Considerations for use of the MLSE model in COM

Adam Healey

Broadcom Inc.

May 2023 (r0)

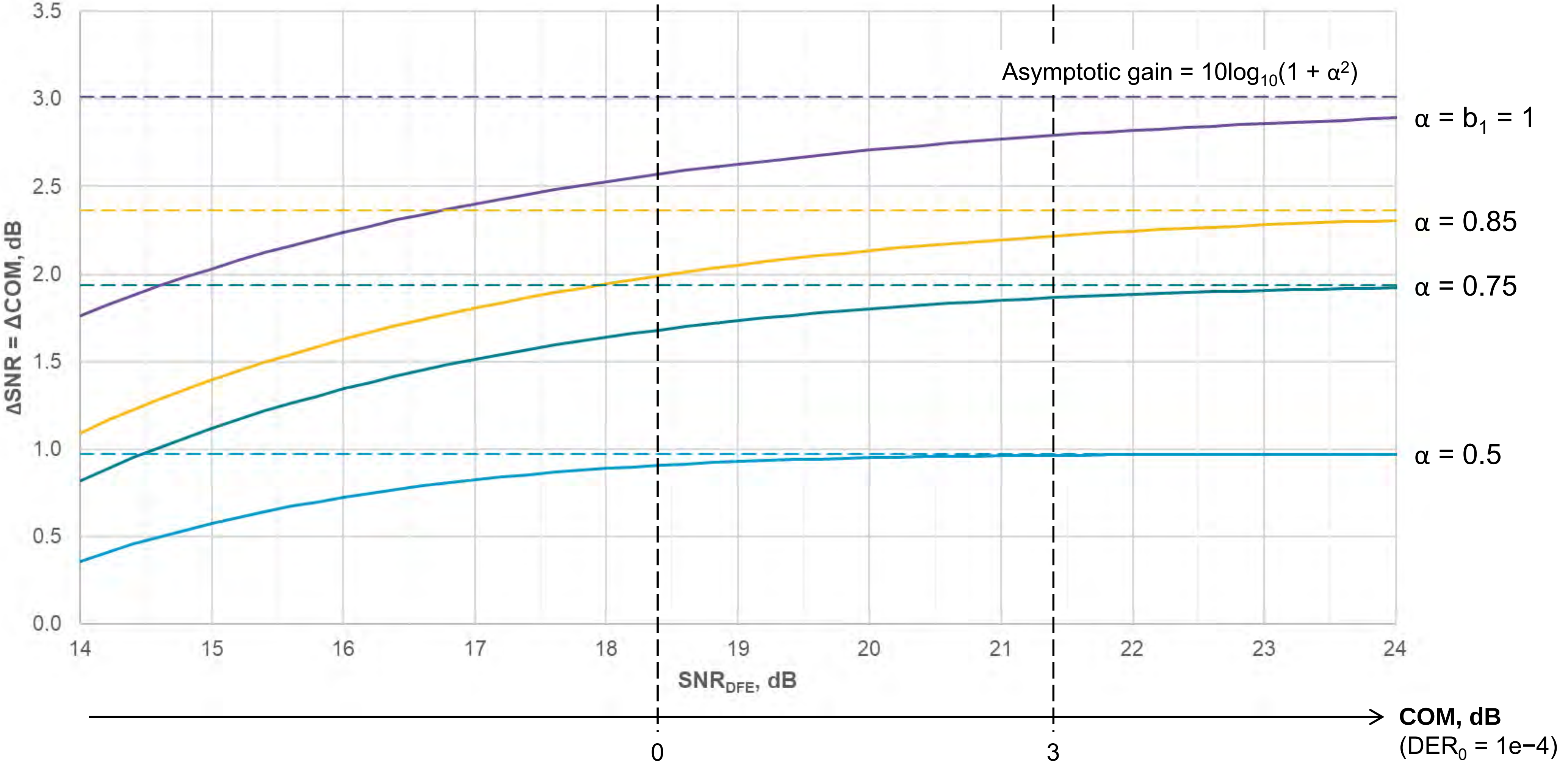
Introduction

- A method to incorporate Maximum Likelihood Sequence Estimation (MLSE) into Channel Operating Margin (COM) has been proposed
  - shakiba_3dj_elec_01_230223 [1]
  - shakiba_3dj_elec_01a_230504 [2]

- This method has been incorporated into the COM calculation script
  - mellitz_3dj_elec_02_230223 [3]

- This presentation offers two considerations for the use of this method
  1. Reference point used to calculate COM improvement from MLSE
  2. Appropriate choices for equalizer parameters

Improvement in COM is a function of COM



NOTE – 1 + αD MLSE performance is based on a comparison of DFE DER to MSLE DER with additive white Gaussian noise.

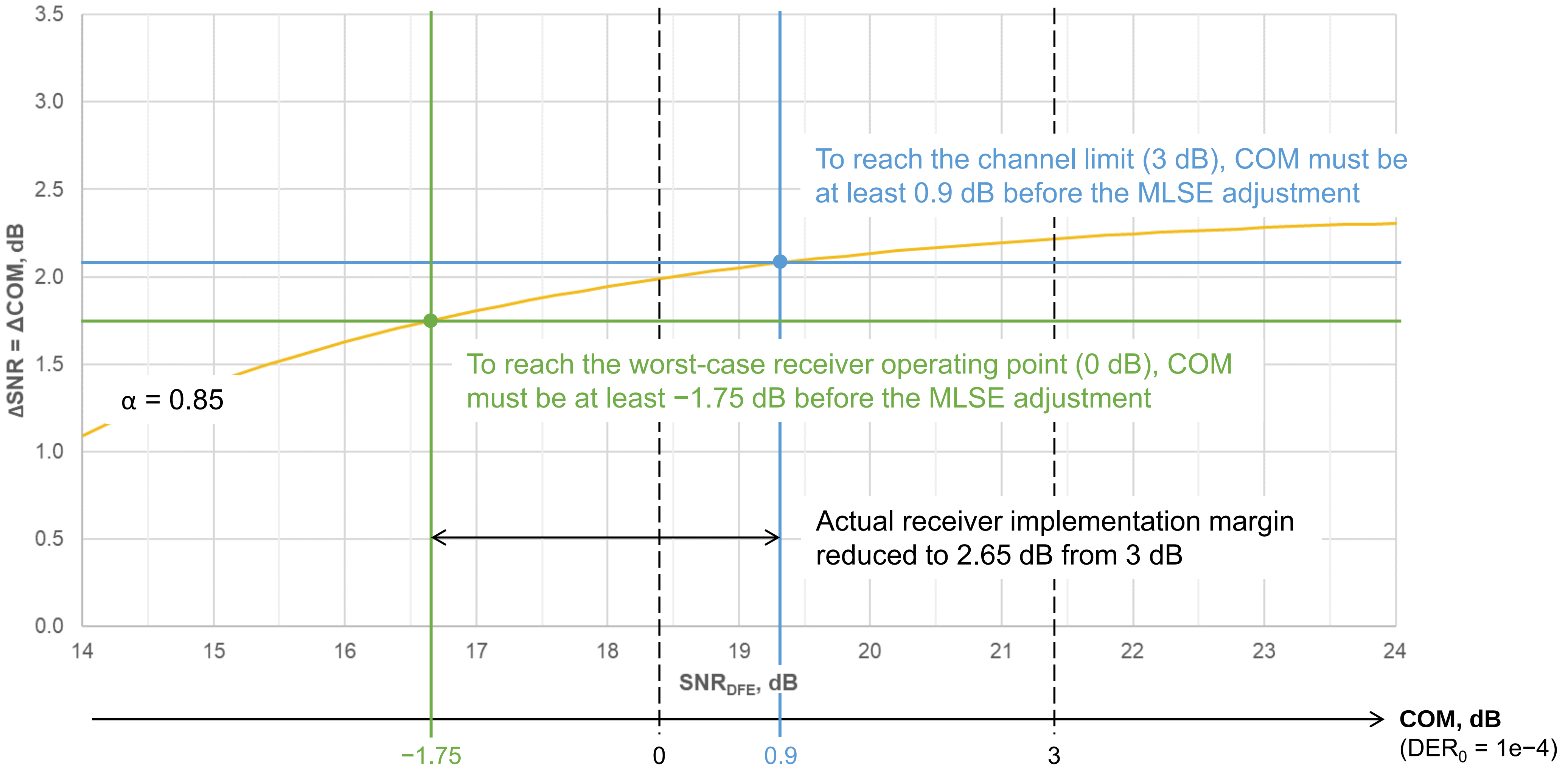
But COM does not represent the receiver operating point

- Minimum COM limit allocates margin for receiver impairments not explicitly considered in the calculation (implementation “realities”)
- This COM limit must be exceeded for channel compliance
- A compliant receiver is one that produces an FEC symbol error ratio below the limit for a test setup that is calibrated to the COM limit
- DER_0 used to calculate COM is related to the FEC symbol error ratio limit
- This suggests that the operating point for a minimally compliant receiver, connected to a minimally compliant transmitter with a minimally compliant channel, corresponds to COM near 0 dB

Receiver impairment allocation needs to be considered

- If the receiver were to implement an MLSE scheme that yielded the same performance as the proposed model, then ΔCOM would be lower because of its operating point
- This mismatch in ΔCOM becomes a <u>reduction</u> in the margin allocated for receiver implementation
- However, it could be argued that the margin allocated for implementation should be increased in consideration of the limitations of practical MLSE implementations

Example



NOTE – MLSE performance with additive white Gaussian noise.

Proposal #1

- Include receiver implementation margin in the calculation of ΔCOM
- This can be done by subtracting the minimum COM limit, COM_{min}, from SNR_{DFE} in step 2 from shakiba_3dj_elec_01a_230504

$$10\log_{10}(SNR_{DFE}) = 10\log_{10}\left(\frac{1}{3}\left(\frac{L+1}{L-1}\right)\left(\frac{main}{\sigma_{noise}}\right)^2\right) - COM_{min}$$

$$\frac{main}{L-1} = \sigma_{noise}\sqrt{\frac{3}{L^2-1}SNR_{DFE}}$$

Subtraction of COM_{min} from SNR_{DFE} effectively reduces this term by the factor $10^{-COM_{min}/20}$

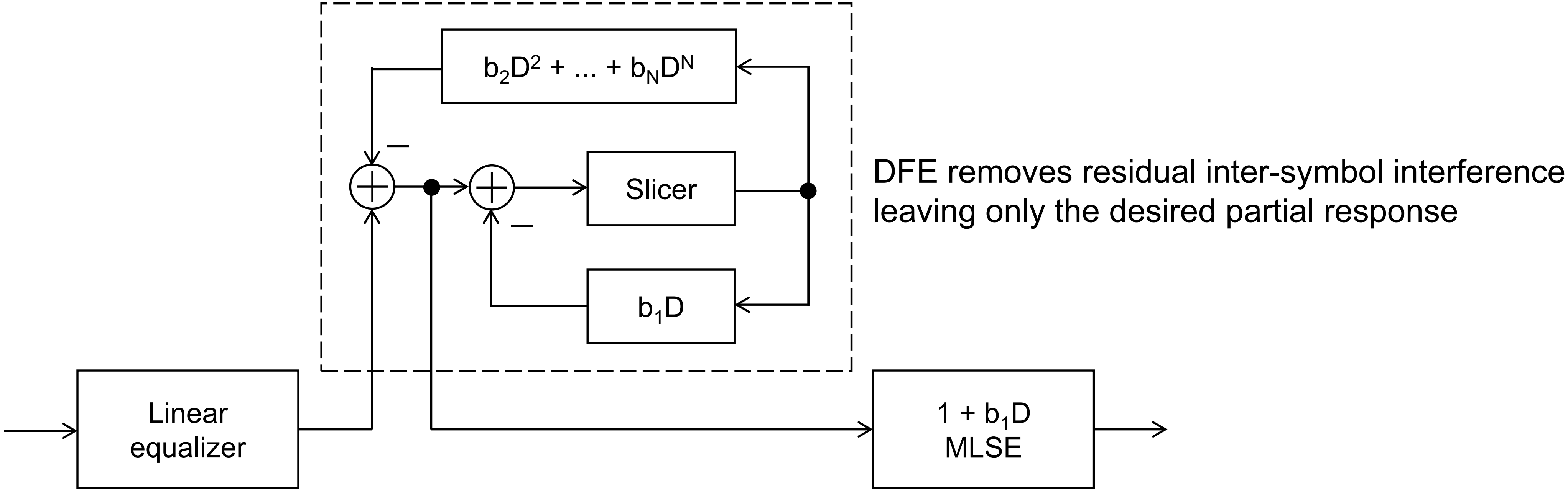
- If noise coloring is considered, it is also necessary to define correlation coefficients corresponding to the "implementation noise"
- It may also be acceptable to set COM_{min} to accommodate penalties due noise coloring

Selection of reference equalizer to use with MLSE

- Derivation of ΔCOM was based on a linear equalizer e.g., feed-forward equalizer (FFE), followed by MLSE
- 1-tap decision feedback equalizer included for the purpose deriving the partial response target, $1+\alpha D$, used by MLSE ($\alpha = b_1$)
- However, the “standard” COM reference receiver is based on a multi-tap decision feedback equalizer (DFE)
- While ΔCOM can be computed for a multi-tap DFE, does the result make sense?

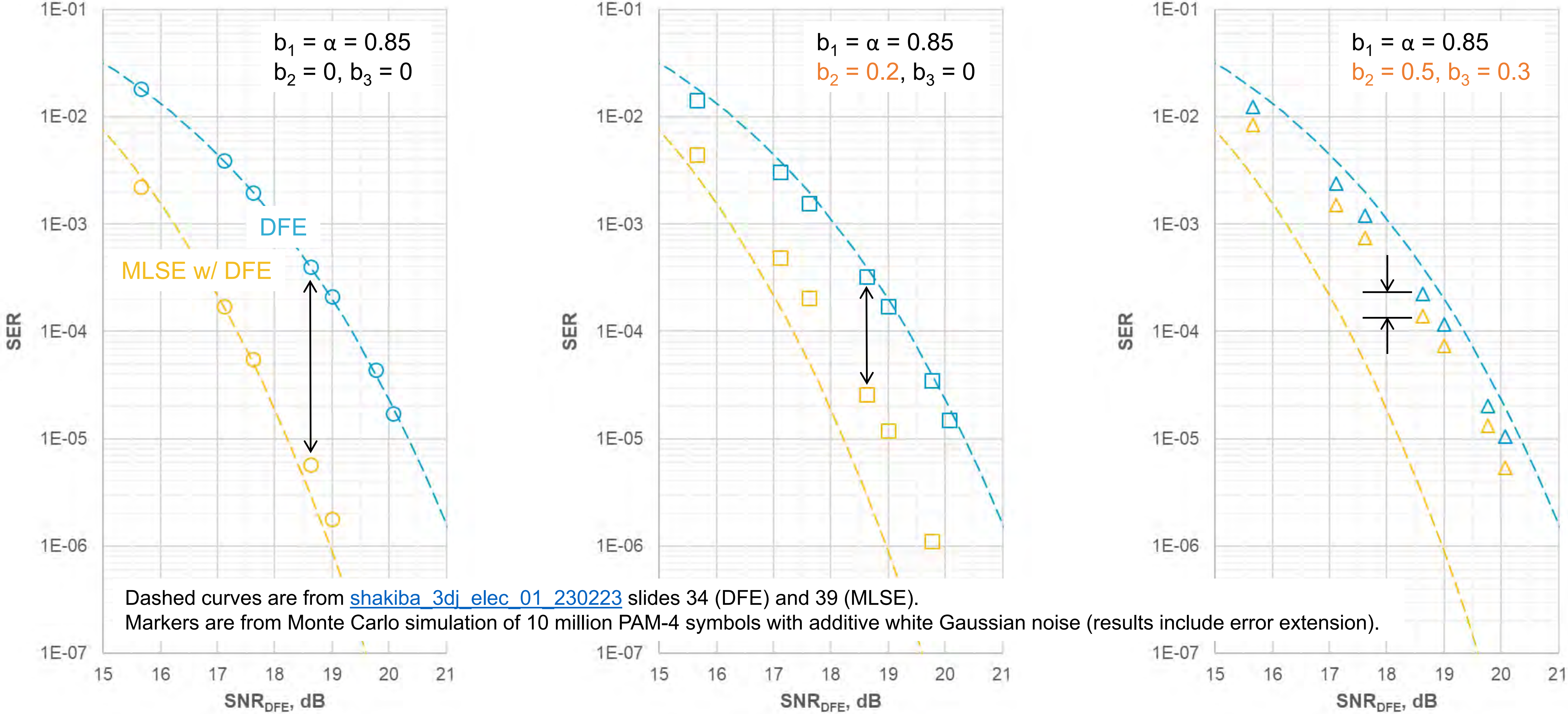
Adding MLSE to a multi-tap DFE reference receiver

- Addition of ΔCOM for a multi-tap DFE reference receiver suggests the following reference architecture



- However, COM calculation only considers the probability of DFE error “events” and not the impact those events have on subsequent blocks

MLSE performance degraded by DFE errors

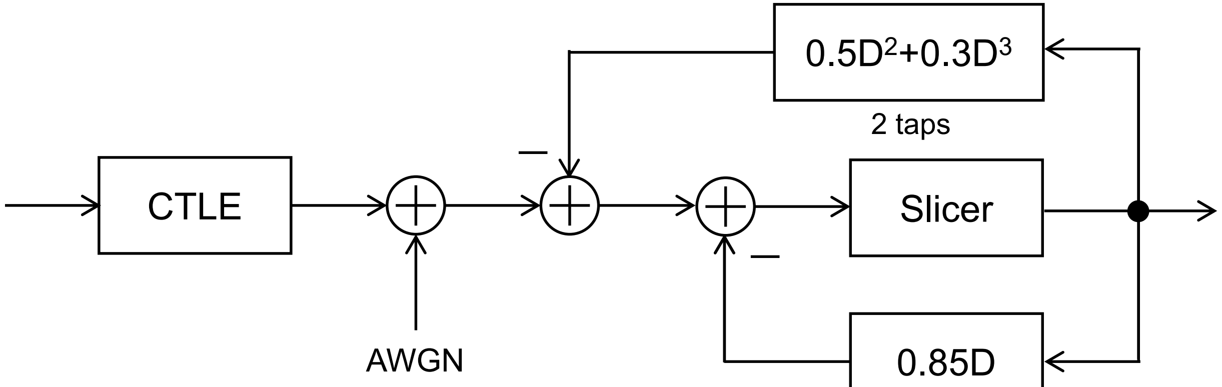


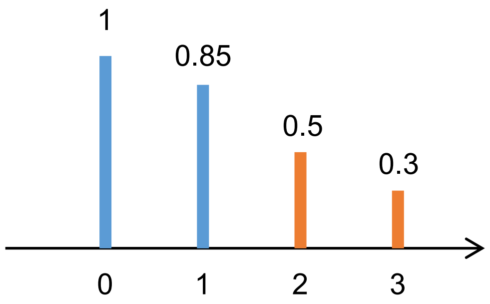
Dashed curves are from shakiba_3dj_elec_01_230223 slides 34 (DFE) and 39 (MLSE).
Markers are from Monte Carlo simulation of 10 million PAM-4 symbols with additive white Gaussian noise (results include error extension).

Consider a different interpretation

- ΔCOM is too optimistic when applied to a multi-tap DFE reference receiver
- Techniques to enable coexistence of DFE and MLSE tend to be expensive (and only partially effective)
- What if the multi-tap DFE reference receiver is not intended to represent an actual DFE, but instead is a convenient proxy for an FFE?

Can DFE be used as a proxy for FFE?

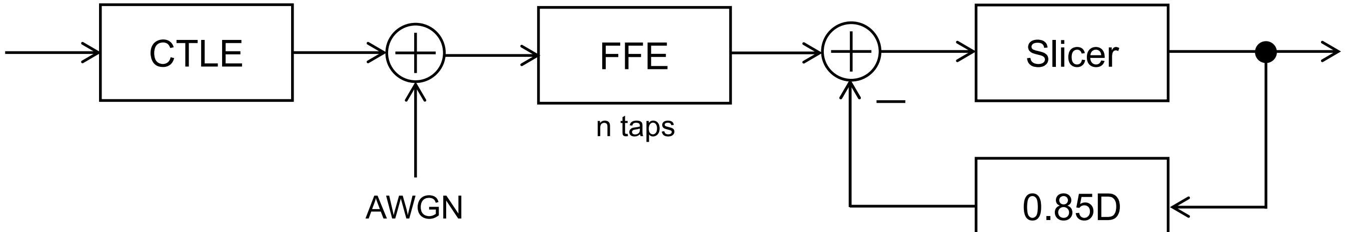


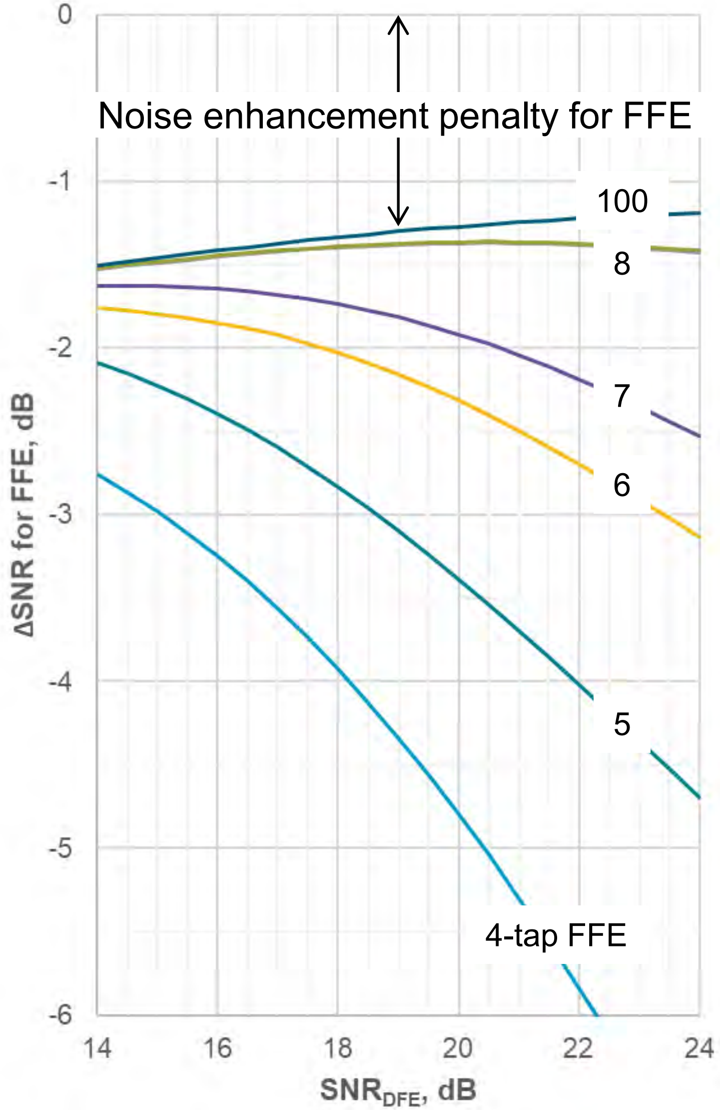


Partial response at CTLE output

DFE simply deletes unwanted inter-symbol interference (ignoring errors, error extension)

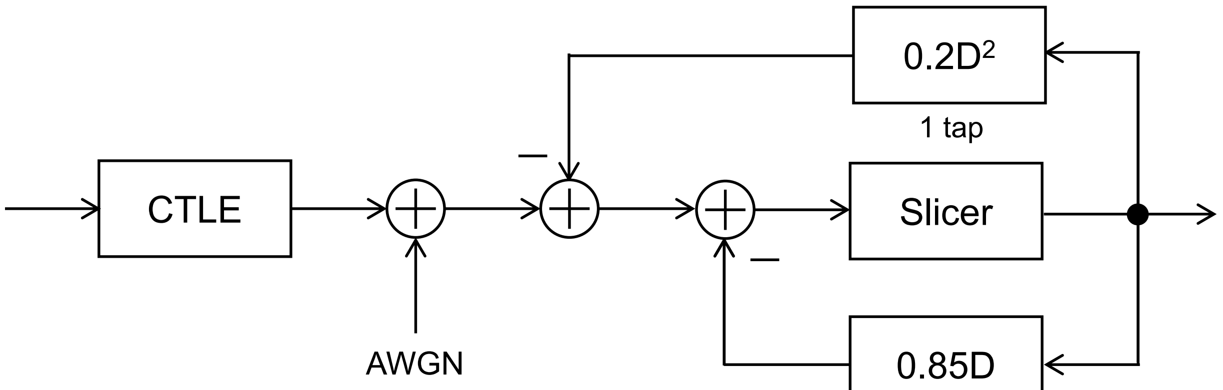
FFE requires more taps to do a similar job and it enhances noise

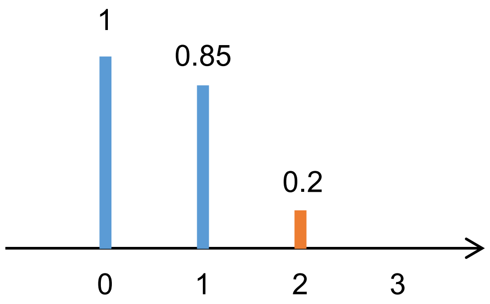




CTLE = continuous-time linear equalizer

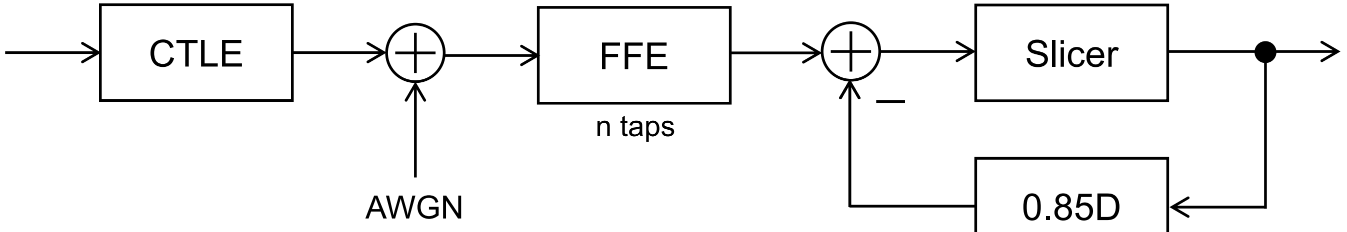
Smaller DFE corrections lead to smaller differences

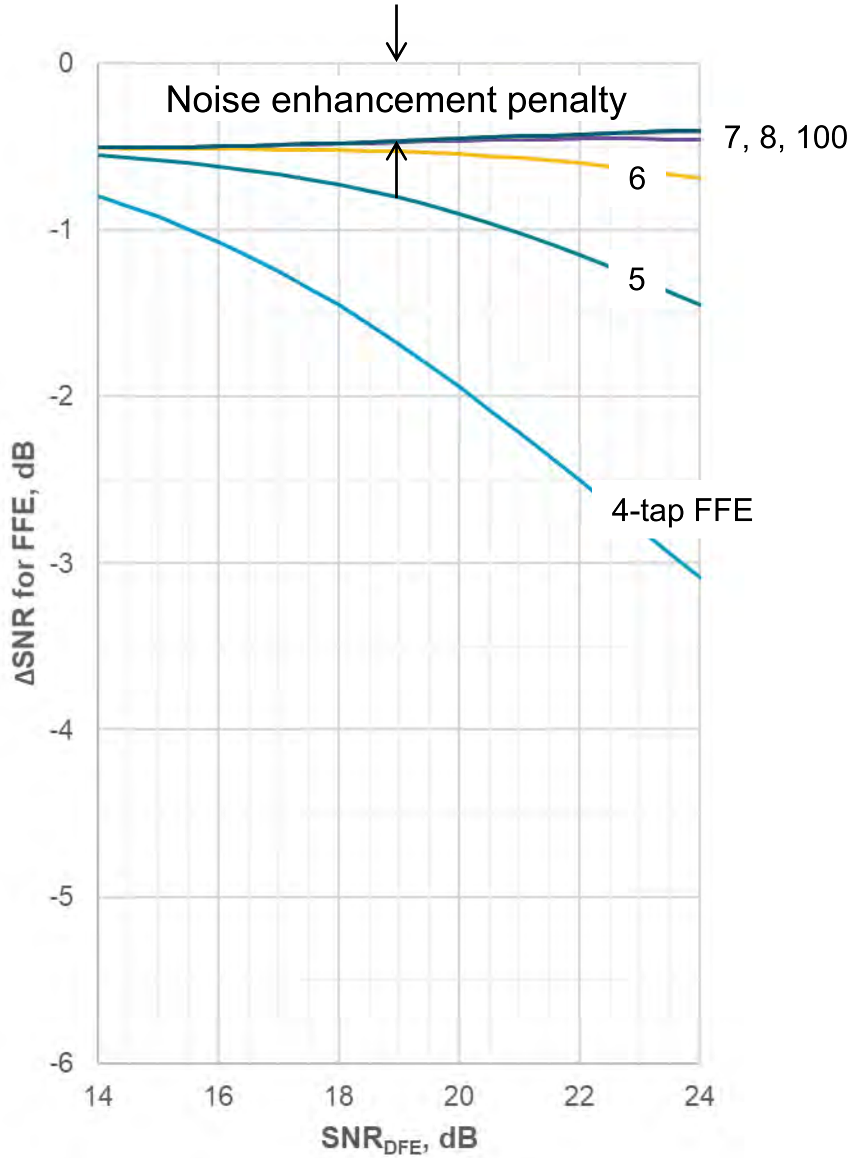




Partial response at CTLE output

FFE requires fewer taps (but still more than DFE) and noise enhancement penalty is reduced





Trade-offs between FFE and multi-tap DFE

- FFE requires more taps to approach DFE performance but cannot match DFE performance in the presence of input-referred noise
- While error extension is expected to be lower for FFE, error ratio targets are set assuming DFE-like error extension (no benefit given to FFE)
- FFE enables pre-cursor inter-symbol interference correction which can be expected to reduce the amount transmitter de-emphasis
- Lower transmitter de-emphasis suggests a high ratio of signal to noise at the receiver input which could improve FFE performance
- A multi-tap DFE reference receiver sweeps all of these trade-offs into the margin allocated for receiver implementation
- Since and MLSE-based receiver will most likely use FFE, FFE is the better performance reference for the application of ΔCOM

Proposal #2

- In order to take advantage of ΔCOM, stick close to the reference receiver used for the ΔCOM derivation
- This means the reference receiver should be FFE-based when MLSE is considered
- This requires formalization of an FFE-based (with 1-tap DFE) reference receiver
- Multi-tap DFE reference receiver could still be considered when ΔCOM is assumed to be 0 (no MLSE)
- However, pay attention to the number of taps assumed, and the limits on the coefficient magnitudes

References

[1] Shakiba, “A Path toward Incorporating Advanced Signal Processing in Electrical Channel Performance Assessment – Recap”, February 2023

[2] Shakiba, “Analysis of Noise Coloring Effect on MLSE COM Using Error Events”, April 2023

[3] Mellitz, “COM 4.0 Update”, February 2023