Problems of high DFE coefficients

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Abstract

- If we allow high DFE coefficients, we cannot meet MTTFPA (Mean Time to False Packet Acceptance) requirements at BER=1E-12 due to burst errors
  - Hence, bmax (max magnitude of relative DFE coefficient) is proposed to be 0.35
- There are some serious problems with bmax = 0.35 or 0.5
  - Problem 1: COM is not accurate when bmax < 1
  - Problem 2: BER (and COM) may be drastically degraded when bmax is 0.35 or 0.5
- COM should not be used with bmax < 1, because
  - COM is not accurate when bmax < 1 (Problem 1)
    - This may be fixed in the future
  - bmax = 0.35 rejects sufficiently good channels (Problem 2)
    - bmax = 0.35 is not necessary to meet the MTTFPA requirement
- We have two other options to satisfy the MTTFPA requirement:
  - Option 1:
    - Revise COM criteria so that we get BER<1E-15, if we pass COM test with DER0=1E-12, and
    - Test Rx for BER<1E-12 with restricted DFE coefficients, or for BER<1E-15 with no restriction
  - Option 2:
    - Use precoding to *eliminate* burst errors due to DFE error propagation

Study of bmax Effect on COM and BER

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- bmax(n)
  - 1.00, 0.50, 0.35 (for all n)
- CTLE
  - fp1: fb/4, fb/15, fb/60
  - fz: same as fp1
  - DC gain:
    - min -12dB, max 0dB, step 1dB when fp1 = fb/4 or fb/15
    - min -8dB, max 0dB, step 0.5dB when fp1 = fb/60
- Channel data
  - 3m cable: B(30Q4) – fair, G(26QQ) – typical, H(26Q4) – good
  - 5m cable: Q(24QQ) – fair, N(26QQ) – typical, R(24QQ) – good
- Test conditions
  - Test 1 (PKG trace = 12mm) and Test 2 (PKG trace = 30mm)
  - DER0 = 1E-12
- Equalizer parameters: optimized by reference COM code (i.e. http://www.ieee802.org/3/bj/public/tools/ran_com_3bj_3bm_01_1114.zip)
- BER and Eye: analyzed by in-house tool
  - Parameters of statistical analysis:
    - TX RJ = 0.01UI (rms), TX DJ = 0.15UI (δ-δ), TX EOJ = 0.035UI (p-p)
    - RX RJ = 0.005UI (rms), RX DJ = 0.075UI (δ-δ), RX EOJ = 0.0175UI (p-p)
    - TX output noise SNR_{TX} = 27 (dB)
    - RX input noise η_0 = 5.20E-8 (V^2/GHz)
    - Receiver 3dB bandwidth = 0.75 (fb)

Effect of fp1 on COM and BER for 3m Cable

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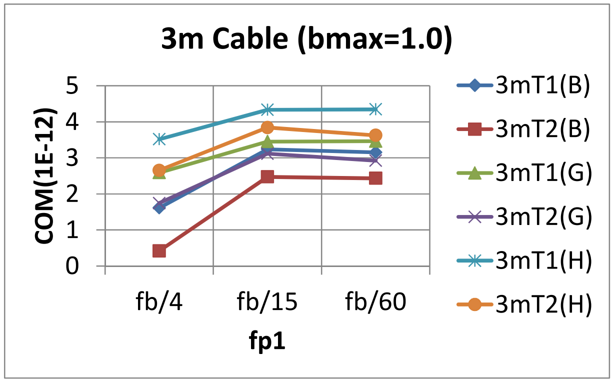
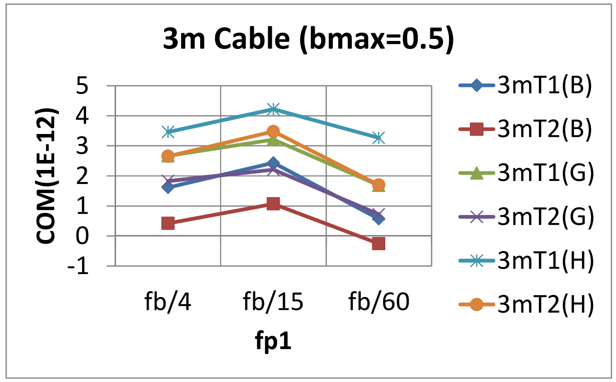
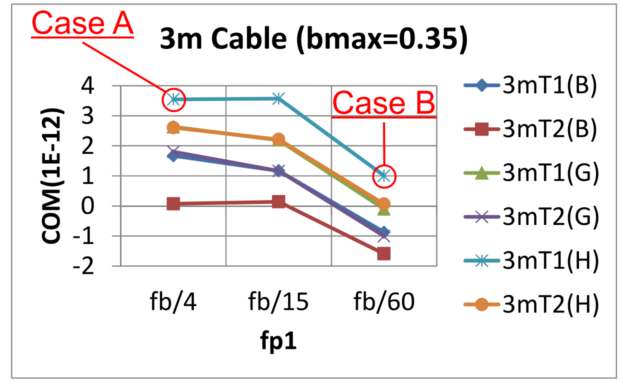
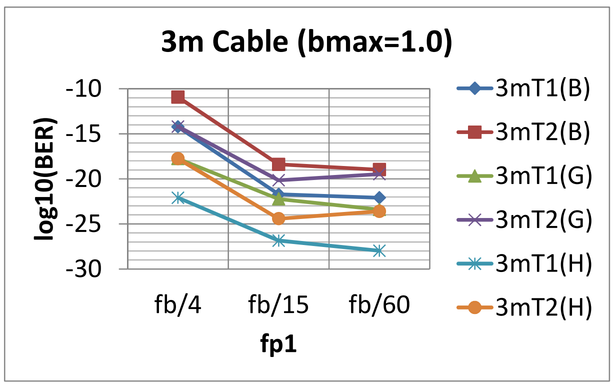
fp1 vs COM (DER0=1E-12)

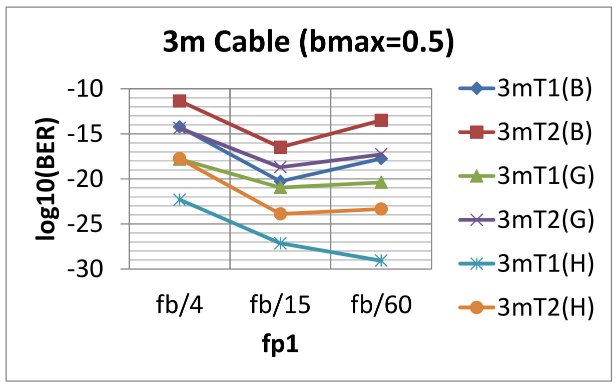


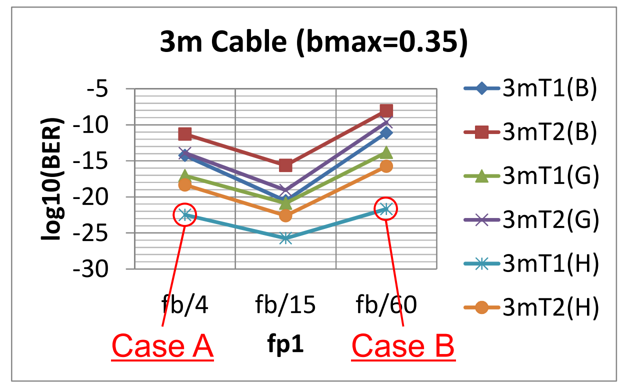




fp1 vs BER



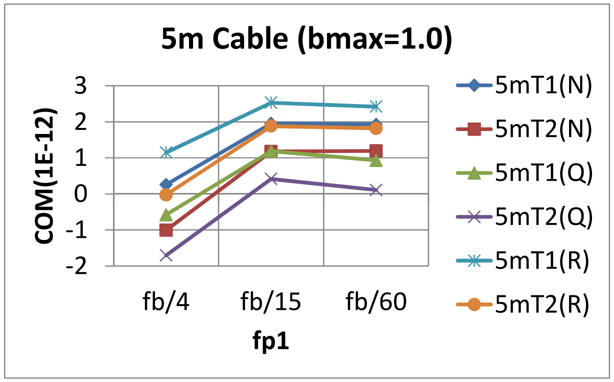


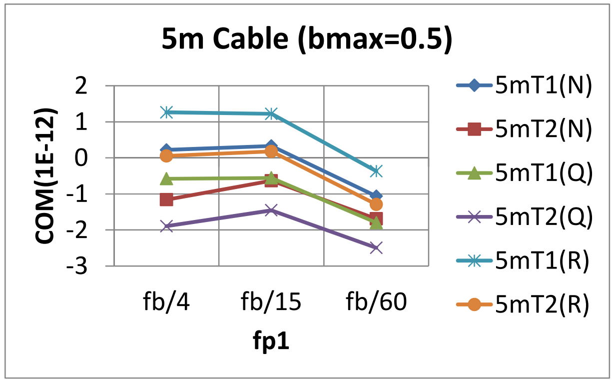


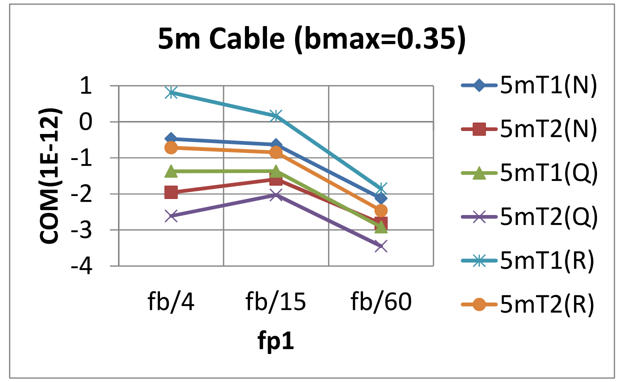
- COM and BER are roughly consistent when bmax=1.0
- COM and BER are very inconsistent when bmax=0.5 or 0.35

Effect of fp1 on COM and BER for 5m Cable

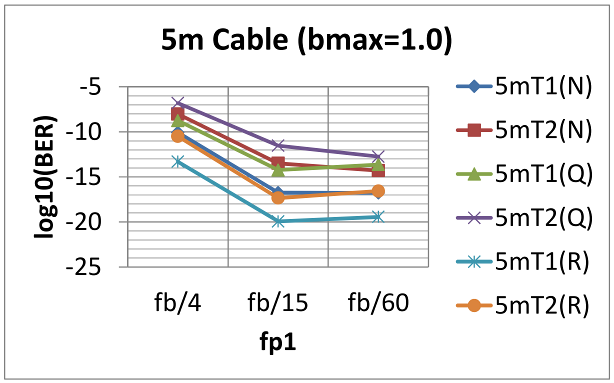
- fp1 vs COM (DER0=1E-12)

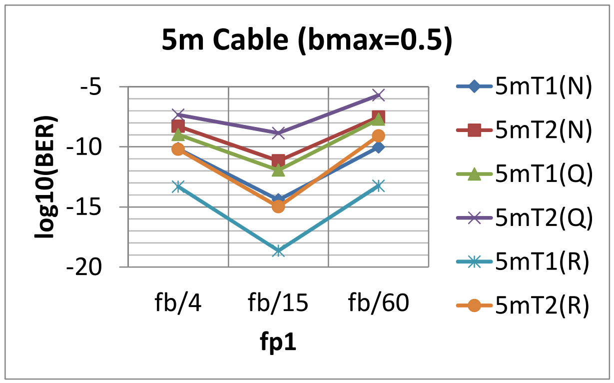


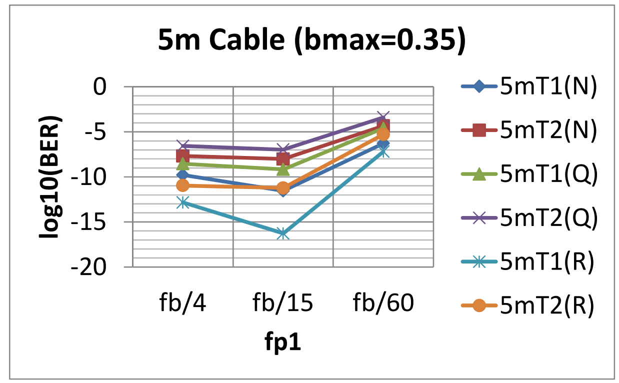




- fp1 vs BER







- COM and BER are roughly consistent when bmax=1.0
- COM and BER are very inconsistent when bmax=0.5 or 0.35

Effect of bmax on COM

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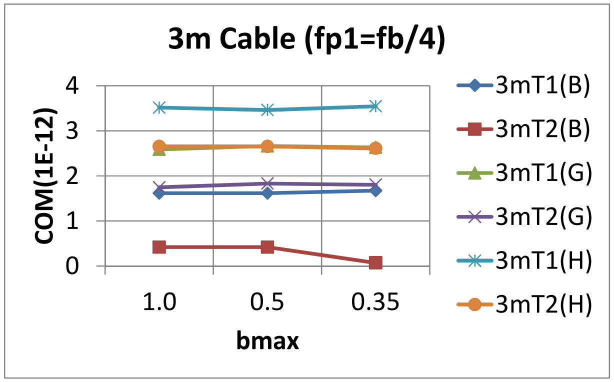
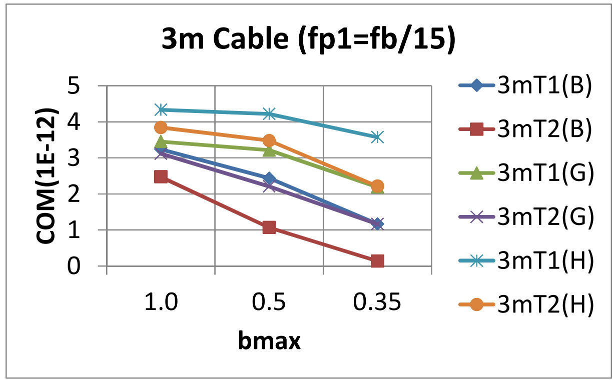
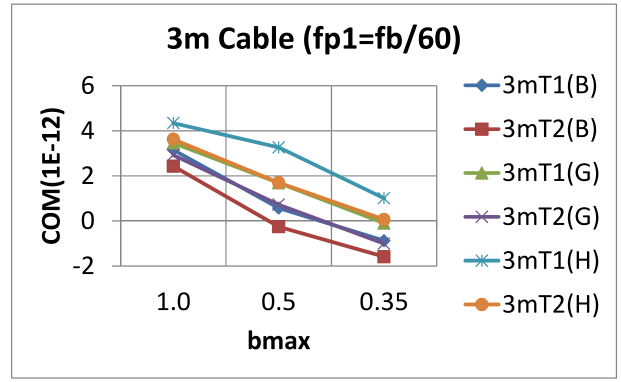
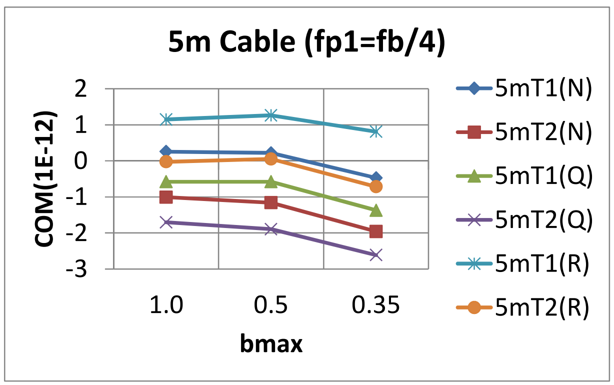
- bmax vs COM (3m Cable)

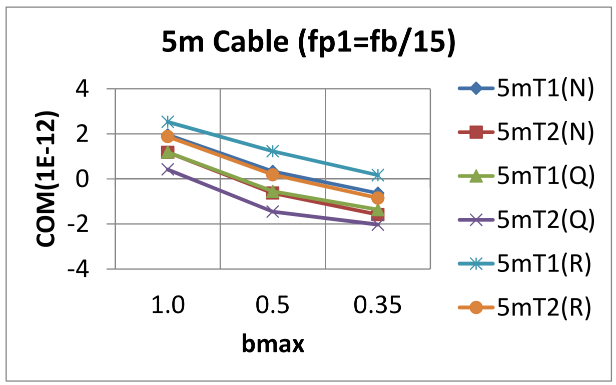


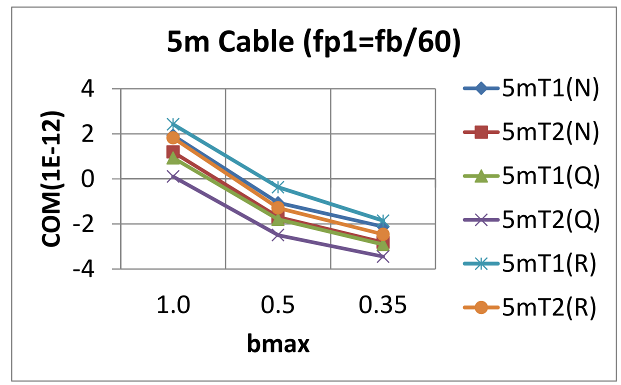




- bmax vs COM (5m Cable)







- COM is not much affected by bmax when fp1 = fb/4
- COM is largely degraded by bmax when fp1 = fb/15 or fb/60

Effect of bmax on BER

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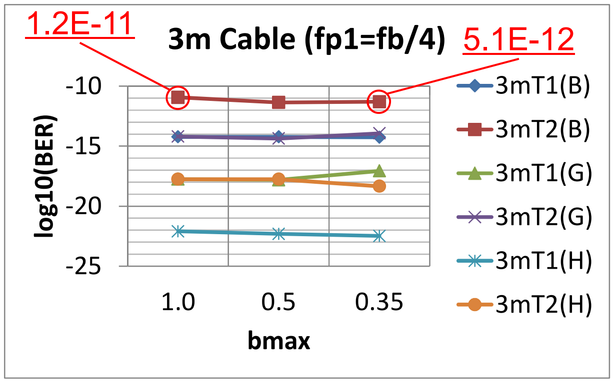
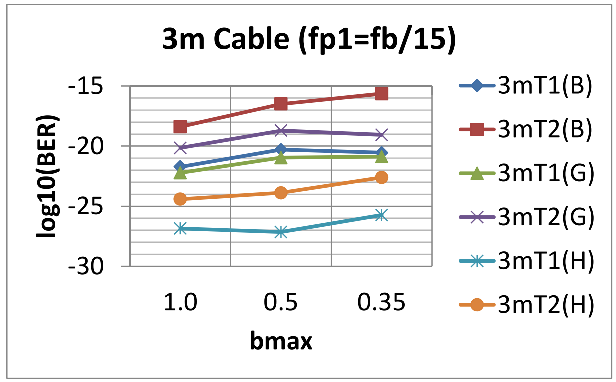
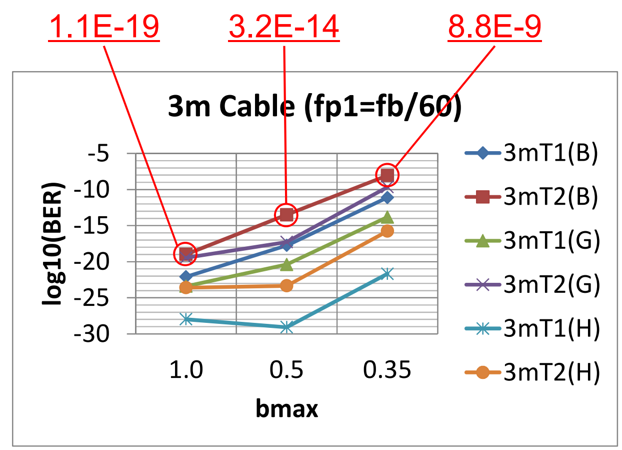
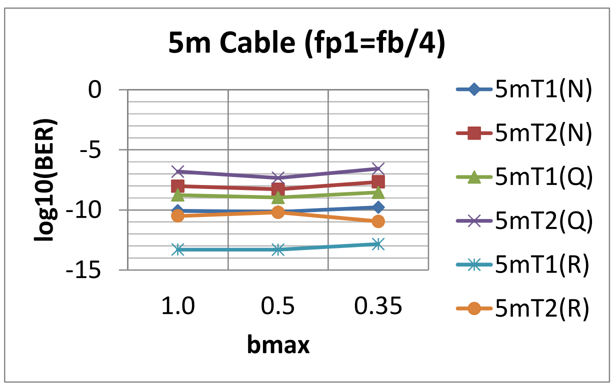
bmax vs BER (3m Cable)

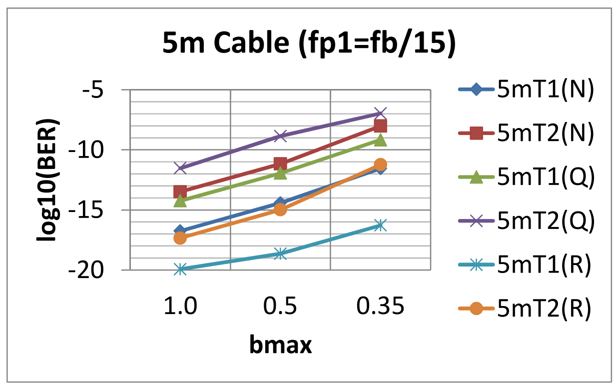


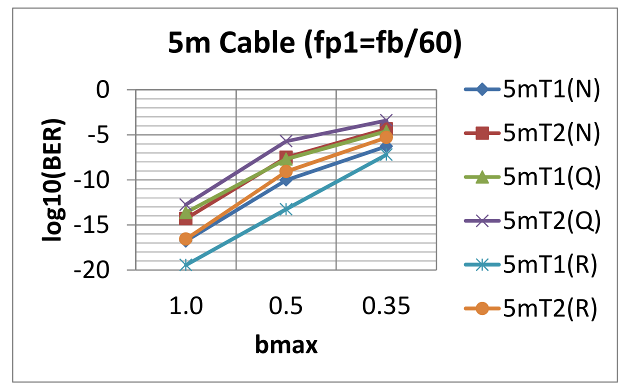




bmax vs BER (5m Cable)







- BER is not affected by bmax when fp1 = fb/4
- BER is largely degraded by bmax when fp1 = fb/15 or fb/60
  - 3m T2(B) is good with fp1=fb/60 and bmax=1, but fails with bmax=0.35

Detail Analysis of Case A and Case B

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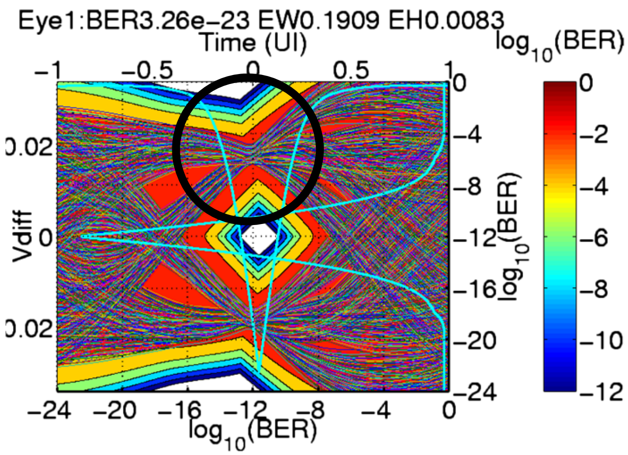
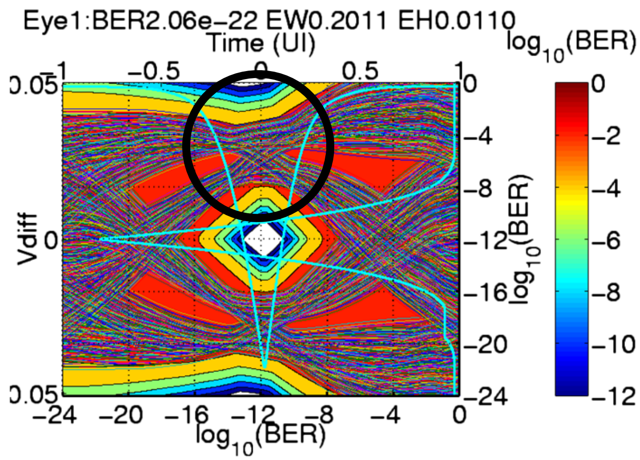
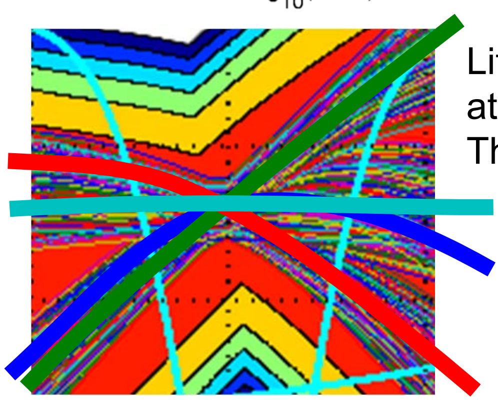
- Channel: 3m cable H(26Q4), Test 1, bmax=0.35
- Case A (fp1=fb/4)
  - DCgain = -12 dB, b(1) = 0.337389 (not restricted)
  - COM (DER0=1E-12)
    - 3.5463 dB (reference implementation)
    - 3.71644 dB (our implementation)
  - BER = 3.26E-23
- Case B (fp1=fb/60)
  - DCgain = -6.5 dB, b(1) = 0.35 (restricted by bmax)
  - COM (DER0=1E-12)
    - 1.0056 dB (reference implementation)
    - 1.37456 dB (our implementation)
  - BER = 2.06E-22

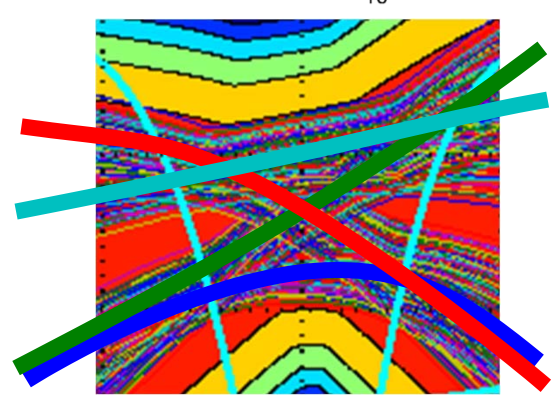






Little data dependence at the best phase.
This is OK.

- 0-1-0
- 0-1-1
- 1-1-0
- 1-1-1



Large data dependence at the best phase.
This causes the problem.

Two Options to meet the MTTFPA requirements

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- Option 1
  - Revise COM criteria (currently 3dB) so that there is enough margin
    - To achieve BER<1E-15, when we pass the COM test with DER0=1E-12
      - Statistically guarantee the channel quality so that we can achieve BER<1E-15
      - I am currently working on this statistical calculation
  - Test Rx for BER<1E-15 with no restrictions on DFE coefficients
    - For a combination of compliant channel and Rx, since BER will be less than 1E-15, we will meet the MTTFPA requirement
    - We may use other means such as plotting a bathtub curve to shorten test time
  - I have considered an alternative Rx test for BER<1E-12 with DFE coefficients < 0.35, but such an alternative test is not acceptable
    - For some good channels, BER can be <1E-15 with high DFE coefficients, whereas BER is degraded >1E-12, if high DFE coefficients are not allowed
      - Such good channels have high loss in high frequency due to material loss, but the channel design is good enough, because we can achieve sufficiently low BER. I think such good design channels should be accepted as compliant.
- Option 2
  - Use precoding to *eliminate* burst errors due to DFE error propagation
    - This is a simple solid solution (next page)

Precoding

- Tx side: encode the transmitting data by b(k) = b(k-1)^a(k)
- Rx side: decode the received data by a'(k) = b(k)^b(k-1)
  - ^: an exclusive-OR operator
  - a(k): original data sequence
  - b(k): transferred data sequence (NRZ)
  - a'(k): recovered data sequence
- Any burst error on b(k) from k1 to k2 (k1<=k2) is converted to two errors on a'(k), one at a'(k1), and another at a'(k2+1)
  - Hence, it eliminates any burst errors
- This is essentially in the same principle as precoding in Duobinary signaling, or precoding in KP4 (although it is a variant for PAM4).
  - We cannot omit DFE to achieve low BER. That is a difference from Duobinary signaling.
- Minor drawbacks
  - If there is no error propagation, BER for random error is doubled
    - I think this is OK, because the packet is anyway dropped, or protected by FEC
  - If there is no DFE, unnecessary extra circuit is required
    - I think this is OK, because DFE is commonly used
  - The encoder has a critical path of an exclusive OR within 1UI
    - I think this is achievable
- I don't know why this hasn't been discussed (maybe everyone is too busy), but I believe this is a solid solution and better than restricting high DFE coefficients
- Is it too late to discuss this scheme? Or, am I missing something?

Appendix

Difference between COM and our BER analysis

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- COM
  - Directly calculate a single probability distribution (i.e. PDF or CDF)
  - Jitter is added at all ISI locations
- Our BER analysis
  - Calculate multiple (4 for NRZ, 32 for PAM4) probability distributions for all the combinations of prior, next, and cursor symbol levels
    - # of cursor symbol levels is half, because of vertical symmetry
    - Jitter is added differently for each distribution, taking account of each transition
      - Jitter at 010 is smaller than at 011 or 110, because derivative is cancelled and small
      - No jitter is added for distribution at 111 sequence, because there is no transition
  - Final CDF is the worst case that is the max value of multiple CDFs:

$$P_{worst}(y) = \frac{1}{2}\max_k[P_k(y)] = \frac{1}{2}\max_k\left[\int_{-\infty}^{y} p_k(y)dy\right]$$

    - Here, $P_{worst}(y)$ and $P_k(y)$ are CDFs and $p_k(y)$ are PDFs.
    - Coefficient $1/2$ is for the fact that this is only for lower side of the entire final CDF:

$$P_{final}(y) = \max[P_{worst}(y), P_{best}(y)] = \max\left[P_{worst}(y), \min_k[P_k(y)]\right]$$

  - No jitter is added at ISI locations other than between prior symbol and cursor symbol or between cursor symbol and next symbol
    - Due to this difference, estimated BER is a little lower than DER0 when COM is 0dB

Very Detail Analysis of Case A and Case B

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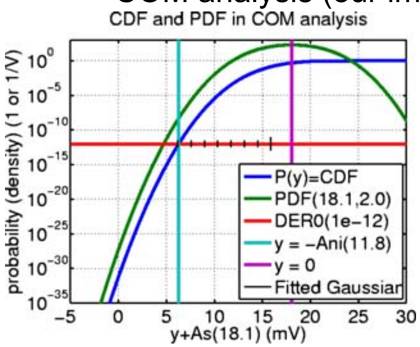
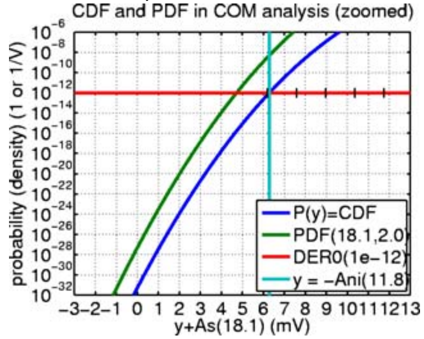
Notation: PDF(μ,σ), μ=mean, σ=RMS

- Case A (fp1=fb/4)
  - COM analysis (our implementation)



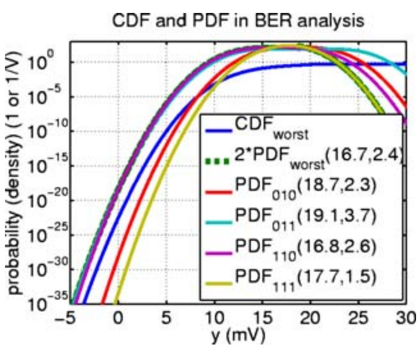


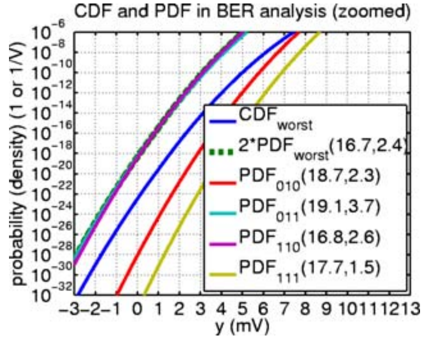
PDF: As=μ=18.1mV, σ=2.0mV, Ani=11.8mV~5.9σ

COM=20*log10(18.1mV/11.8mV)=3.72dB

BER=P(-As)=5.3E-32

  - BER analysis (vertical PDF/CDF at the best phase)



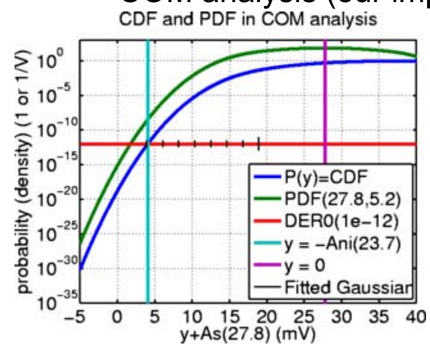


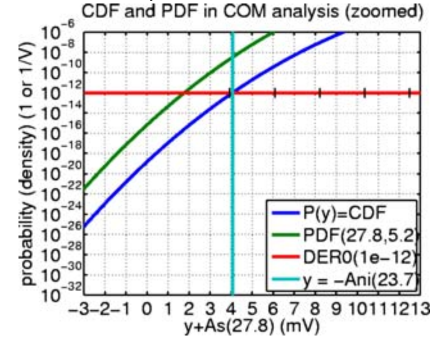
2*PDF_{worst} (μ=16.7,σ=2.4) follows PDF_{110} (μ=16.8,σ=2.6)

σ of PDF_{010} & PDF_{111} is smaller than PDF_{011} & PDF_{110}

μ is similar between PDFs with respect to σ value

- Case B (fp1=fb/60)
  - COM analysis (our implementation)





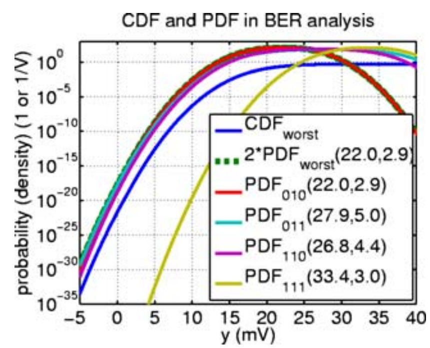
PDF: As=μ=27.8mV, σ=5.2mV, Ani=23.7mV~4.6σ

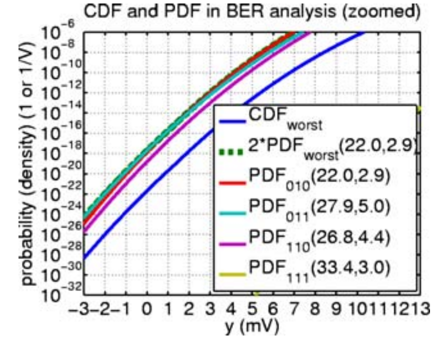
COM=20*log10(27.8mV/23.7mV)=1.38dB

BER=P(-As)=1.51E-19

σ and BER are much larger (COM is smaller) than Case A

  - BER analysis (vertical PDF/CDF at the best phase)





2*PDF_{worst} (μ=22.0,σ=2.9) follows PDF_{010} (μ=22.0,σ=2.9)

σ of PDF_{010} & PDF_{111} is smaller than PDF_{011} & PDF_{110}

μ of PDF_{010} and PDF_{111} are quite different w.r.t. σ value

σ of 2*PDF_{worst} and BER are similar to Case A

Suggestions for COM

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- In our BER analysis, use of multiple distributions was the key to obtain satisfactory results for test cases where a single large ISI (i.e. the largest ISI) is *close to the RSS value of all ISIs*
  - Our BER analysis is not necessarily the best, but probably better than COM
- COM is very likely inaccurate when a DFE coefficient is restricted by bmax < 1, because restriction of a DFE coefficient causes the single large residual ISI close to the RSS value
- We may fix the COM formula in a similar way to our BER analysis, but I have not come to a complete suggestion yet
  - I may provide it later, but it takes some time
- In the mean time, it is OK to use the current COM with bmax = 1 and high tap-count DFE, because no single large ISI is left after DFE cancels major ISIs
  - In fact, I do not see a large discrepancy between COM and BER as long as I use bmax = 1

References

[1] http://grouper.ieee.org/groups/802/3/by/public/May15/sun_3by_01_0515.pdf

[2] http://www.ieee802.org/3/by/public/adhoc/architecture/sun_061015_25GE_adhoc.pdf

References of Channel Data

- ~ = http://www.ieee802.3.org/3/
- 3 meter cable assembly
  - A: ~/100GCU/public/ChannelData/CD_11_0415/3m_QSFP_30AWG.zip (Tx2-Rx2.s4p)
  - B: ~/by/public/channel/TE_QSFP_4SFP_3m_30AWG.zip (TE_3m30AWG_QSFP_4SFP_P1_TX1_P2_RX1_THRU.s4p)
  - C: ~/100GCU/public/ChannelData/Molex_11_0516/bugg_02_0511.zip (3m 30AWG Unicore/Cable 1/P1 RX1/TX1.s4p)
  - D: ~/by/public/channel/TE_QSFP_4SFP_3m_28AWG.zip (TE_3m28AWG_QSFP_4SFP_P1_TX1_P2_RX1_THRU.s4p)
  - E: ~/by/public/channel/TE_QSFP_QSFP_3m_26AWG_MaxLossExample_15p993dB.zip
  - F: ~/by/public/channel/Amphenol_NDACGJ-0003-QSFP-4SFP_3m_26AWG_APN43140033HXJ.zip (P2TX1_P1RX1.s4p)
  - G: ~/100GCU/public/ChannelData/Molex_11_0516/bugg_02_0511.zip (3m 26AWG leoni/P1 RX1/TX1.s4p)
  - H: ~/by/public/channel/TE_QSFP_4SFP_3m_26AWG.zip (TE_3m26AWG_QSFP_4SFP_P1_TX1_P2_RX1_THRU.s4p)
  - J: ~/by/public/channel/TE_QSFP_QSFP_3m_25AWG_MaxLossExample_15p35dB.zip
  - K: ~/by/public/channel/TE_QSFP_QSFP_3m_24AWG_MaxLossExample_14p49dB.zip
  - L: ~/by/public/channel/TE_QSFP_4SFP_3m_24AWG.zip (TE_3m24AWG_QSFP_4SFP_P1_TX1_P2_RX1_THRU.s4p)
- 5 meter cable assembly
  - M: ~/100GCU/public/ChannelData/CD_11_0415/5m_QSFP_26AWG.zip (Tx1-Rx1.s4p)
  - N: ~/100GCU/public/ChannelData/Molex_11_0516/bugg_02_0511.zip (5m 26AWG Leoni/P1 RX1/TX1.s4p)
  - P: ~/by/public/channel/Amphenol_NDACGJ-0005-QSFP_4SFP_5m_26AWG_APN14440053HYT.zip(P2TX1_P1RX1.s4p)
  - Q: ~/100GCU/public/ChannelData/Molex_11_0210/5m/5m_all.zip (P1 RX0/TX0.s4p)
  - R: ~/100GCU/public/ChannelData/molex_12_0310/cableb_bugg_03_0312.zip (P1RX1/P2TX1.s4p)

Thank you