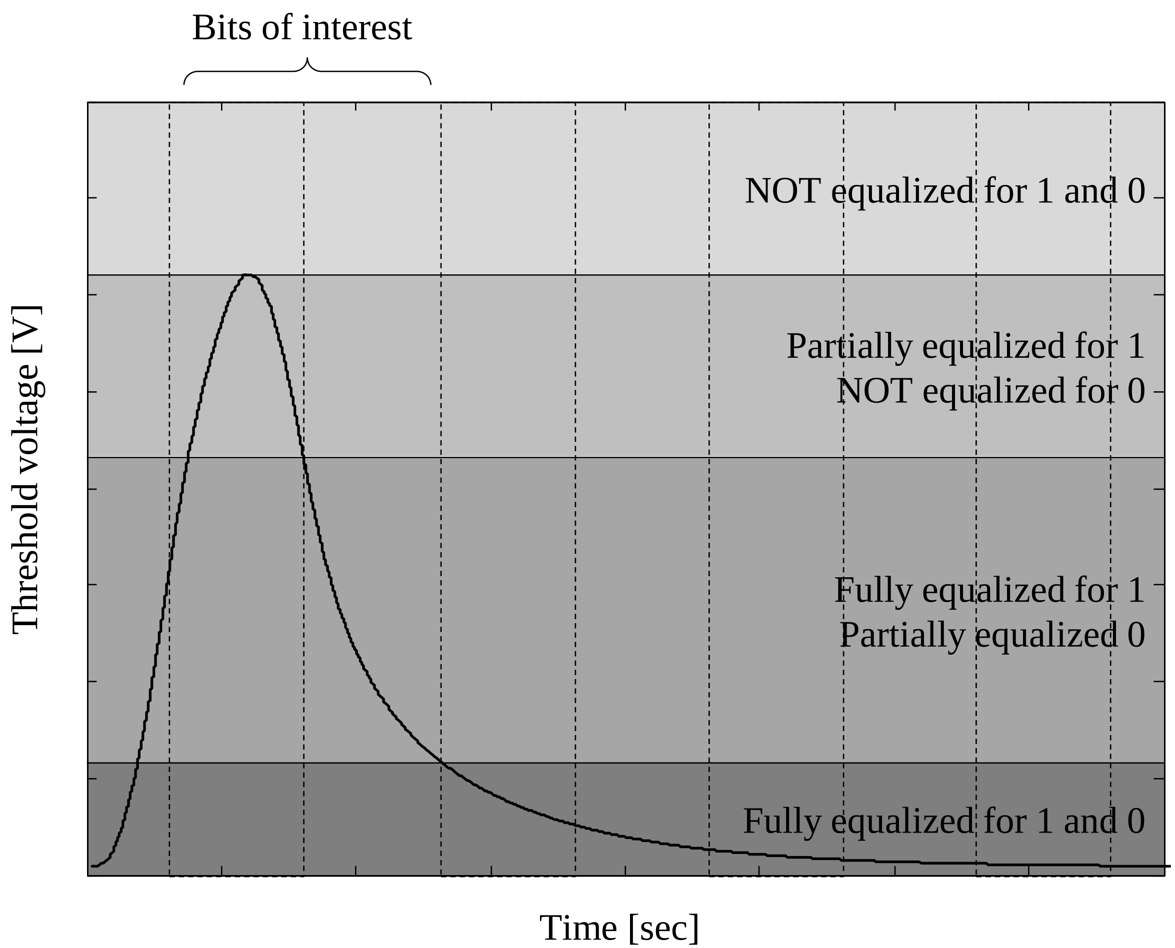


- Case #2: Although the received bit is 0, the DFE is ON





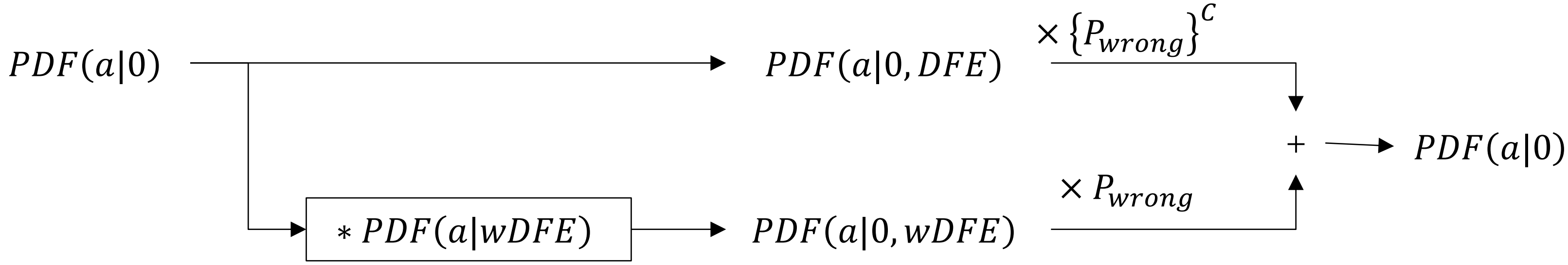
DFE's Behavior Depending on Threshold Voltage



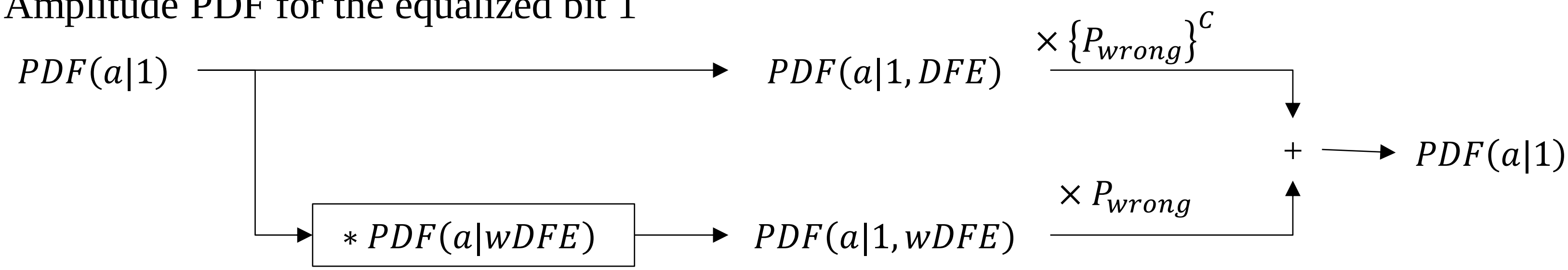
- The threshold voltage determines the DFE's behavior

Overall Procedure to Predict eye diagram Including non-ideal DFE

- Amplitude PDF for the equalized bit 0



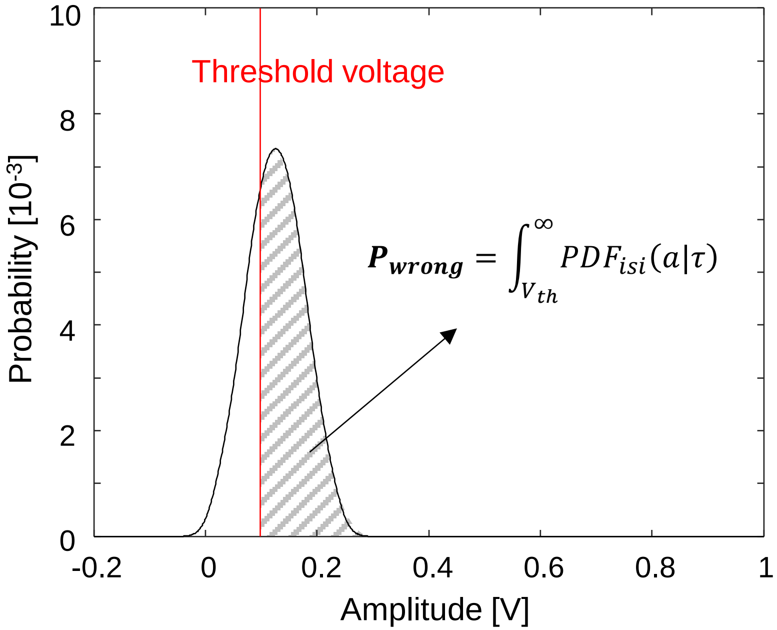
- Amplitude PDF for the equalized bit 1



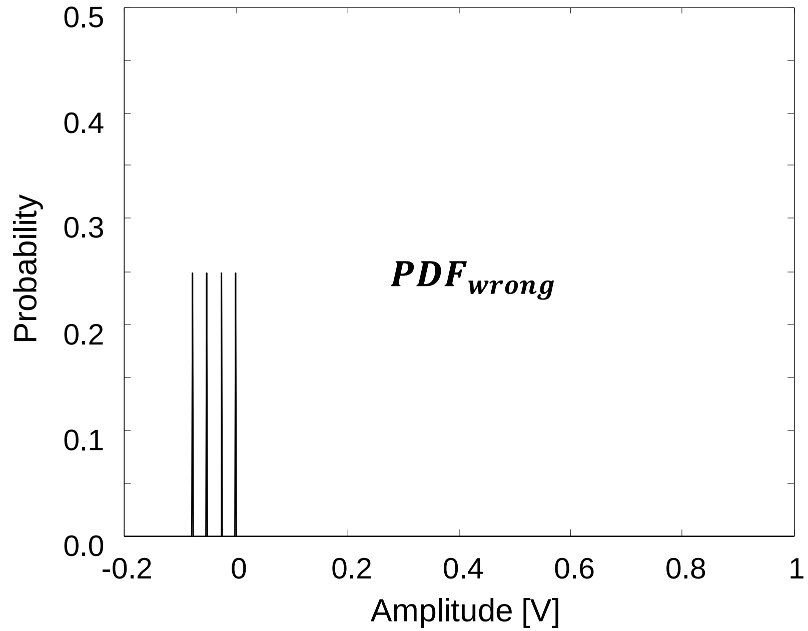
- Amplitude PDF for the equalized bit at sampling time τ

$$\{P(0) \cdot PDF(a|0)' + P(1) \cdot PDF(a|1)'\}|\tau$$

Amplitude PDF when the DFE Makes Wrong Decision



< Amplitude PDF for 0 bit >



< Amplitude PDF by wrong decision >

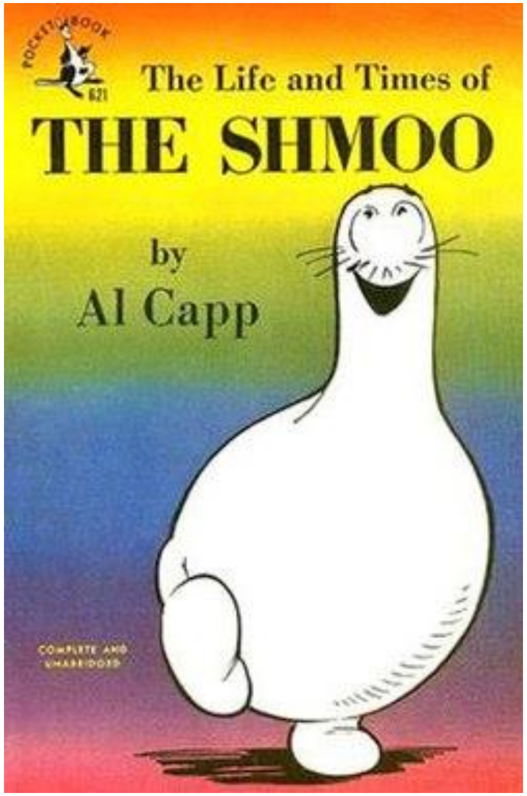
Probability of wrong decision

Effect on amplitude by wrong DFE

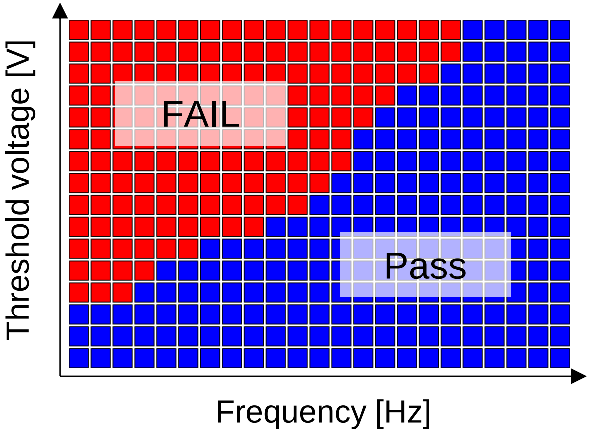
- With above PDFs, the DFE is defined within the statistical eye diagram

Application: Shmoo Plot for Semiconductor Test

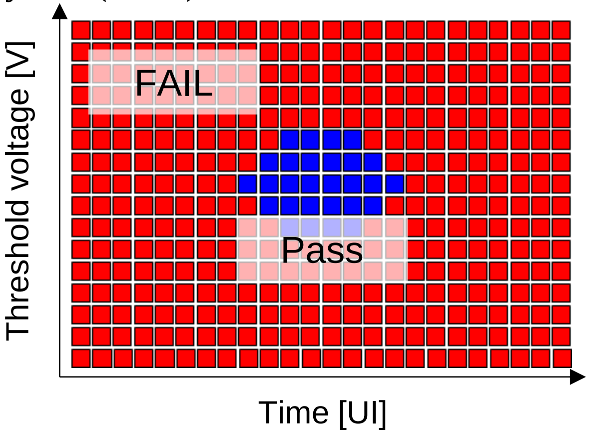
- Origin: from animation



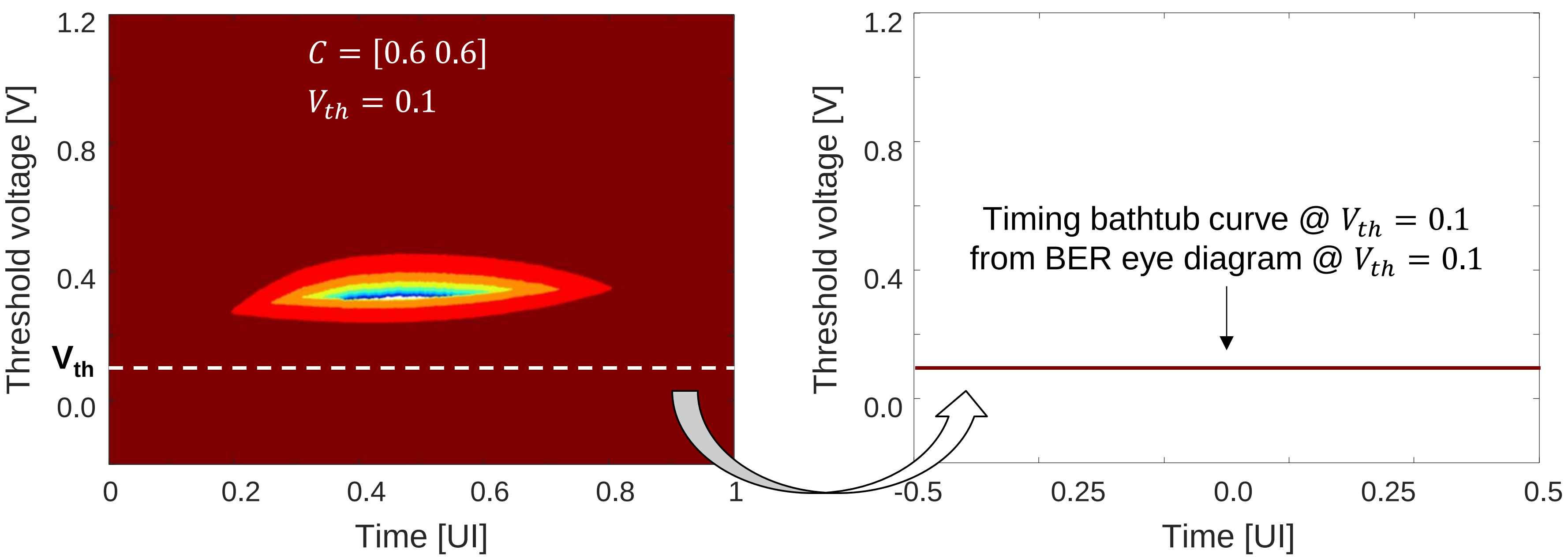
- Definition: semiconductor performance evaluation depending on operating condition
  - ✓ General test



  - ✓ Memory test (DDR)



Conversion From BER eye diagram to Shmoo Plot



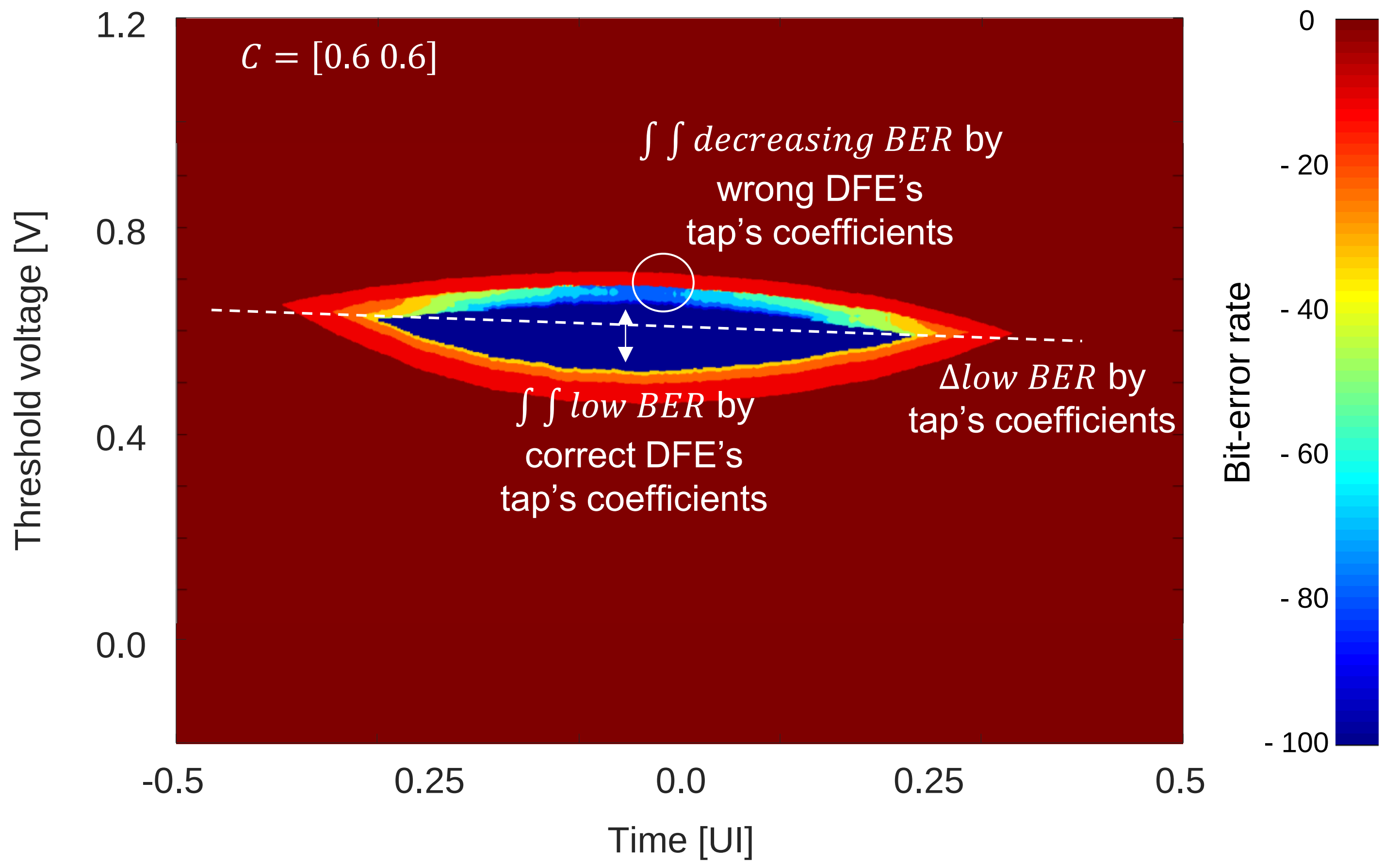
< BER eye diagram @ $V_{th} = 0.1$ >

< Shmoo plot under acquisition @ $V_{th} = 0.1$ >

- Shmoo plot is the set of the timing bathtub curves depending on the threshold voltage

$$\bigcup_{\upsilon=-0.2}^{1.2} BER(\tau|\upsilon)$$

Analysis on Statistical Shmoo Plot with nonideal DFE



- The obtained shmoo plot is determined by the following:

  Channel performance (S_{21}), functioning DFE, malfunctioning DFE

Thank you

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