OIF CEI-25 LR overview

David R Stauffer, Ph.D.
IBM Senior Technical Staff Member
OIF Physical & Link Layer WG Chair

Tom Palkert (no Ph. D.)
Luxtera, Xilinx
OIF PLL Interop Chair

Jan 12, 2011

References

- Material in this presentation is drawn from the following OIF contributions:
  - oif2007.240 "A performance comparison study of CEI-25 signaling options", Dong Kam, et al (IBM), Aug. 2007.
  - oif2007.346 "Performance Comparison of CEI-25 Signaling Options and Sensitivity Analysis", Dong Kam, et al (IBM), Nov. 2007.
  - oif2008.114 "Link Simulations for Partial Response Signaling ", David Stauffer, et al (IBM), Apr. 2008.
  - oif2009.043 "CEI-25 Simulations over Compliant LR Channel", David Stauffer, et al (IBM), Jan. 2009.
- Portions of this work were supported by DARPA (Grant # HR0011-06-C-0074).

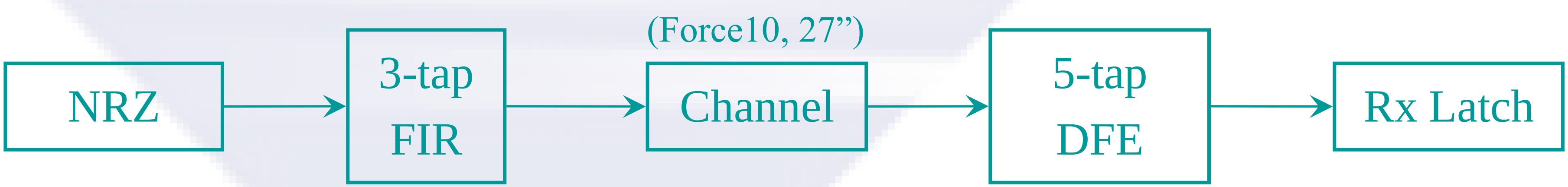
Signaling Schemes Considered

- **Signaling contributions to CEI-25 compared the following signal coding schemes:**

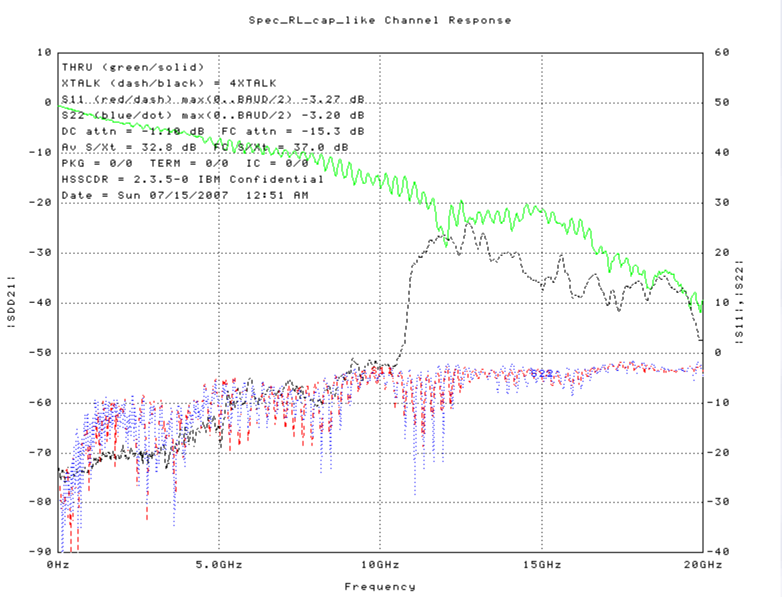
- **NRZ with FFE/DFE Equalization**
- **PR2 (Duobinary) with FFE/DFE Equalization**
- **PR3 with FFE/DFE Equalization**
  - **PR3 is a special case of PAM-4 where only transitions between adjacent levels are allowed. (Better spectrum and crosstalk than PAM-4.)**

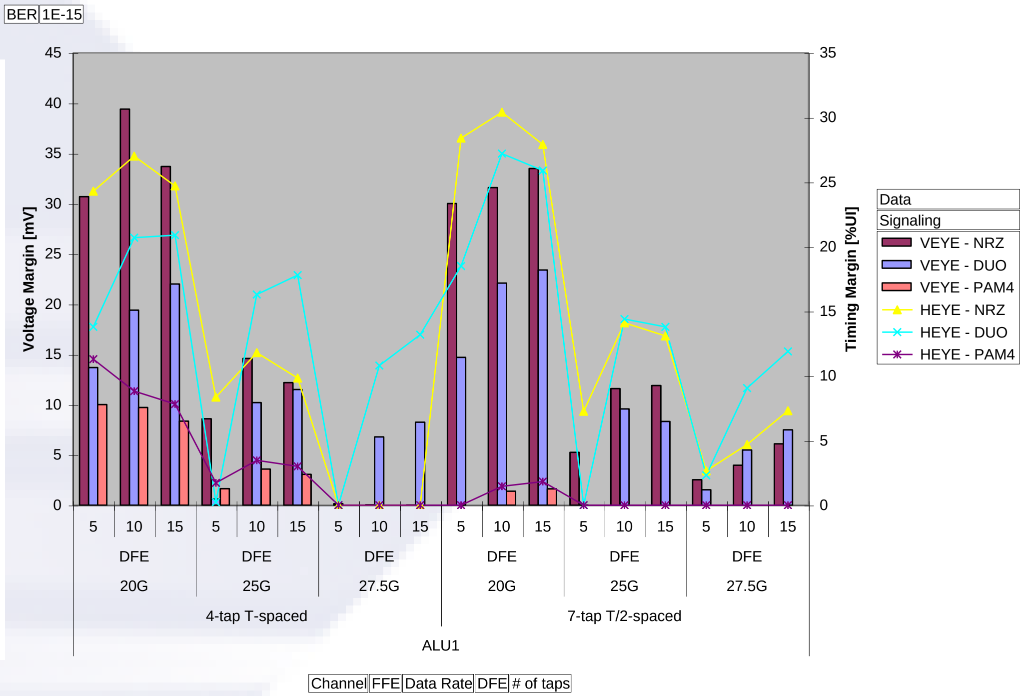
Analysis Approach

- **Analysis for each case:**
  - **Signal waveform and PSD at output of precoder**
  - **Signal waveform and PSD at output of FIR**
  - **Signal eye and PSD at input of DFE**
  - **Signal eye at output of DFE**



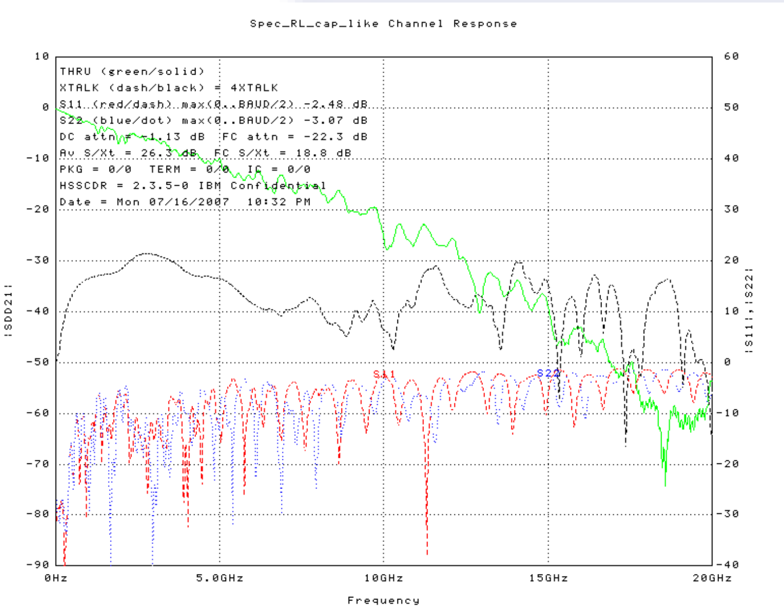
Signaling Comparisons (ALU1)

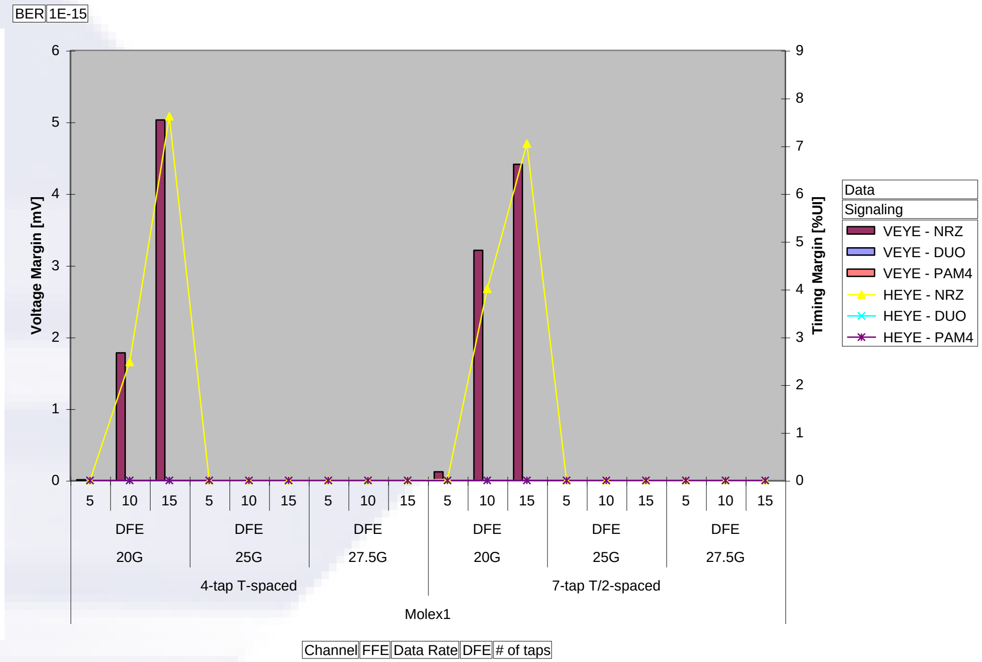




- ◆ **Early signaling contributions to OIF compared eye opening for equalized NRZ, duobinary, and PAM-4 signaling.**
- ◆ **ALU1 channel is lower insertion loss but has crosstalk which is significant at frequencies of interest.**
- ◆ **NRZ performed equivalent to duobinary on this channel.**

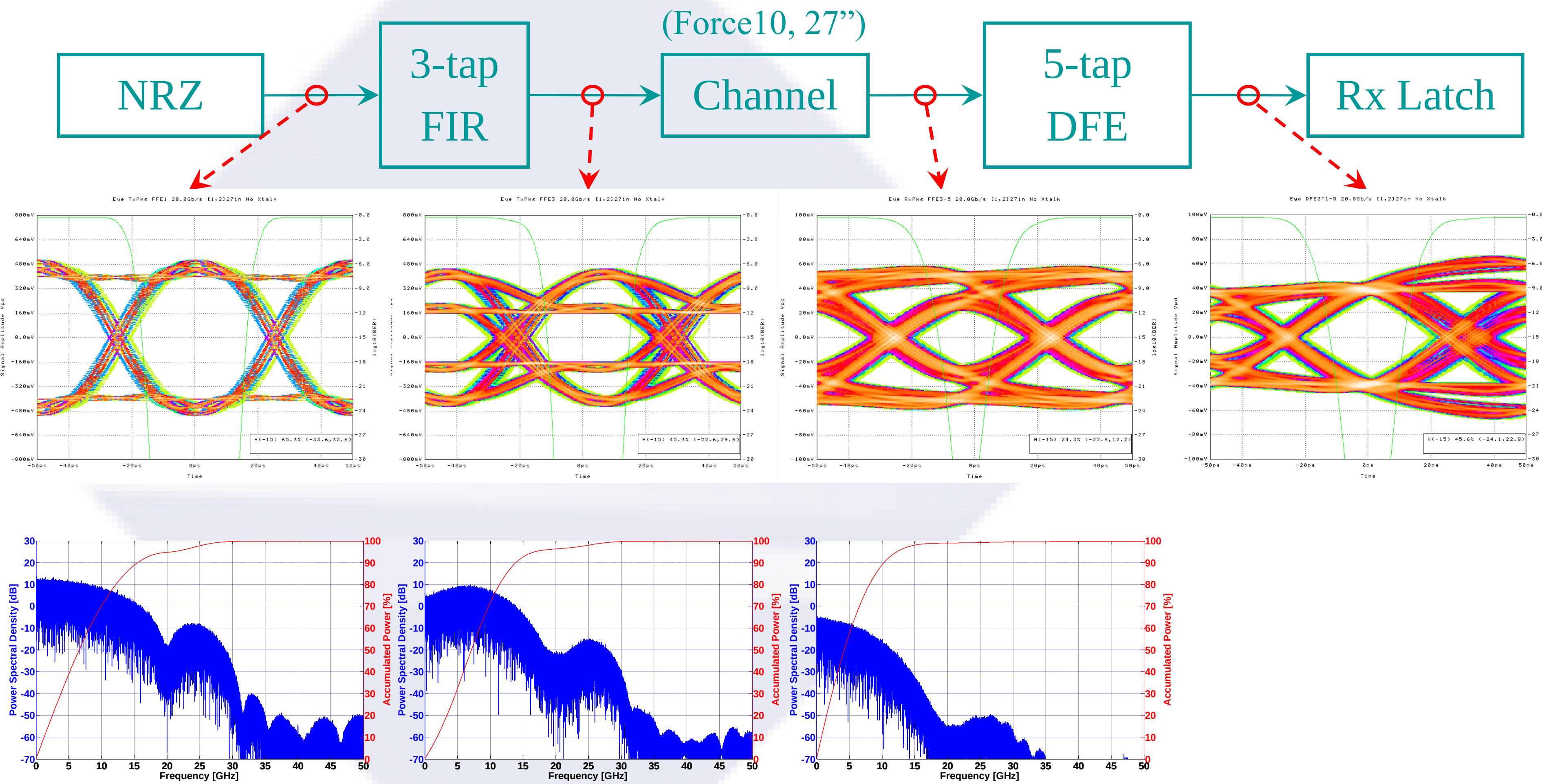
Signaling Comparisons (Molex1)



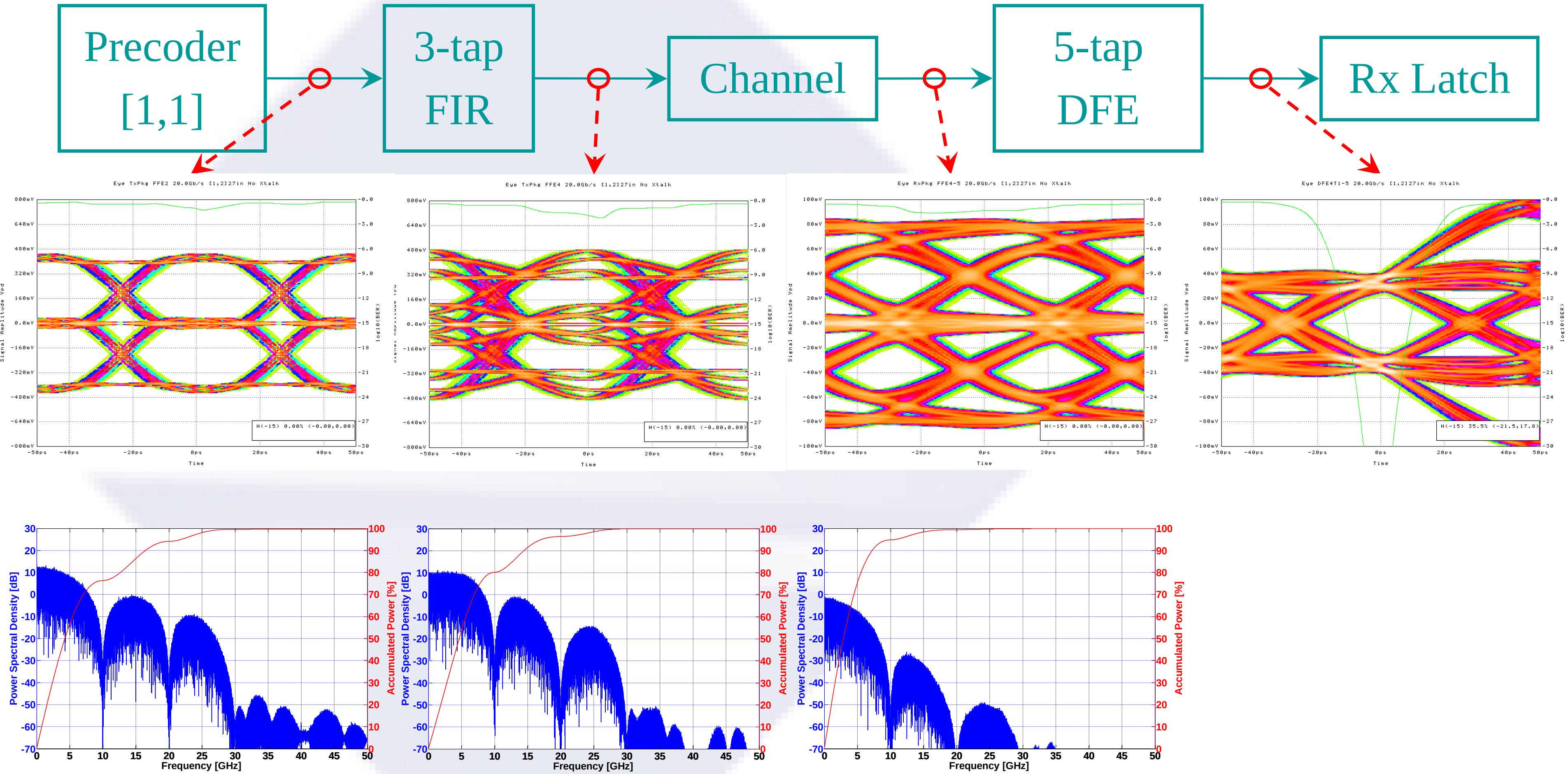


- Channels with higher insertion loss (such as the Molex1 channel) had a closed eye at 25 Gb/s.
- In general, equalized NRZ performed equivalent or better than other signaling schemes.
- IBM subsequently contributed analysis which explained these results.

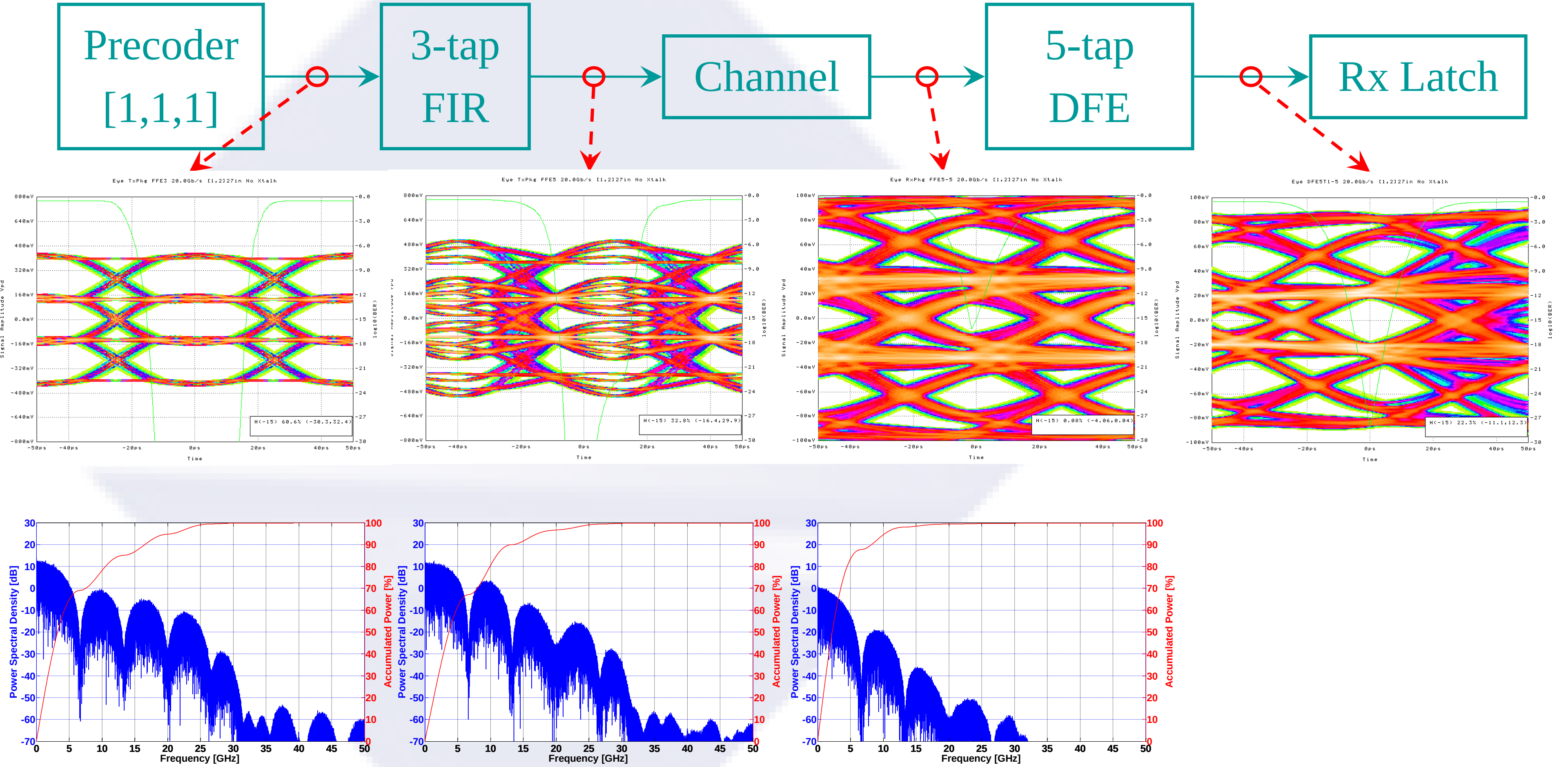
NRZ @ 20Gbps


NRZ
3-tap FIR
(Force10, 27")
Channel
5-tap DFE
Rx Latch
Power Spectral Density [dB]
Accumulated Power [%]
Frequency [GHz]

PR2 @ 20Gbps

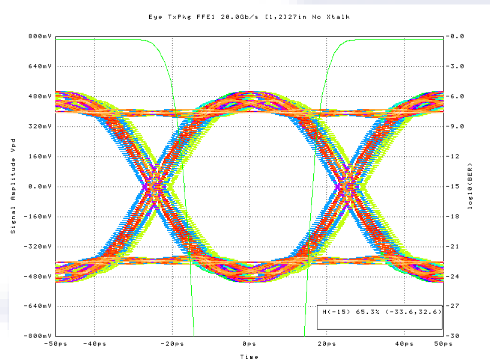

Precoder
[1,1]
3-tap
FIR
Channel
5-tap
DFE
Rx Latch
Power Spectral Density [dB]
Accumulated Power [%]
Frequency [GHz]

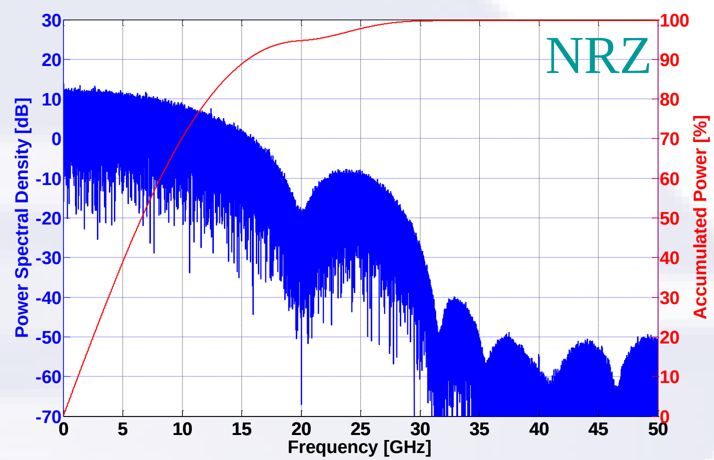
PR3 @ 20Gbps


Precoder
[1,1,1]
3-tap
FIR
Channel
5-tap
DFE
Rx Latch
Power Spectral Density [dB]
Accumulated Power [%]
Frequency [GHz]

NRZ vs. PR2 PSD Comparison

PSD for PR2 only marginally changes envelope from that of NRZ.

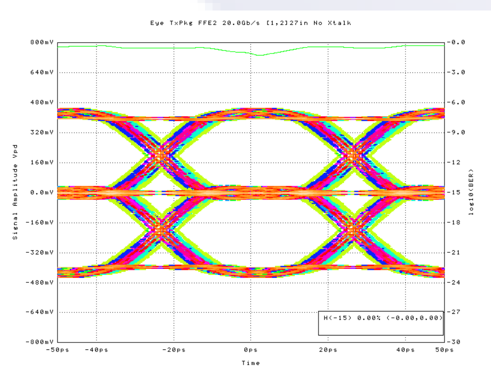


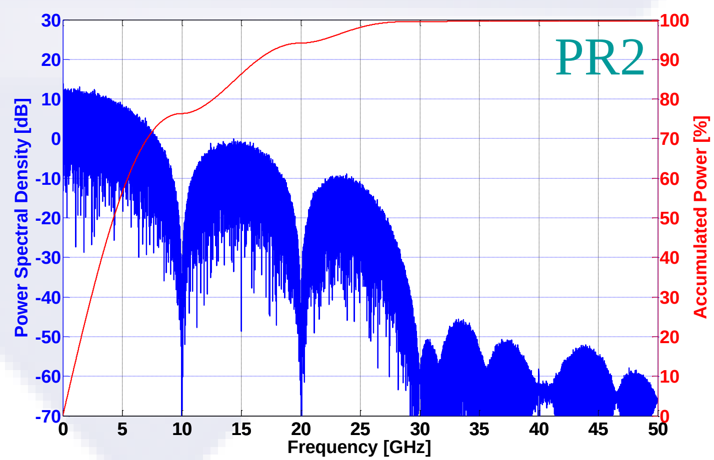


70% power below 10 GHz

80% power below 12 GHz

90% power below 15 GHz





70% power below 7 GHz

80% power below 13 GHz

90% power below 16 GHz

PSD Comparison Conclusions

- **Observations:**
  - FIR output is multilevel in all cases.
  - PSDs do not show significant differences except in position of notches.
  - Eye height at DFE output is largest for equalized NRZ. Eye height is reduced for PRx.
- **Postulations:**
  - Note that PR2/PR3 can be generated by existing FFE architectures….
  - Therefore, PR2 and PR3 are special cases within the potential solution space of a link using equalized NRZ signaling.
  - Therefore, PR2 and PR3 are cases which are considered by FFE/DFE optimization algorithms.
  - Therefore equalized NRZ results should be equivalent or better than PR2/PR3 special cases.

Literature

- The spectrum of NRZ vs. duobinary is analyzed in: A. Sekey, "An Analysis of the Duobinary Technique," IEEE Trans. Comm. Technology, vol. COM-14, no. 2, 1966, pp. 126-130.

$$W_y(f) = W_x(f)\cos^2 \pi T f$$

Power spectrum of NRZ

Power spectrum of PR2

- If NRZ has frequency components above f=1/2T, PR2 will also have finite components there, except at discrete points where cos(pi*T*f)=0. Thus the bandwidth as defined in the Sampling Theorem is not compressed at all.

Literature

- In the *special case of the rectangular pulse*, the spectrum is compressed by 2-to-1 along the frequency axis. This means that certain parameters of the spectrum, which are sometimes used to define “bandwidth” in a loose sense, are also halved. These are, e.g:
  - the frequency at which the spectrum first falls to zero,
  - the frequency below which lies a specified proportion (e.g., 90%) of the spectral energy, etc.

$$g(t) = \begin{cases} A, & |t| \le 1/2T \\ 0, & \text{elsewhere} \end{cases}$$

$$G(f) = A\frac{\sin \pi Tf}{\pi f}$$

$$W_x(f) = \frac{A^2}{T}\cdot\frac{\sin^2 \pi Tf}{(\pi f)^2}$$

$$W_y(f) = \frac{A^2}{T}\cdot\frac{\sin^2 \pi Tf}{(\pi f)^2}\cdot\cos^2 \pi Tf = \frac{A^2}{T}\cdot\frac{\sin^2 2\pi Tf}{(2\pi f)^2} = W_x(2f)$$

Literature Conclusions

- The literature suggests that the spectral energy does get pushed to lower frequencies to some extent by PR2 and PR3 signaling.
- This leads to the expectation that multilevel signaling has an advantage for some channels, particularly channels with high crosstalk.
- But if PR2/PR3 are part of the solution space searched for equalized NRZ, then equalized NRZ will achieve equalivalent results to duobinary.

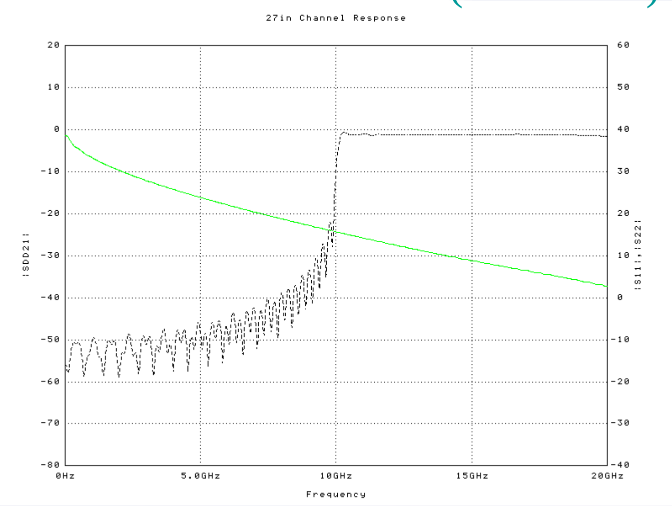
NRZ for a Duobinary "Friendly" Channel

- **Analysis used:**
  - **Force 10 channel parameters for a 27" channel.**
  - **Substantial crosstalk component added.**
- **Postulation: In the presence of excessive crosstalk, the FFE optimization algorithm should naturally pick a PRx (x = number of FFE taps available).**

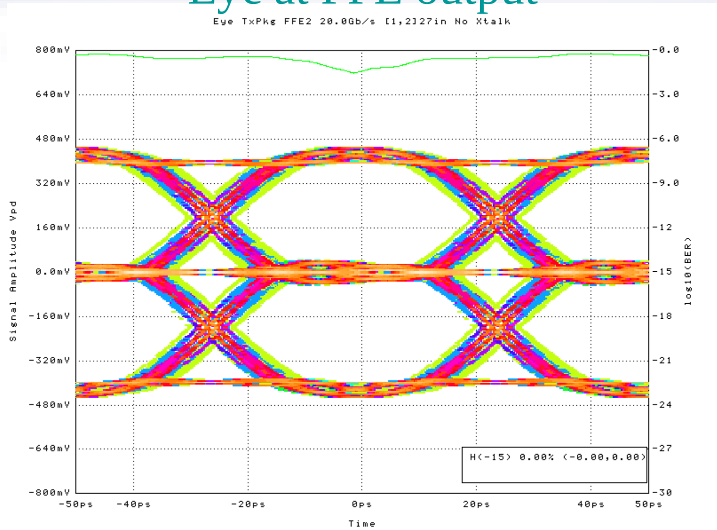
2-tap FFE Optimization

- **Channel has a significant crosstalk component.**
- **Optimized FFE tap coefficients: [0.5062,0.4938].**
- **Equalized NRZ signaling is equivalent to duobinary.**

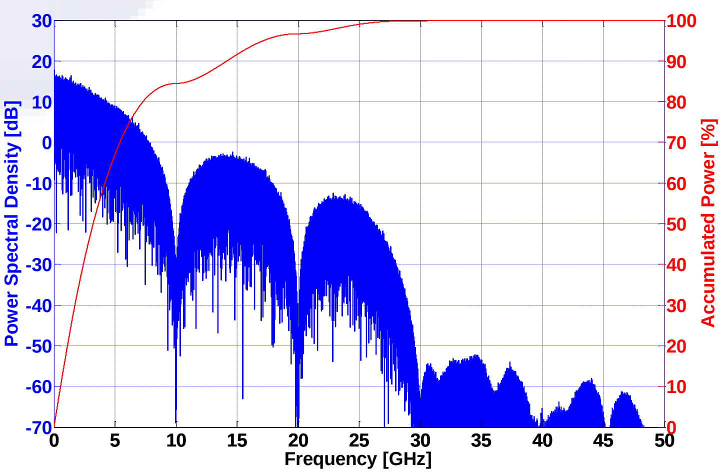
Xtalk ~ 0 dB (f > 10GHz)



Eye at FFE output



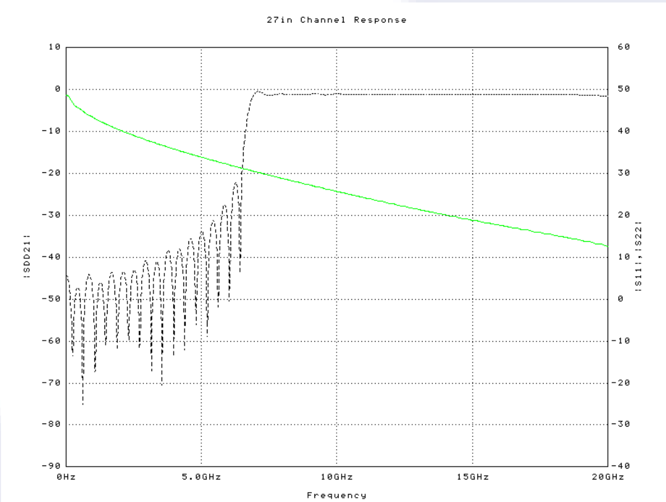
Duobinary!



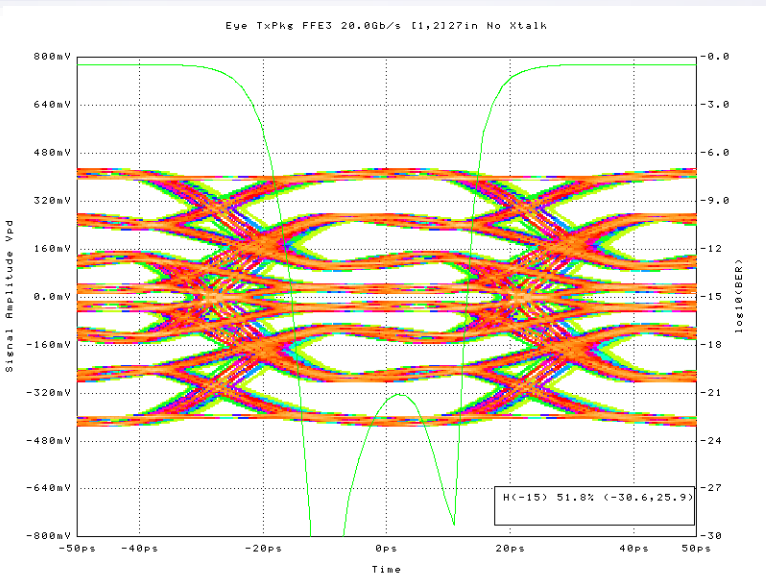
3-tap FFE Optimization

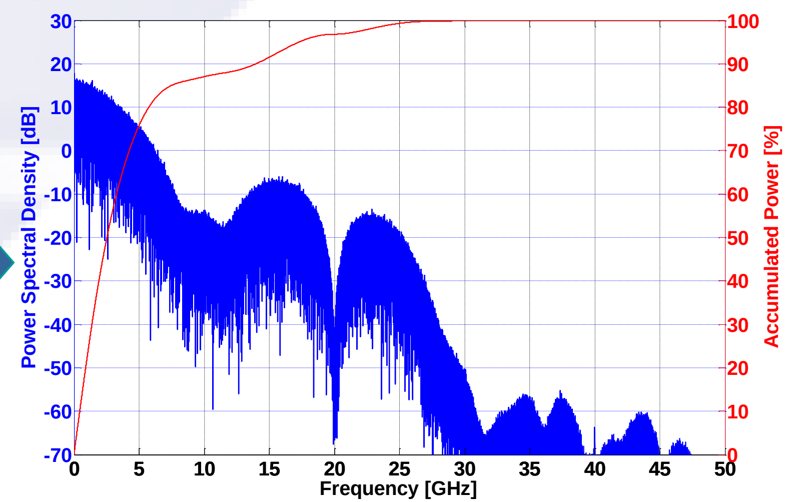
- **Optimized FFE tap coefficients: [0.3509,0.4574,0.1917].**
- **Equalized NRZ signaling is equivalent to PR3.**

Xtalk ~ 0 dB (f > 6.67GHz)



Eye at FFE output





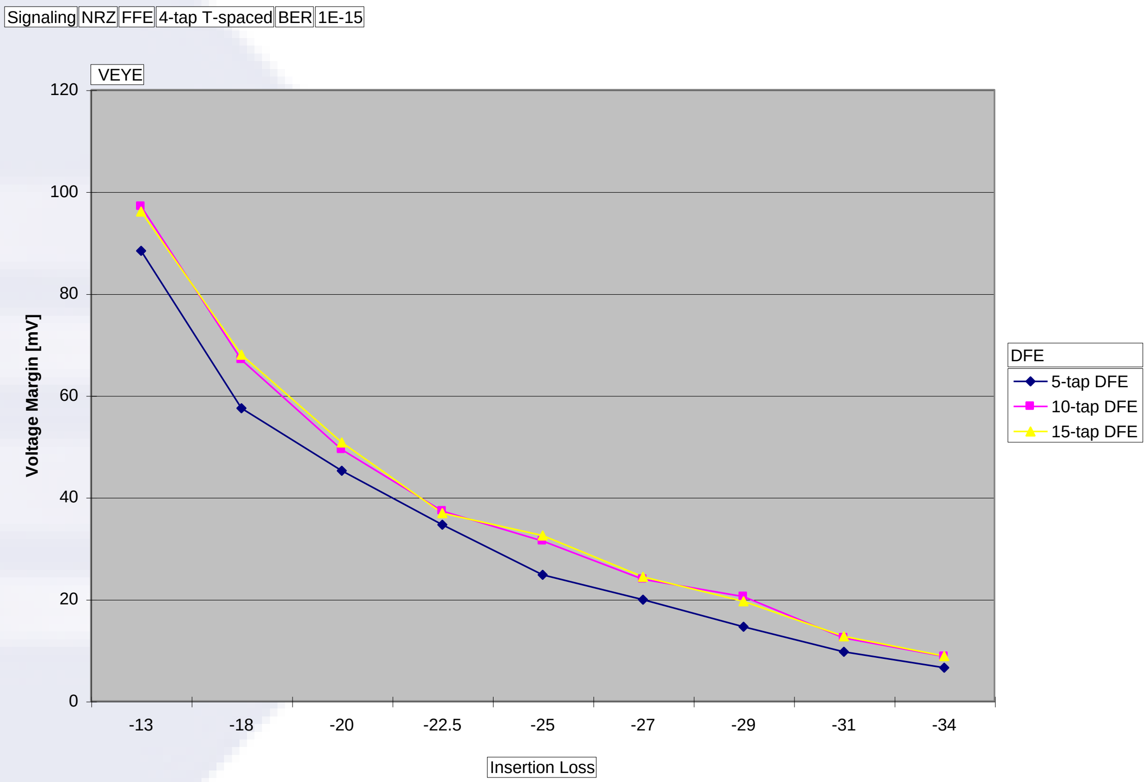
Signaling Conclusions

- **Multi-level signaling will not produce better results *because it is already part of the potential solution space for equalized NRZ.***
- **OIF selection of equalized NRZ signaling for CEI-25 was partially based on this conclusion. Additionally:**
  - **No contributions were received which demonstrated advantage to any other signaling scheme over a range of channels.**
  - **Contributions which were received demonstrated that equalized NRZ performed equivalent or better than alternatives.**

Sensitivity Analysis for Equalized NRZ

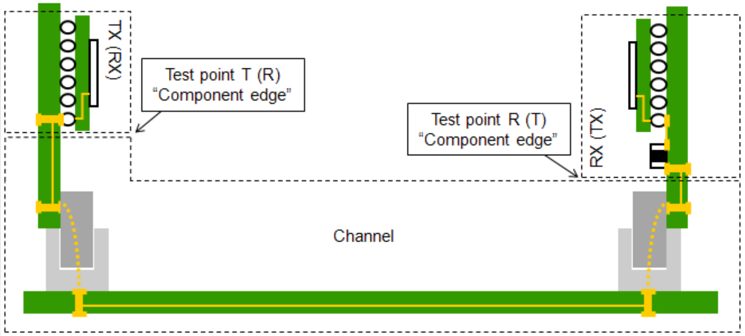
Given equalized NRZ signaling:

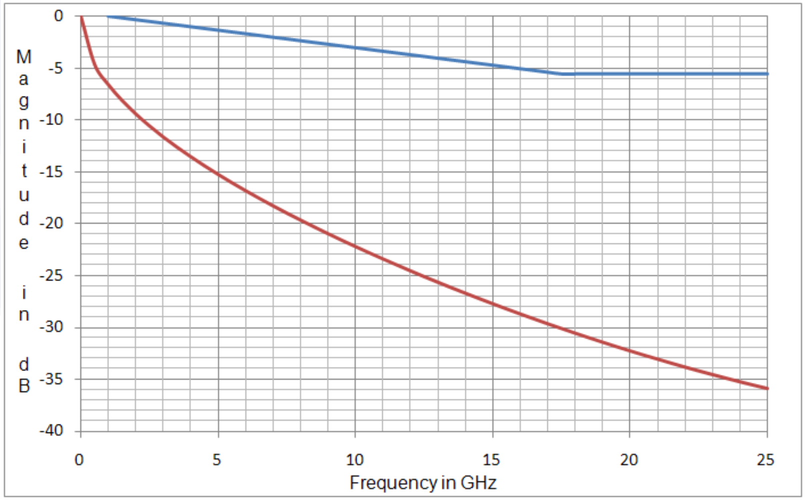
- **Rx requires approx. 30mV of eye height at the sampling latch.**
- **Simulations show this is equivalent to an insertion loss at Nyquist of approx. -25dB.**
- **Channels must meet this performance in order to have a feasible solution for the CEI-25 IA.**



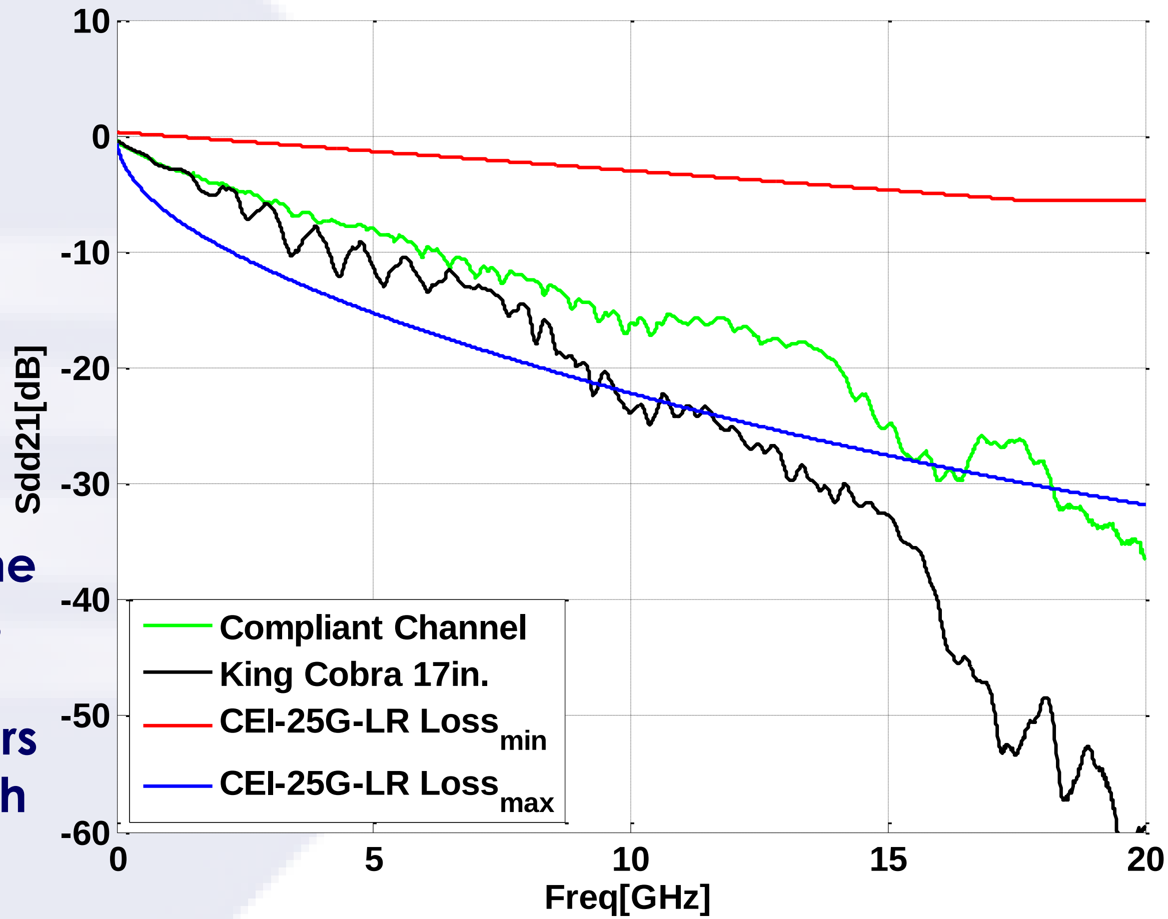
CEI-25 Long Reach Channel Requirements

- Channel insertion loss is specified consistent with sensitivity analysis:
  - Sdd21 insertion loss of -25 dB at 12.5 GHz.
  - Specify both max. and min. Sdd21 limits.
  - Specify limits for Sdd21 deviation & crosstalk.
- Backplane applications typically require up to 30“ of trace with up to 2 connectors.
- Feasability requires signaling simulations using S-Parameters for backplane channel designs meeting the channel specification.





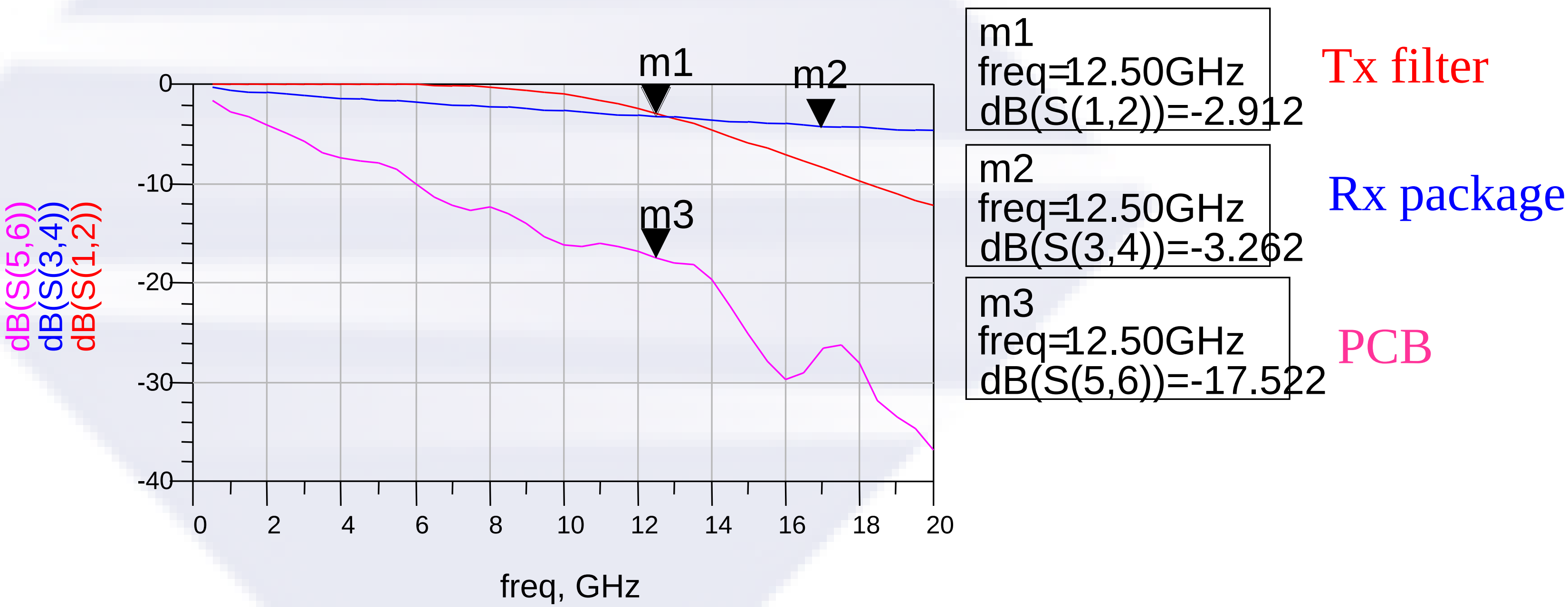
Compliant Channel Example



Channel description:

- 22" Channel Backplane
- 8 Crosstalk Aggressors
- Production Capable
- Measured S-Parameters
- Sdd21 is compliant with CEI-25G-LR.

Breakdown of Channel Loss

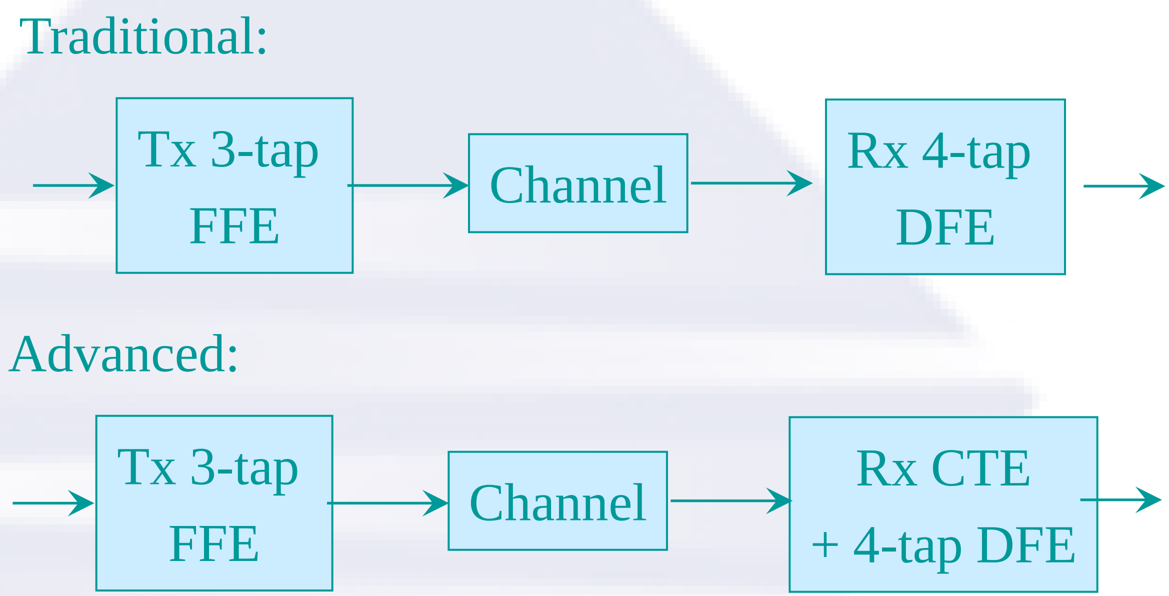


Overall channel loss = 2.9 + 17.5 + 3.3 = 23.7 dB @ 12.5 GHz

Simulation Conditions

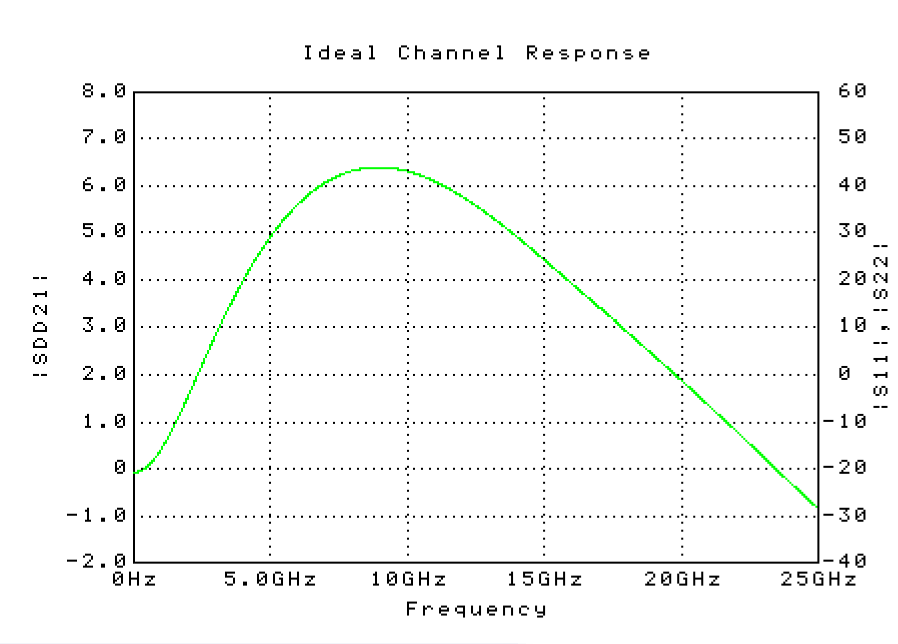
- ✓ PRBS15
- ✓ BER=1E-12 and 1E-15
- ✓ Tx level=800mVpd
- ✓ Tx DCD=3.5%UIpp duty cycle
- ✓ Tx RJ=1.07%UI RMS
- ✓ Tx edge rate filter=60 dB/dec LPF with corner frequency at 12.5 GHz
- ✓ Rx RJ=1.07%UI RMS
- ✓ Rx SJ=10%UIpp, 1E-2 cycles/UI freq
- ✓ Gaussian amplitude noise=1.46mV RMS
- ✓ Latch sensitivity=0mV
- ✓ Rx term=50ohm
- ✓ Rx PKG=IBM (55mm_T33mm115ohm_lowBGAcoupling)
- ✓ # of bits simulated=3M
- ✓ AGC level target=300mV
- ✓ 3-tap (1 pre- & 1 post-cursor) baud-spaced FFE
- ✓ 8 crosstalk aggressors

Signal Processing Flows Considered



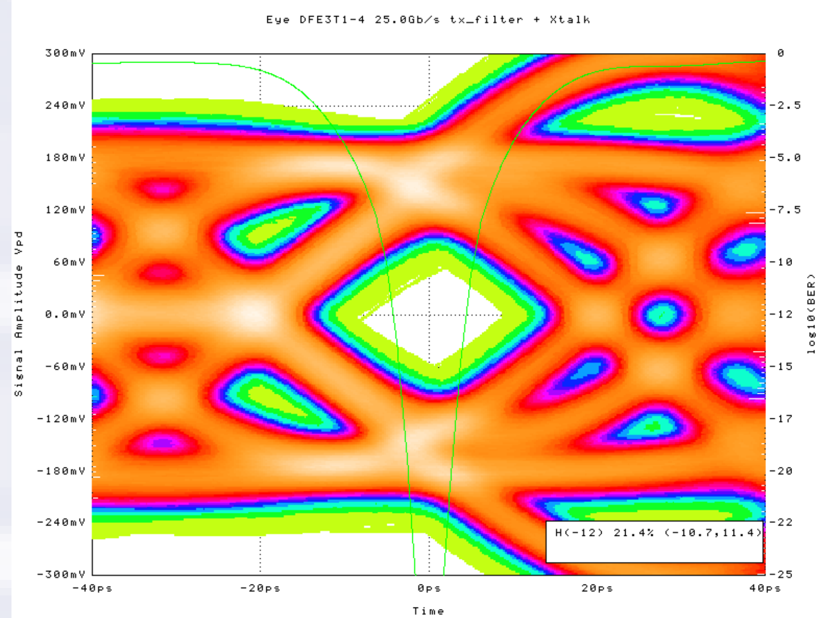
- **CTE = Continuous Time Equalizer**
- **Criteria for an "open" eye**
  - **HEYE $\geq$ 0.15 UI**
  - **VEYE $\geq$ 30 mV**

Frequency Response of Rx CTE (6dB peak, 1st order)



Signaling Simulations

- Simulation shows open eye for a CEI-25G-LR compliant channel.
  - Addition of CTE key to achieving open eye at BER=1E-12.
  - Robust solution may require more DFE taps.
- Simulations show some DFE will be required for SR applications.



Tx FFE = 4 taps	@1E-12 BER
Rx CTE = yes	HEYE= **21.4%** UI
Rx DFE = 4 taps	VEYE= **30.3** mV

Conclusions

- OIF decision to base CEI-25 (both SR and LR) on equalized NRZ signaling was based on signaling simulations contributed throughout 2005-2008.
- CEI-25G-LR Channel Model is based on feasibility limits as determined by sensitivity analysis for equalized NRZ signaling.
- Backplane channel design has been demonstrated which meets the requirements of the CEI-25G-LR Channel Model.
  - Achievable due to evolution of channel design techniques, board materials, and connectors.
- Signaling simulations demonstrate that reasonable receiver designs can be used to receive signals over CEI-25G-LR compliant channels.
  - Achievable due to evolution of Serdes design to include both CTE and DFE in the Receiver.