DFE Adaptation Method for PCIe® 8GT/s Testing

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Disclaimer

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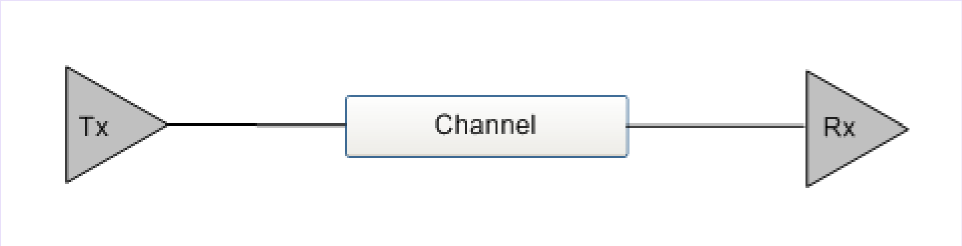
Content

- PCIe 8GT/s data link.
- DFE adaption requirements.
- An explicit solution for DFE adaptation.
- Compare peak to peak based and LMS based adaptation methods for 1-tap DFE.
- CTLE, FFE and DFE.
- Interaction between CTLE and DFE.

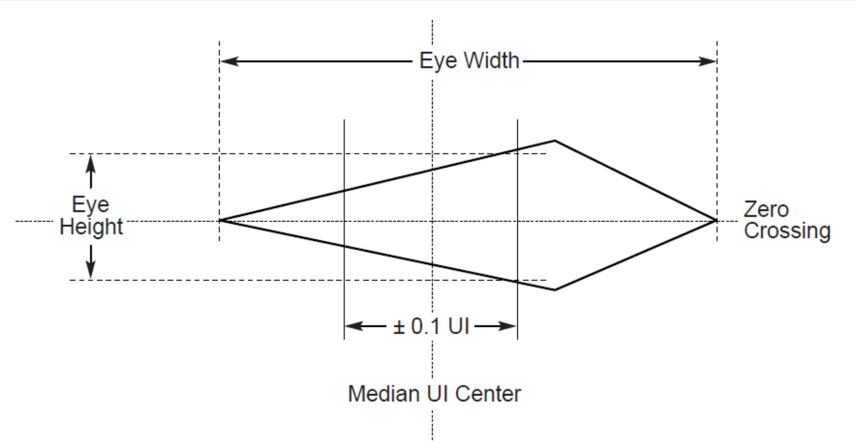
PCIe 8GT/s Data Link

- Tx: 3 tap FFE.
- Channel: compliance channel. S parameter.
- Rx: CTLE and DFE.
  - ✓ CTLE: 2 poles and 1 zero.
  - ✓ DFE: 1 tap



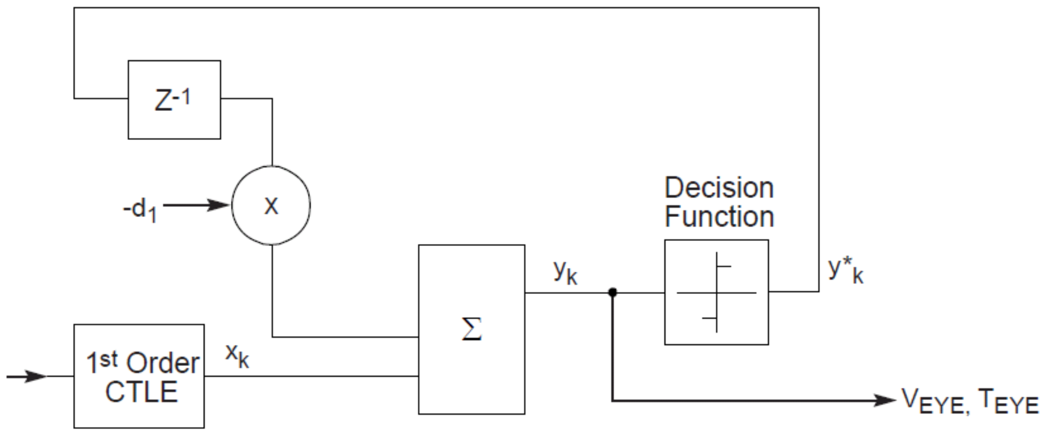
DFE Optimization Criteria

- Eye area is defined as horizontal eye opening times vertical eye opening. It is a peak to peak value.



DFE Adaptation Requirements

- Optimize tap within [-30mV, 30mV] to maximize eye opening area.



$y_k = x_k - d_1 \mathrm{sgn}(y_{k-1})$

y_k = DFE summer differential output voltage.

y^*_k = decision function output voltage. $|y^*_k| = 1$

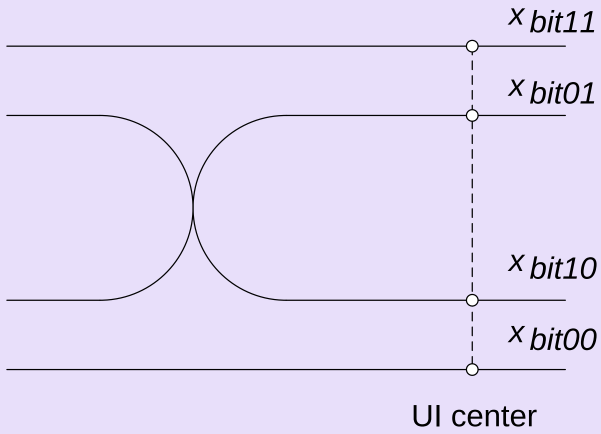
x_k = DFE differential input voltage

d_1 = feedback coefficient

k = sample index in UI

DFE Adaptation Derivation - 1

- Single tap DFE looks at one previous bit.



$$y_k = x_k - d_1 sgn(y_{k-1})$$

DFE Adaptation Derivation - 2

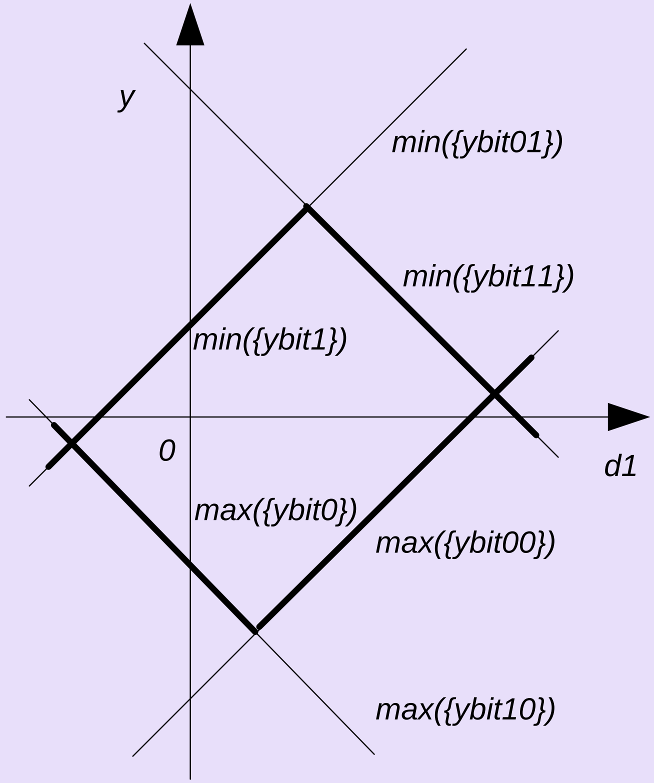
- Vertical eye height as peak to peak.

$$
\begin{aligned}
V_{eye} &= \min(\{y_{bit\,1}\}) - \max(\{y_{bit\,0}\}) \\
&= \min(\{y_{bit\,11}\}, \{y_{bit\,01}\}) - \max(\{y_{bit\,10}\}, \{y_{bit\,00}\}) \\
&= \min(\min(\{y_{bit\,11}\}), \min(\{y_{bit\,01}\})) - \max(\max(\{y_{bit\,10}\}), \max(\{y_{bit\,00}\}))
\end{aligned}
$$

$$
\begin{aligned}
\min(\{y_{bit\,11}\}) &= \min(\{x_{bit\,11}\} - d_1) = \min(\{x_{bit\,11}\}) - d_1 = x_{bit\,11}^{min} - d_1 \\
\min(\{y_{bit\,01}\}) &= \min(\{x_{bit\,01}\} + d_1) = \min(\{x_{bit\,01}\}) + d_1 = x_{bit\,01}^{min} + d_1 \\
\max(\{y_{bit\,10}\}) &= \max(\{x_{bit\,10}\} - d_1) = \max(\{x_{bit\,10}\}) - d_1 = x_{bit\,10}^{max} - d_1 \\
\max(\{y_{bit\,00}\}) &= \max(\{x_{bit\,00}\} + d_1) = \max(\{x_{bit\,00}\}) + d_1 = x_{bit\,00}^{max} + d_1
\end{aligned}
$$

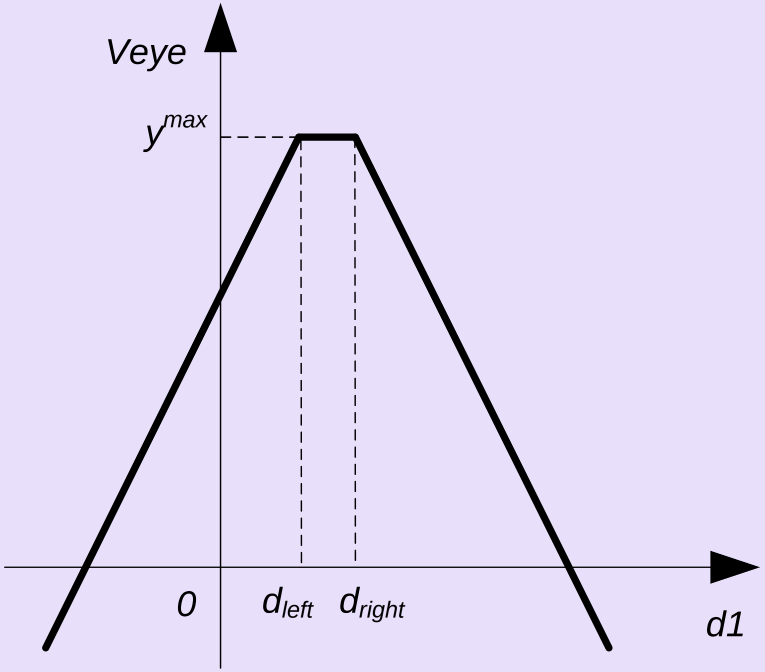
DFE Adaptation Derivation - 3

- Min/max of eye bit pattern as a function of DFE tap value.



DFE Adaptation Derivation - 4

- Vertical eye opening as a function of DFE tap value.
- For adaptation, and for predicting.



DFE Adaptation Solution

- Vertical eye opening as a function of DFE tap value.

$$V_{eye} = \min(\{y_{bit\,1}\}) - \max(\{y_{bit\,0}\}) = \begin{cases} y^{max} + 2(d_1 - d_{left}), & d_1 < d_{left} \\ y^{max}, & d_{left} \le d_1 \le d_{right} \\ y^{max} + 2(d_{right} - d_1), & d_1 > d_{right} \end{cases}$$

$$\begin{aligned} d_{left} &= \min\left(0.5(x_{bit\,11}^{min} - x_{bit\,01}^{min}), \quad 0.5(x_{bit\,10}^{max} - x_{bit\,00}^{max})\right) \\ d_{right} &= \max\left(0.5(x_{bit\,11}^{min} - x_{bit\,01}^{min}), \quad 0.5(x_{bit\,10}^{max} - x_{bit\,00}^{max})\right) \\ y^{max} &= 0.5(x_{bit\,11}^{min} + x_{bit\,01}^{min} - x_{bit\,10}^{max} - x_{bit\,00}^{max}) - (d_{right} - d_{left}) \end{aligned}$$

Example

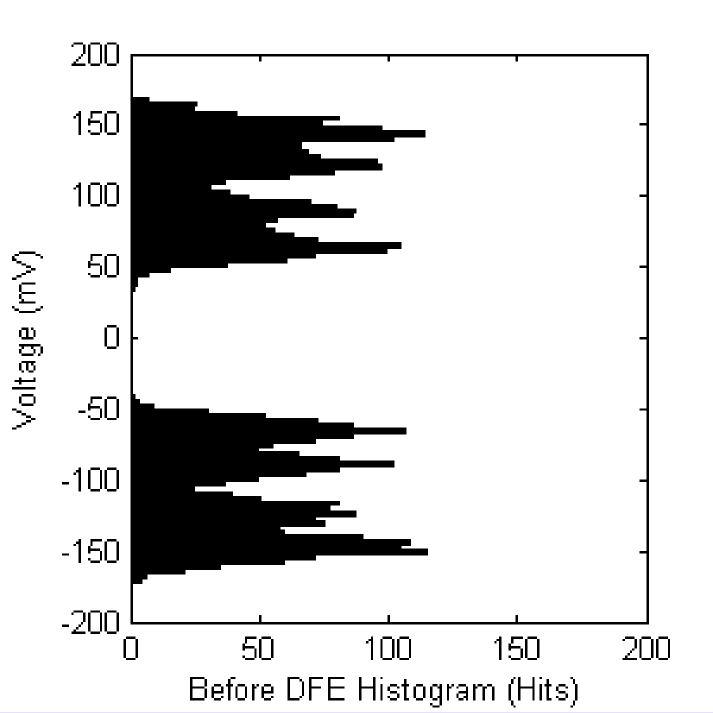
- Vertical histogram at eye center.

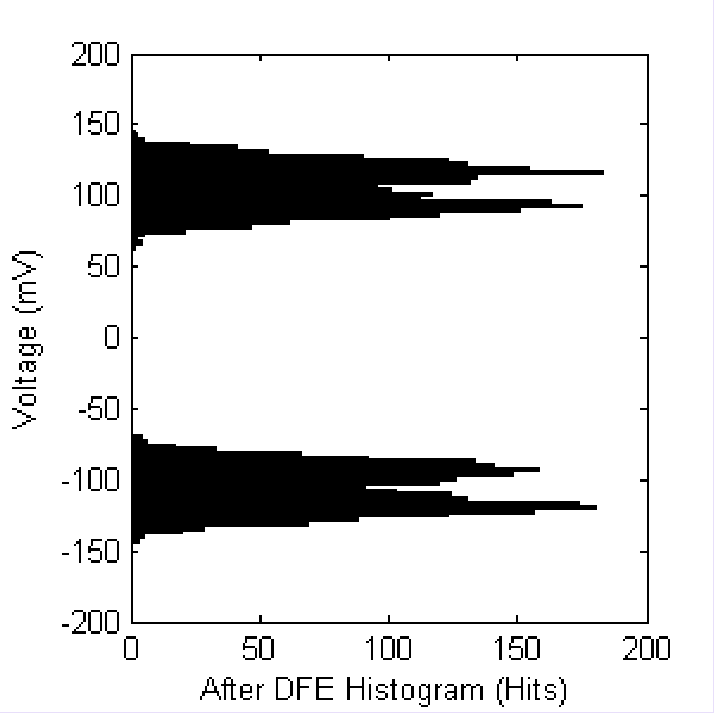
$$x_{bit\,11}^{min} = 96.4\text{mV}$$
$$x_{bit\,01}^{min} = 34.3\text{mV}$$
$$x_{bit\,10}^{max} = -41.5\text{mV}$$
$$x_{bit\,00}^{max} = -99.7\text{mV}$$

V_{eye} = 134.0mV (With DFE)

V_{eye} = 75.7mV (Without DFE)

d_1 can be any value at [29.1mV, 30mV]





DFE LMS Criteria

- Optimization based on Least Mean Squared criteria.

$$LMS = \sum\left(y_{bit\,1} - y_{bit\,1}^{mean}\right)^2 + \sum\left(y_{bit\,0} - y_{bit\,0}^{mean}\right)^2$$

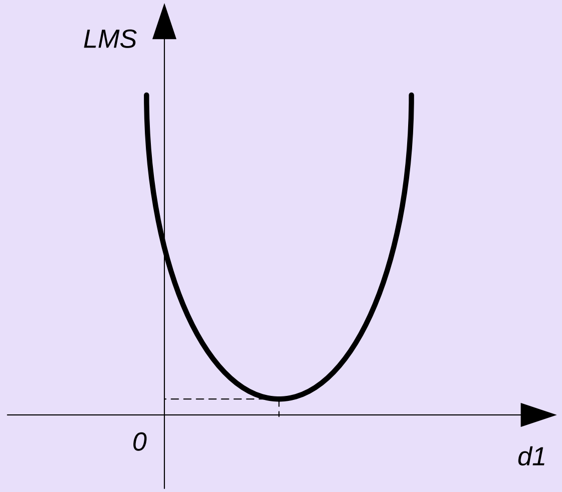
$$= \sum\left(y_{bit\,11} - y_{bit\,1}^{mean}\right)^2 + \sum\left(y_{bit\,01} - y_{bit\,1}^{mean}\right)^2 + \sum\left(y_{bit\,10} - y_{bit\,0}^{mean}\right)^2 + \sum\left(y_{bit\,00} - y_{bit\,0}^{mean}\right)^2$$

Note

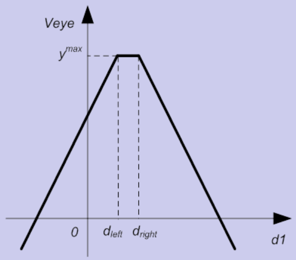
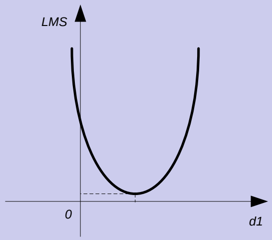
$$\sum(y_{bit\,11} - y_{bit\,1}^{mean})^2 = n \times \left(\left(y_{bit\,11}^{std}\right)^2 + (y_{bit\,11}^{mean} - y_{bit\,1}^{mean})^2\right) = n \times (\left(x_{bit\,11}^{std}\right)^2 + (x_{bit\,11}^{mean} - d_1 - y_{bit\,1}^{mean})^2)$$

DFE LMS Adaptation

- Assume four bit patterns get same amount of hits from the signal. For example, PRBS.
- Every term for each of the four bit patterns is a quadratic function, whose graph is parabola.
- What function is the sum of the four quadratic functions? Explicit solution?

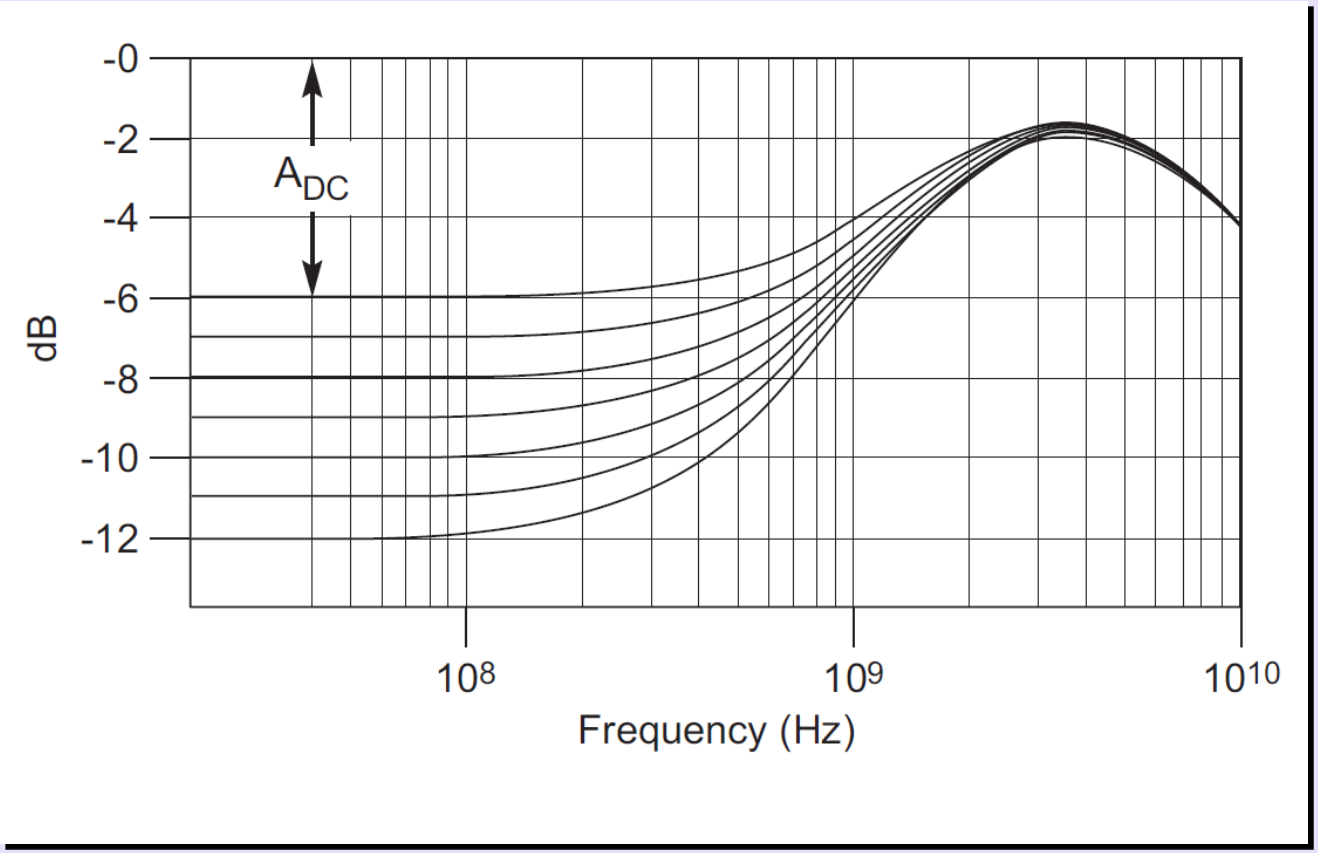


LMS vs. Peak to Peak

Criteria	Peak to Peak	LMS
Based statistics of bit patterns	Min, Max (Slide 10)	Mean (Slide 12)
Continuous	Yes	Yes
Derivative	No	Yes (Slide 12)
Optimal tap value	Range (Other criteria)	Single value
		

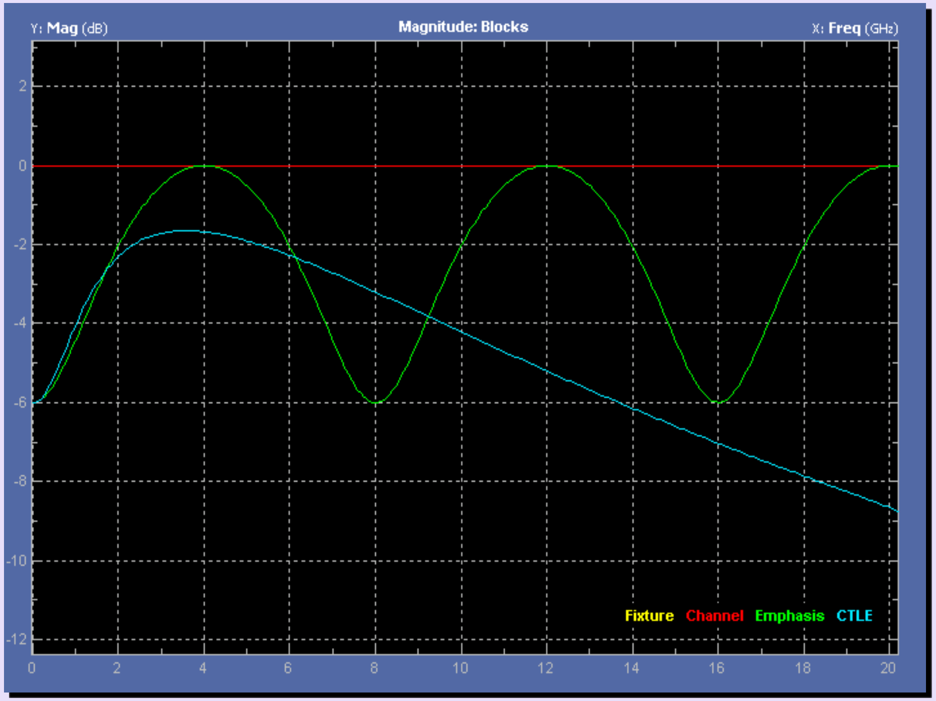
PCIe 8GT/s CTLE

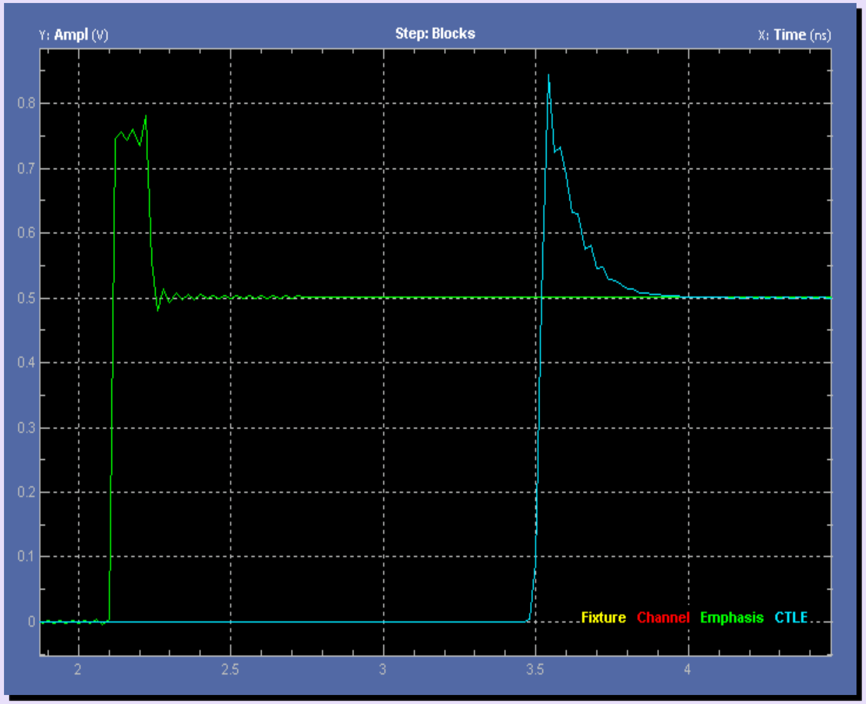
- Second order IIR.



CTLE vs. FFE

- CTLE operates on continuous time.
- FFE operates on discrete time. Observe the images in its frequency response.
- 6dB 2-tap FFE and CTLE responses are shown.





CTLE, FFE, DFE

Method	CTLE	FFE	DFE
Signal that the coefficients are applied to	Analog	Analog	Digital
Time	Continuous	Discrete	Discrete
Frequency response control	Infinite frequency	Nyquist	Non Linear
Impulse response	IIR	FIR	Non Linear

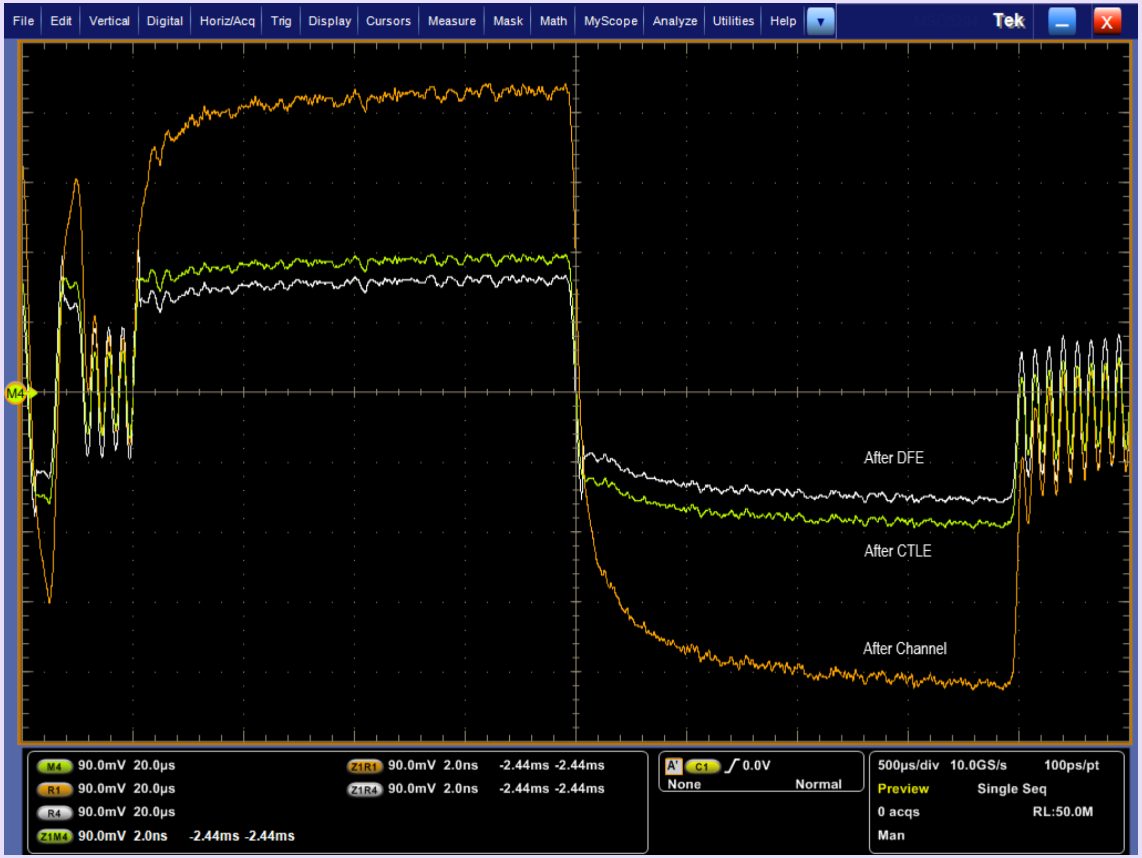
Interaction Between CTLE, DFE

- Numerical example.

CTLE(dB)	DFE Tap(mV)	Eye Area(UI*mV)	Eye Height(mV)	Eye Width(UI)
-6	30	49.66	88.4	0.56
-7***	29.79	63.21	101.94	0.62
-8	26.97	57.9	96.94	0.6
-9	22.88	48.72	86.43	0.56
-10	18.7	40.89	76.86	0.53
-11	12.3	32.73	68.49	0.48
-12	10.39	25.89	60.89	0.43

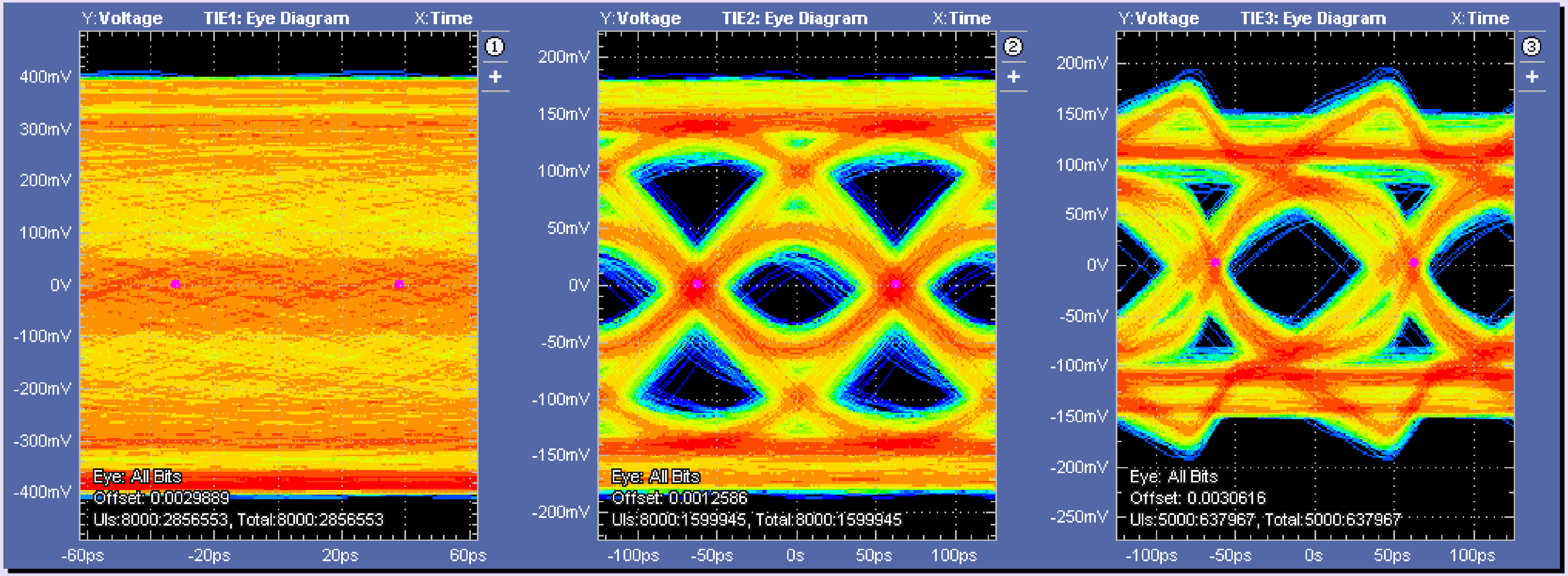
Waveforms – Example

- Waveform at end of channel, waveform after 7dB CTLE and waveform after DFE.



Eye Diagrams – Example

- Eye diagram at end of channel, eye diagram after 7dB CTLE and eye diagram after DFE.



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