EDI CON 2018
Electronic Design Innovation Conference & Exhibition
October 17-19 2018
Santa Clara Convention Center
Santa Clara, CA

COM for PAM4 Link Analysis –What you need to know

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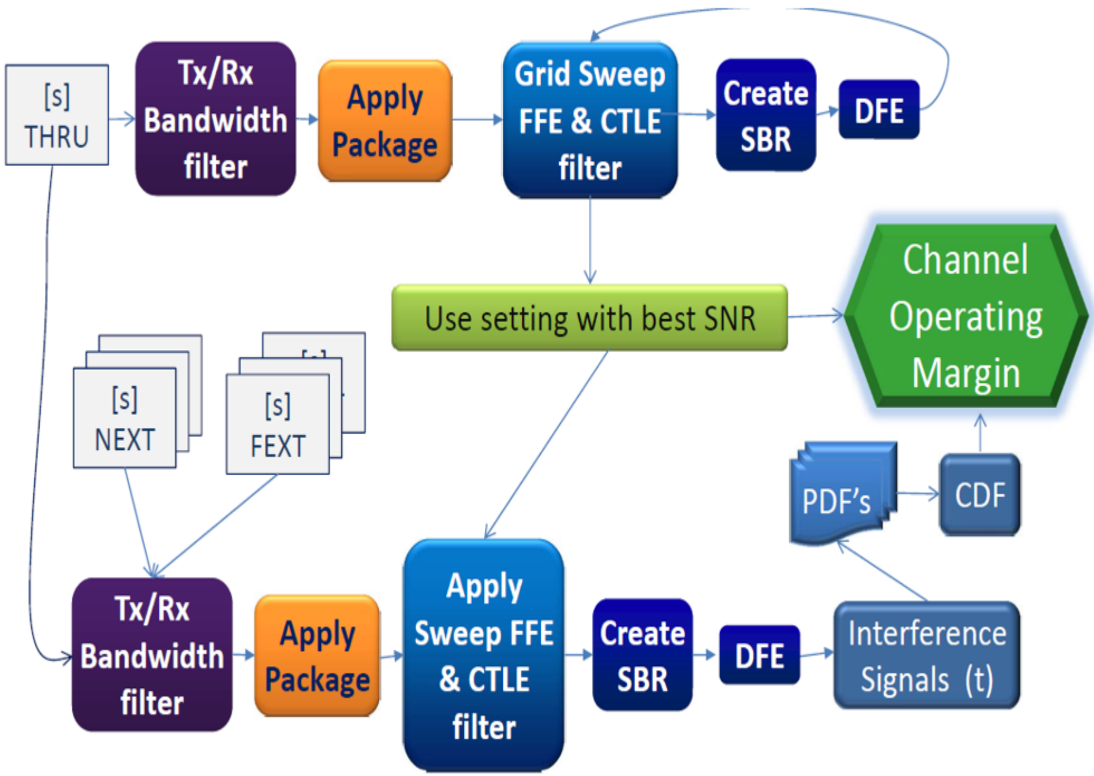
Outline

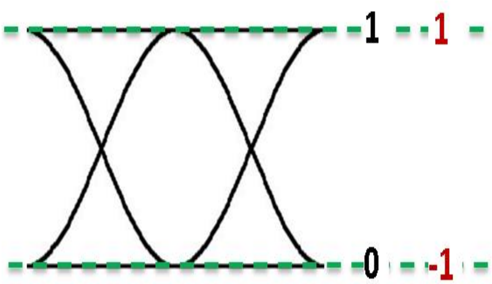
- **COM in a nutshell**
- **PAM4 in Brief**
- **Data Sampling Time in COM**
- **DFE Tap Coefficients**
- **Treatment of Jitter in COM**
- **TX Output Level Separation Mismatch**
- **CTLE in COM**
- **COM Margin**
- **DFE Error Propagation Impact**
- **FEC Fundamentals**
- **Summary and Future Work**

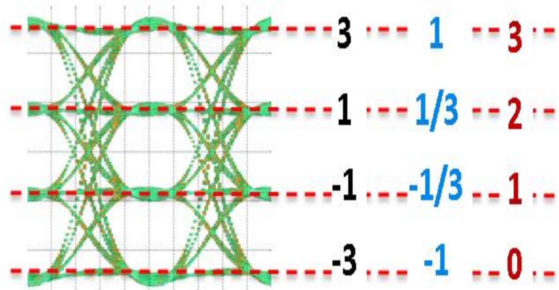
COM in a Nutshell

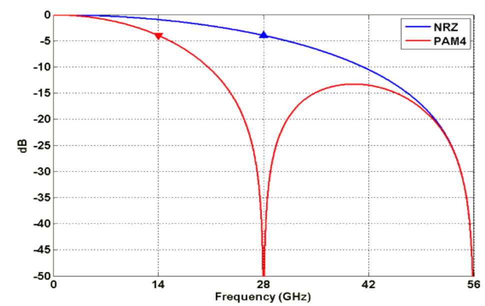


- THRU and aggressor channels
- S-parameter representations
- Package models
- Single bit response (SBR)
- TX FFE: pre- & post- cursor taps
- RX CTLE transfer functions
- DFE and its tap coefficients
- Computation of FOM
- PDF's of various impairments
- Computation of COM
- COM margin against DER_0

PAM4 in Brief

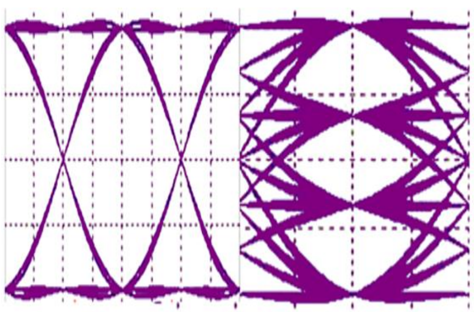


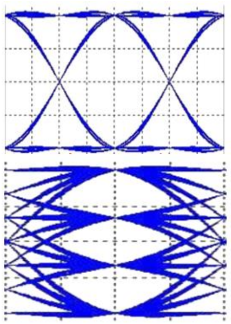




- NRZ: 1 symbol = 1 bit; 2 levels and 1 eye
- PAM4: 1 symbol = 2 bits; 4 levels and 3 eyes

- Signal PSD for NRZ and PAM4
  - PAM4 requires half the BW
  - PAM4 symbol is twice wide



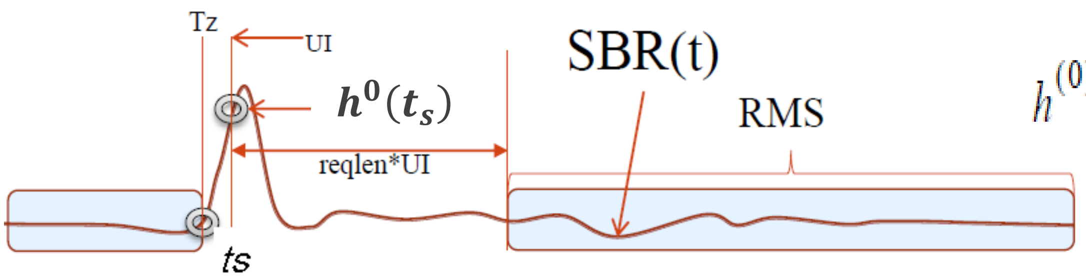


- PAR: Peak to Average Ratio

$$\sigma_x^2 = \frac{2}{L}\cdot \sum_{k=1,3,\dots L-1}\left(\frac{k}{L-1}\right)^2 = \begin{cases} 1 & \text{for NRZ} \\ 5/9 & \text{for PAM4} \end{cases}$$

$$\sigma_x = 0.7454$$

Data Sampling Time in COM



$$h^{(0)}(t_s - T_b) = h^{(0)}(t_s + T_b) - h^{(0)}(t_s)b(1)$$

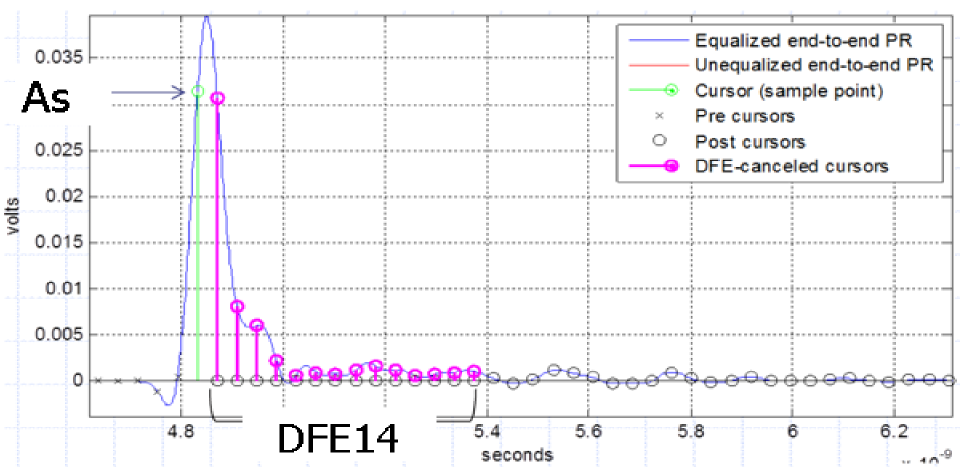
- Mueller-Muller baud-rate phase detector is emulated in COM
  - After equalization 1st residual pre-cursor ≈ 1st residual post-cursor
  - As long as $b(1)$ does not limit (default <0.7), $h^0(t_s - T_b) = 0$
- This choice of t_s reduces the impact of pre-cursor ISI. However
  - It is usually at the expense of moving the sampling phase left of the SBR peak
    - Increased $b(1)$, due to both reduced $h^0(t_s)$ and increased $h^0(t_s + T_b)$
    - The consequence will be discussed in more details later

DFE Tap Coefficients

$$b(n) = \begin{cases} -b_{\max}(n) & h^{(0)}(t_s + nT_b)/h^{(0)}(t_s) < -b_{\max}(n) \\ b_{\max}(n) & h^{(0)}(t_s + nT_b)/h^{(0)}(t_s) > b_{\max}(n) \\ h^{(0)}(t_s + nT_b)/h^{(0)}(t_s) & \text{otherwise} \end{cases}$$

COM parameter for DFE specified in CEI-56G-LR-PAM4

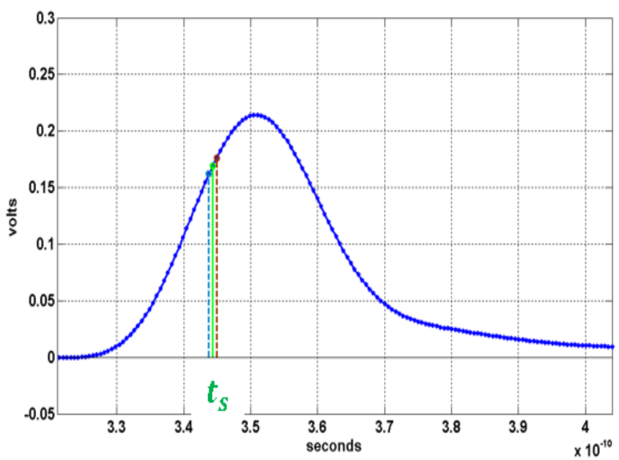
Parameter	Symbol	Value
Decision feedback equalizer (DFE) length	*Nb*	12
Normalized DFE coefficient magnitude limit for n = 2 to Nb	*bmax(1)* *bmax(2-Nb)*	0.7 0.2

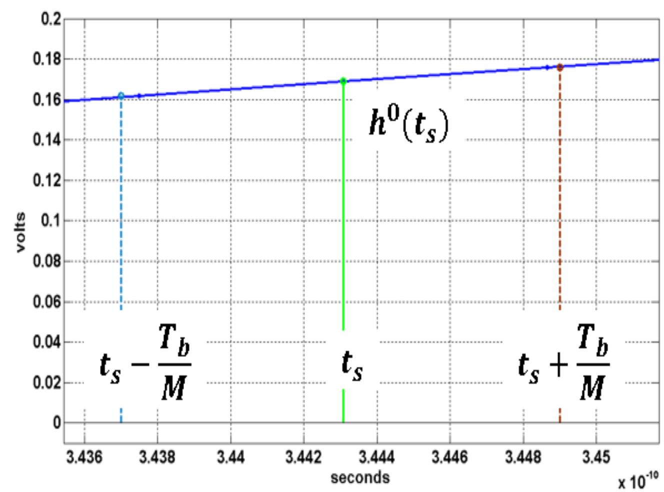


- for 56G and 112G PAM4 most standards specify the raw BER between 1e-6 to 1e-4
- The impact of larger DFE tap values, together with multiple DFE taps, on real channel performance might be huge

Treatment of Jitter in COM

- In COM jitter impact is converted to signal amplitude error before SNR is computed





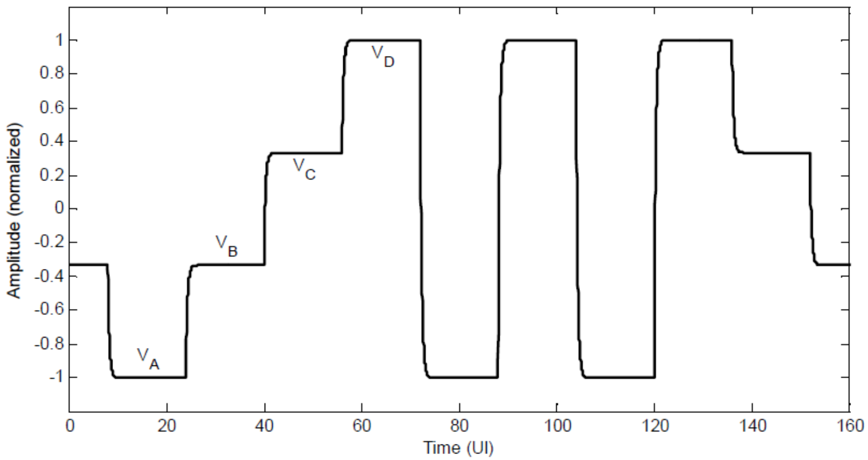
$$h_J(n) = \frac{h^{(0)}(t_s + (n + 1/M)T_b) - h^{(0)}(t_s + (n - 1/M)T_b)}{2/M}$$

The equalized SBR slope for the THRU path

$$\sigma_J^2 = (A_{DD}^2 + \sigma_{RJ}^2)\sigma_X^2 \sum_n h_J^2(n)$$

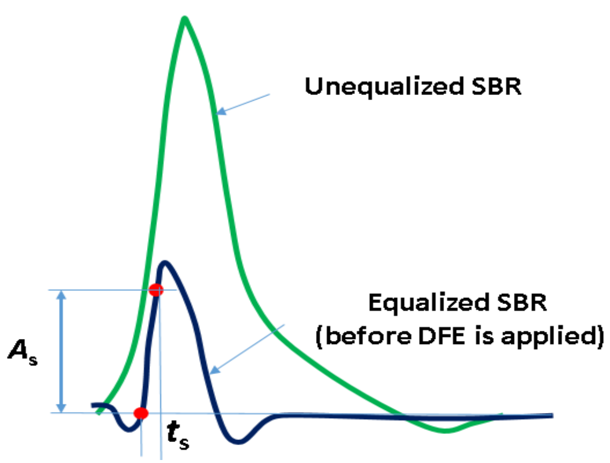
The variance of the amplitude error due to timing jitter

TX Output Level Separation Mismatch



- Level separation mismatch ratio, R_{LM}
- R_{LM} is typically specified > 0.95
  - The distribution of 4 levels is unknown

$$S_{min} = \frac{min(V_D - V_C, V_C - V_B, V_B - V_A)}{2}, \qquad R_{LM} = \frac{6 \cdot S_{min}}{V_D - V_A}$$



- A_s is the available signal for NRZ
- For PAM4 it is scaled as below

$$A_s = R_{LM} \cdot h^{(0)}(t_s)/(L-1)$$

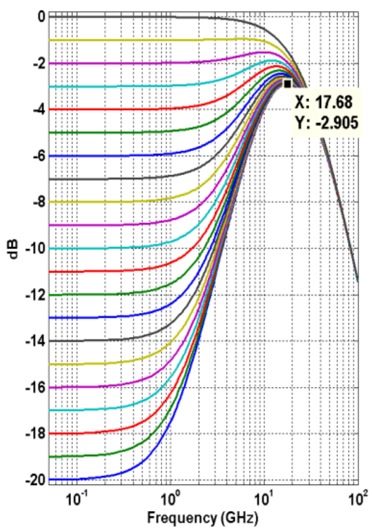
CTLE in COM

- There are two stages of CLTE specified in COM for CEI-56G-LR-PAM4

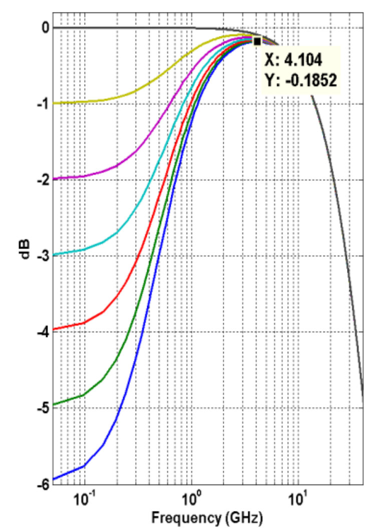
$$H_{CTLE}(f) = f_{p2} \cdot \frac{j \cdot f + f_z \cdot 10^{\frac{G_{DC}}{20}}}{(j \cdot f + f_{p1}) \cdot (j \cdot f + f_{p2})}$$

$$H_{CTLE2}(f) = f_{p2} \cdot \frac{j \cdot f + f_{LF} \cdot 10^{\frac{G_{DC2}}{20}}}{(j \cdot f + f_{LF}) \cdot (j \cdot f + f_{p2})}$$

Parameter	Symbol	Value	Units
Continuous time filter, DC gain Minimum value Maximum value Step size	g_{DC}	 –20 0 1	 dB dB dB
Continuous time filter, DC gain2 Minimum value Maximum value Step size	g_{DC2}	 –6 0 1	 dB dB dB
Continuous time filter, scaled zero frequency	f_z	f_b/2.5	GHz
Continuous time filter, pole frequencies	f_{p1} f_{p2}	f_b/2.5 f_b	GHz GHz
Continuous time filter, low frequency pole/scaled zero	f_{LF}	f_b/40	GHz



HF stage



LF stage

When the peaking is excessive, the design becomes practically very challenging in one stage, thus more parasitic poles should be added

COM Margin

- FOM is firstly computed to decide the optimal equalization settings

$$FOM = 10\log_{10}\left(\frac{A_s^2}{\sigma_{TX}^2 + \sigma_{ISI}^2 + \sigma_J^2 + \sigma_{XT}^2 + \sigma_N^2}\right)$$

$$\sigma_{TX}^2 = [h^{(0)}(t_s)]^2 10^{-SNR_{TX}/10}$$

$$\sigma_{ISI}^2 = \sigma_X^2 \sum_n h_{ISI}^2(n)$$

$$\sigma_J^2 = (A_{DD}^2 + \sigma_{RJ}^2)\sigma_X^2 \sum_n h_J^2(n)$$

$$[\sigma_m^{(k)}]^2 = \sigma_X^2 \sum_n [h^{(k)}((m/M+n)T_b)]^2$$

$$\sigma_{XT}^2 = \sum_{k=1}^{K-1} [\sigma_i^{(k)}]^2$$

$$\sigma_N^2 = \eta_0 \int_0^\infty |H_r(f) H_{ctf}(f)|^2 df$$

- COM is computed based on the optimal settings
  - The best FOM is not always equal to the best COM
  - A_{ni} is the total peak noise at DER_0

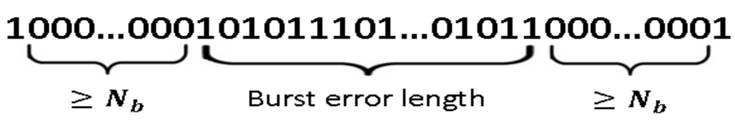
$$\boldsymbol{COM = 20 \cdot log_{10}(A_s/A_{ni})}$$

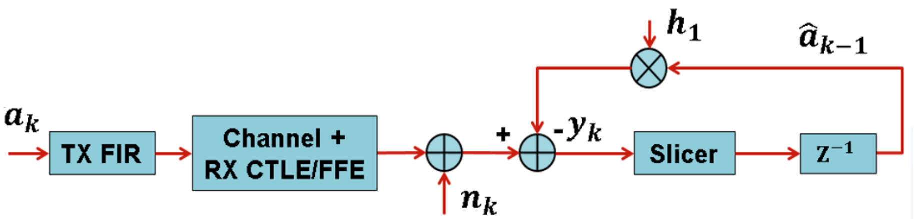
- In COM $k = 1/2$ for NRZ and PAM4
- For PAM4 it should be $k = 3/8$

$$\boldsymbol{DER_0 = k \cdot erfc\left(\frac{h_0/\sigma_{total}}{\sqrt{2}}\right)}$$

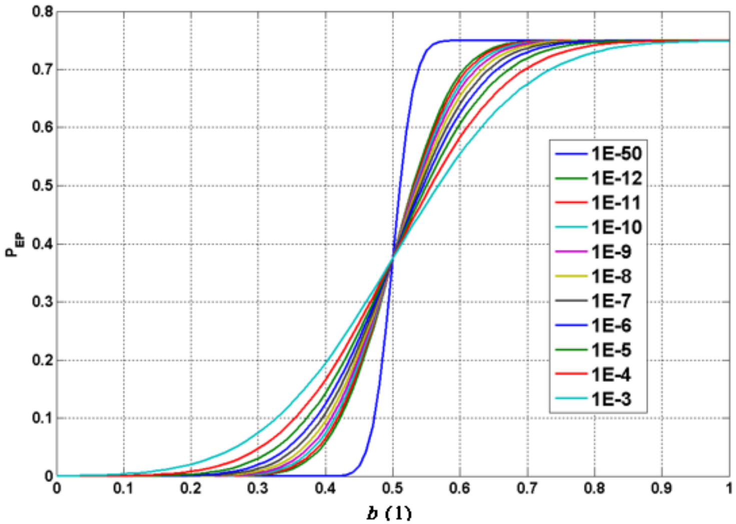
DFE Error Propagation Impact

- 1-tap DFE error propagation model
- Burst error definition

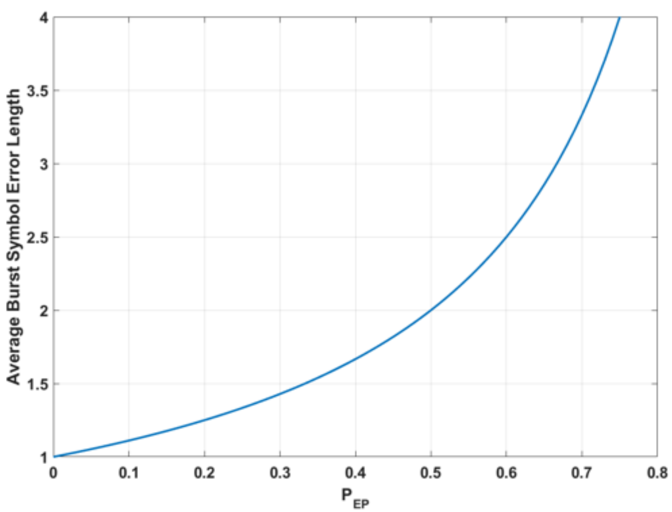




- 1-tap DFE error propagation probability

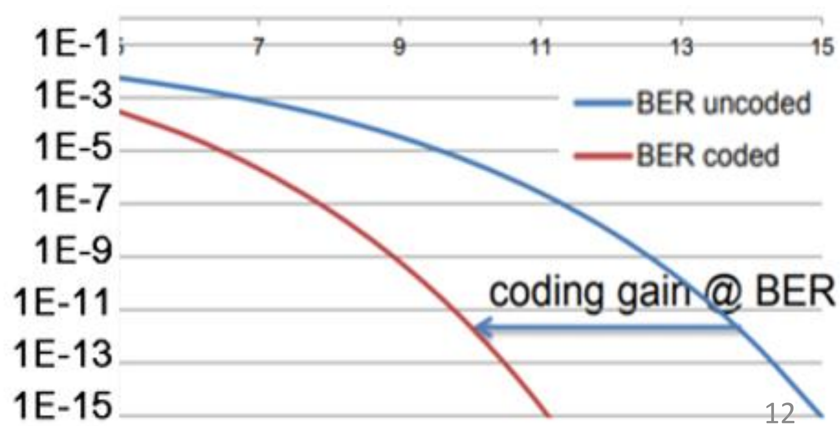


- Average burst error length for 1-tap DFE



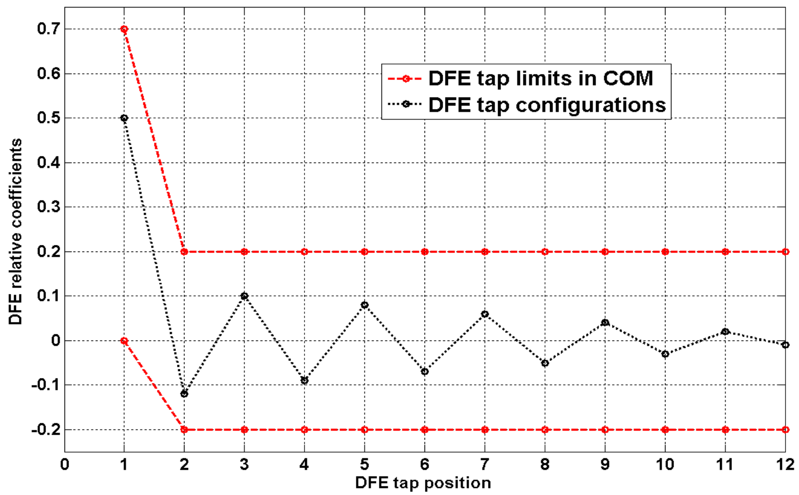
KP4 FEC Fundamentals

- The KP4 FEC, *RS(544, 514, T=15, M=10)*
  - In a codeword, 514 FEC symbols are encoded to form 544 FEC symbols
  - Each FEC symbol contains *M* (=10) bits
  - The FEC can correct up to *T* (=15) symbol errors within each codeword, regardless of number of bit errors
  - This implies that
    - At its most effective, KP4-FEC can correct as many as 150 bit errors in a codeword
    - The other extreme, it can correct no more than 15 bit errors
- FEC coding gain is the reduction in the required SNR that can be accommodated while still achieving the desired BER
  - Under typical conditions, tests from system houses showed that KP4 FEC can achieve up to 8 dB in CG
- The exact CG value is a function of BER and error signature



DFE EP and FEC Correction Example

- 12-tap DFE setting for a case study
  - Settings comply fully with CEI-56G-LR-PAM4



- Observations
  - The SER increase after DFE is not alarmingly large; the raw BER is still better than specs
  - The “average burst error length” is larger than the “SER ratio with EP” in the DFE case.
  - The *RS*(544, 514) KP4 FEC fails completely even with limited sample size in the example
  - Error signature is more relevant than BER itself in assessing FEC correction capability
  - Without DFE EP the FEC can correct all the errors even though SER is two orders worse

Base SER	SER with EP	SER ratio after EP	Max burst error length	Average burst error length	Max KP4 FEC symbol errors
1.0324e-6	3.3779e-6	3.2719	81	4.2757	17 (>15)
1.0050e-4	n/a	n/a	2	2	6 (<16)

Summary and Future Work

- COM is a great tool for qualifying a high speed serial link channels
- Focused on the COM for PAM4 signaling. We particularly analyzed
  - The potential impact from the sampling time and the DFE coefficient limits; both could lead to severe error propagations
  - KP4 FEC is discussed to provide a basic idea of error correction
  - An example of DFE EP is provided to show that even DFE tap coefficients are well within the COM limits, the FEC can become dysfunctional
  - Running COM to get the SNR margin does not guarantee the system to meet the desired performance
- Future work includes the following
  - DFE error propagation in a PAM4 link with multiple DFE taps
  - Error signature and its impact on FEC coding gain analysis
  - Precoding effect in terms of burst error removal

Thank you!