Sensitivity to Timing Error Jitter for NRZ and PAM-4

for IEEE 802.3bj 100Gb/s Backplane and Copper Cable Assemblies Task Force

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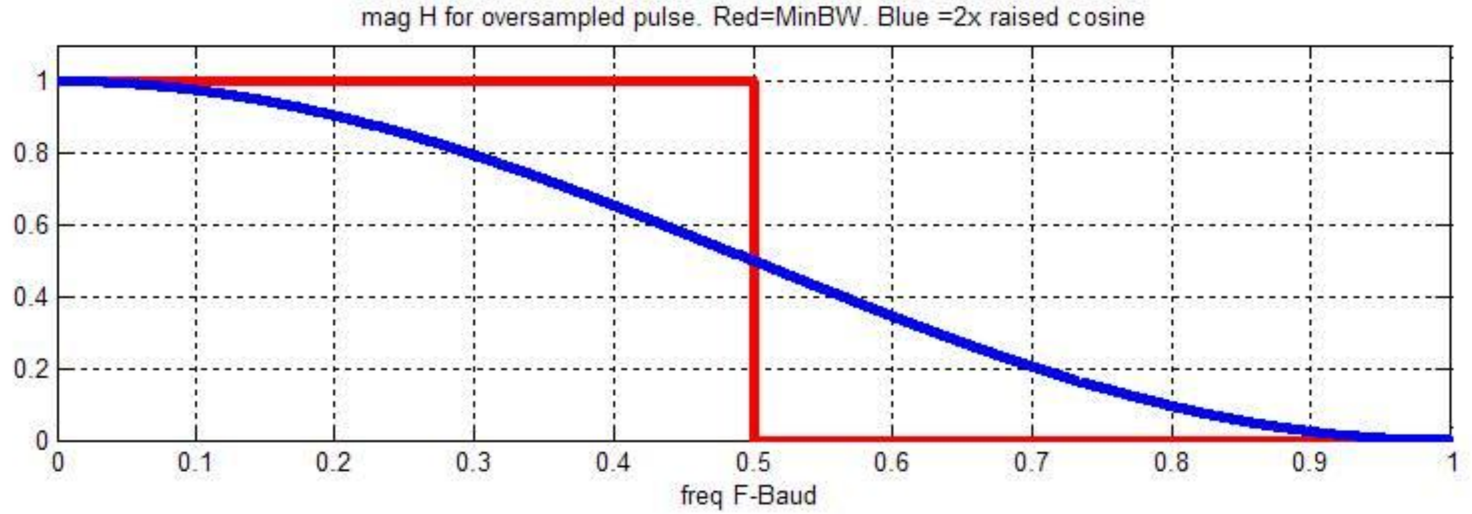
Overview of Eye Diagrams and Jitter Specifications

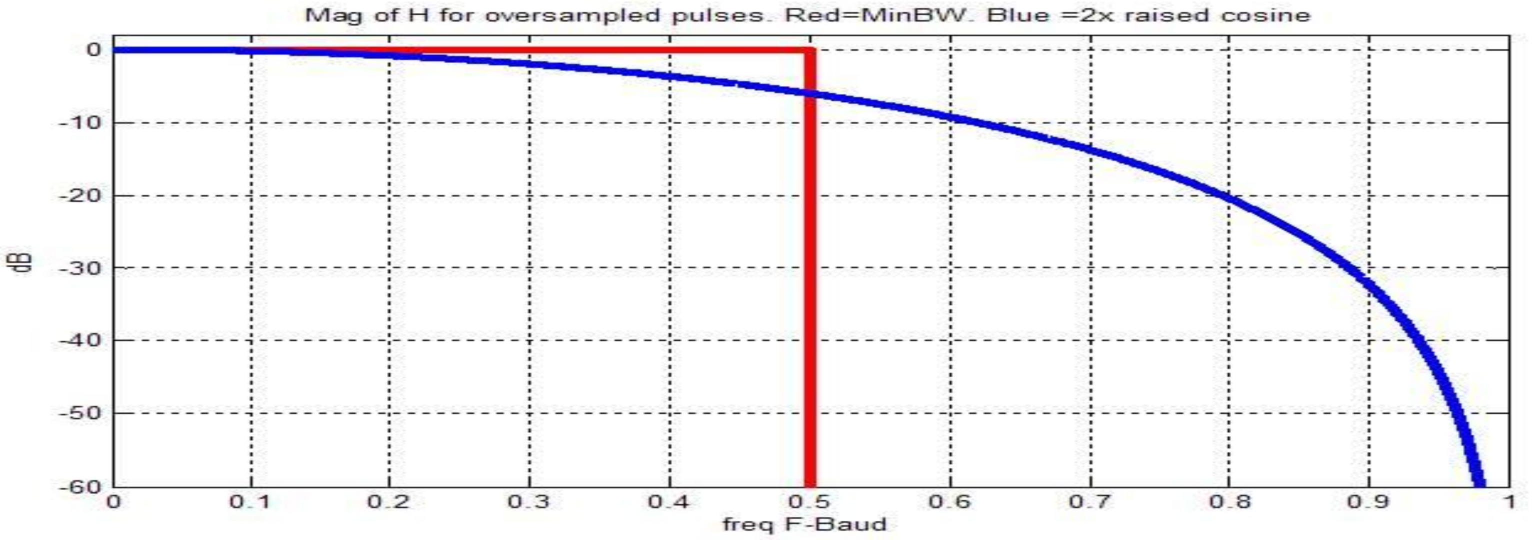
- Several presentations at the Study Group, Task Force, and other venues have expressed concern over 'very small' horizontal eye openings for PAM-4
- Several presentations have compared PAM-4 and NRZ using equal 'UI' jitter, where a 'UI' is a Baud period, meaning the physical jitter for PAM-4 is twice that of NRZ w/ the same user data rate
  - No theoretical motivation for running PAM-4 at twice the physical jitter
  - PAM-4 is motivated by channels that lack BW, but that have 'enough' SNR to achieve 2 bits/Baud
- Since PAM-4 systems operate at higher SNR, in general the system designer must reconsider all components of the SNR budget, and not assume that prior tradeoffs for NRZ systems will remain optimal or viable
- This presentation looks at both NRZ and PAM-4 systems with different amounts of 'analog BW' and their performances in 'low frequency' jitter

Excess Analog Bandwidth and Eye Diagrams

- To clarify the relationship between choice of modulation (NRZ and PAM-4 here) and ‘Eye Shape’, we consider only
  - No noise or distortion, so ‘signal only’
  - No mis-equalization
  - So the vertical eye is maximally open, except for ‘sample time errors’
- Two different choices of ‘Excess Analog Bandwidth’ are considered
  - Minimum BW, which only includes signal energy up to the Nyquist rate
  - A full raised cosine roll off, which includes energy up to the Baud Rate, which is twice the BW of ‘minBW’
  - Both of these examples are ‘idealized’ (hard to achieve in practice), but they well bracket any practical Baud rate system
  - Note that the same physical BW of 13GHz is minBW for NRZ but is ‘full raised cosine’ BW for PAM-4 at the same user rate.

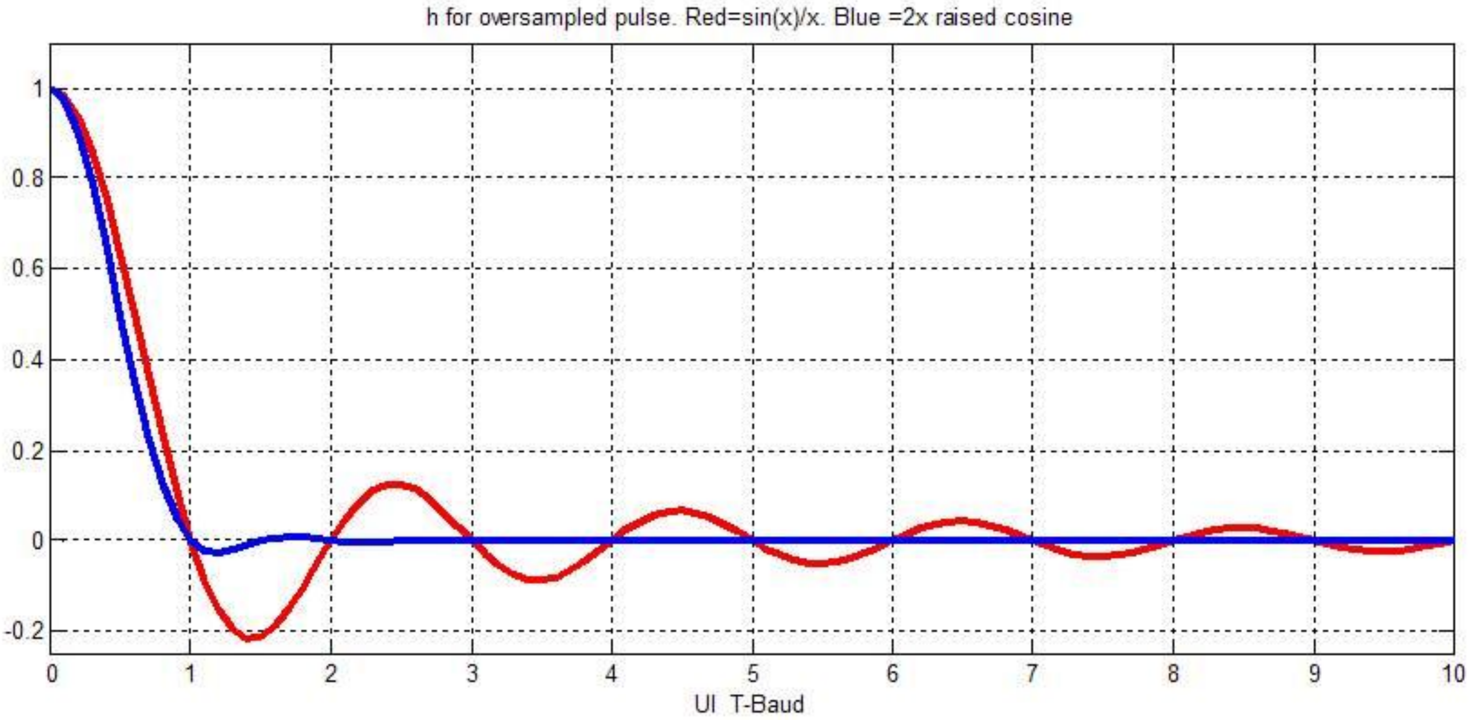
Excess BW in the Frequency Domain





- Red = Minimum BW, also known as ‘brick wall’
- Blue = Raised Cosine in frequency, BW up to the Baud rate, which is twice the minimum BW

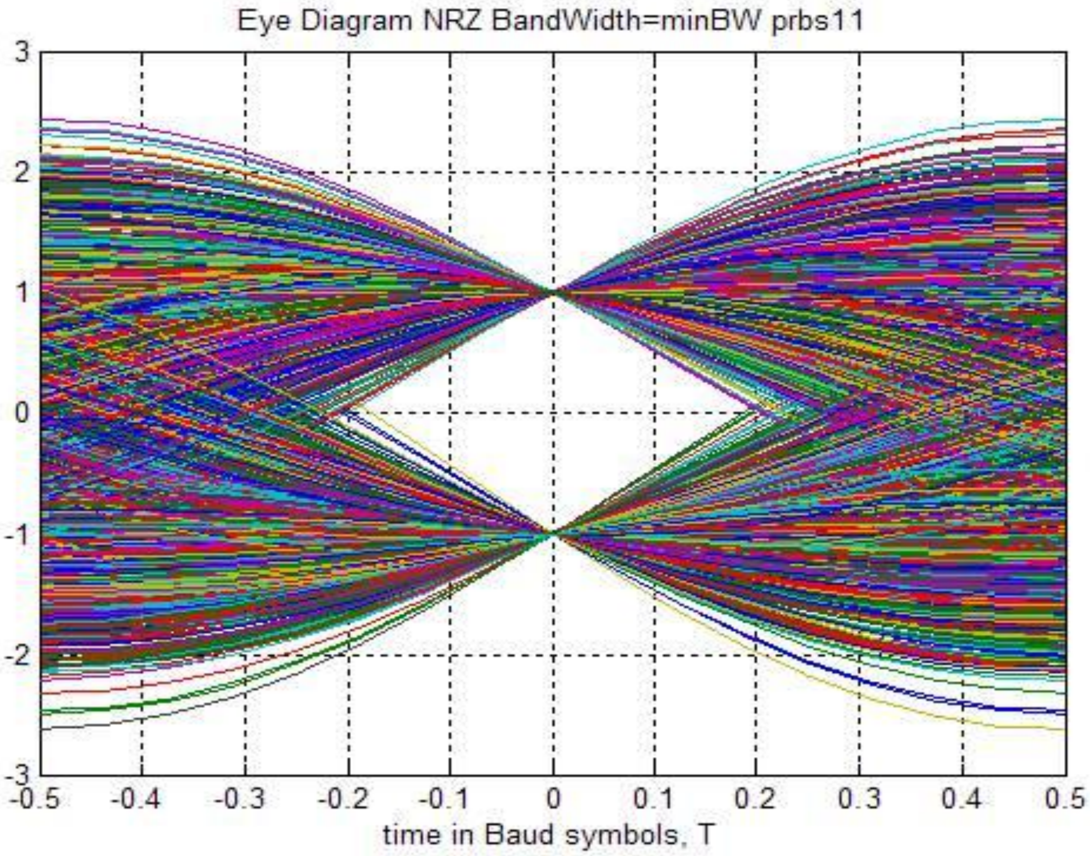
Excess BW in the time domain



- Red = Minimum BW, which gives as Sin(x)/x
  - Large overshoots that last many Baud periods
- Blue = Raised Cosine with BW up to the Baud rate
  - Much smaller overshoots that die out much quicker
- Both pulses are even symmetric around zero, only positive time shown

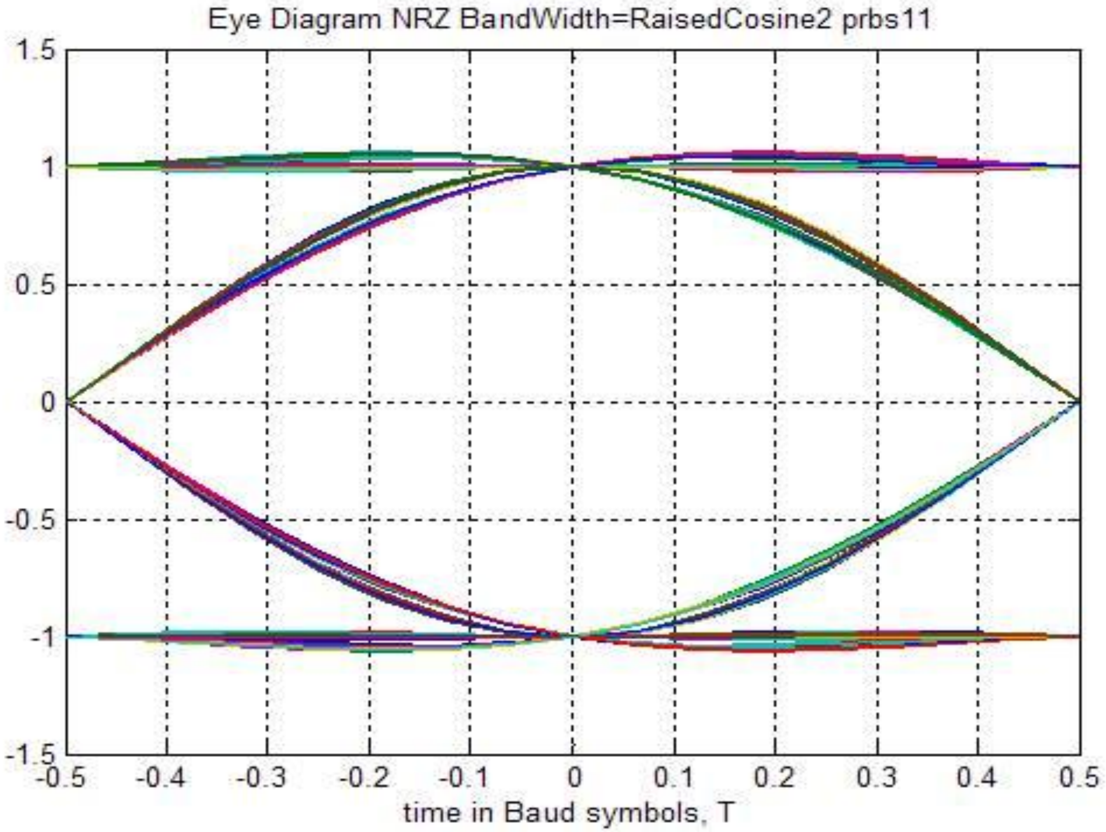
NRZ with Minimum BandWidth (no DFE)

- Minimum Bandwidth is a ‘brick wall’ cutoff at Nyquist, so no ‘excess bandwidth’ is used
    - I.e., a13MHz analog BW for 26Mbps raw data rate
- The vertical opening is 2 by definition of scaling and ‘perfect equalization’
- The horizontal opening is only about +/- 0.18T due to the minimum bandwidth



NRZ with Raised Cosine (no DFE)

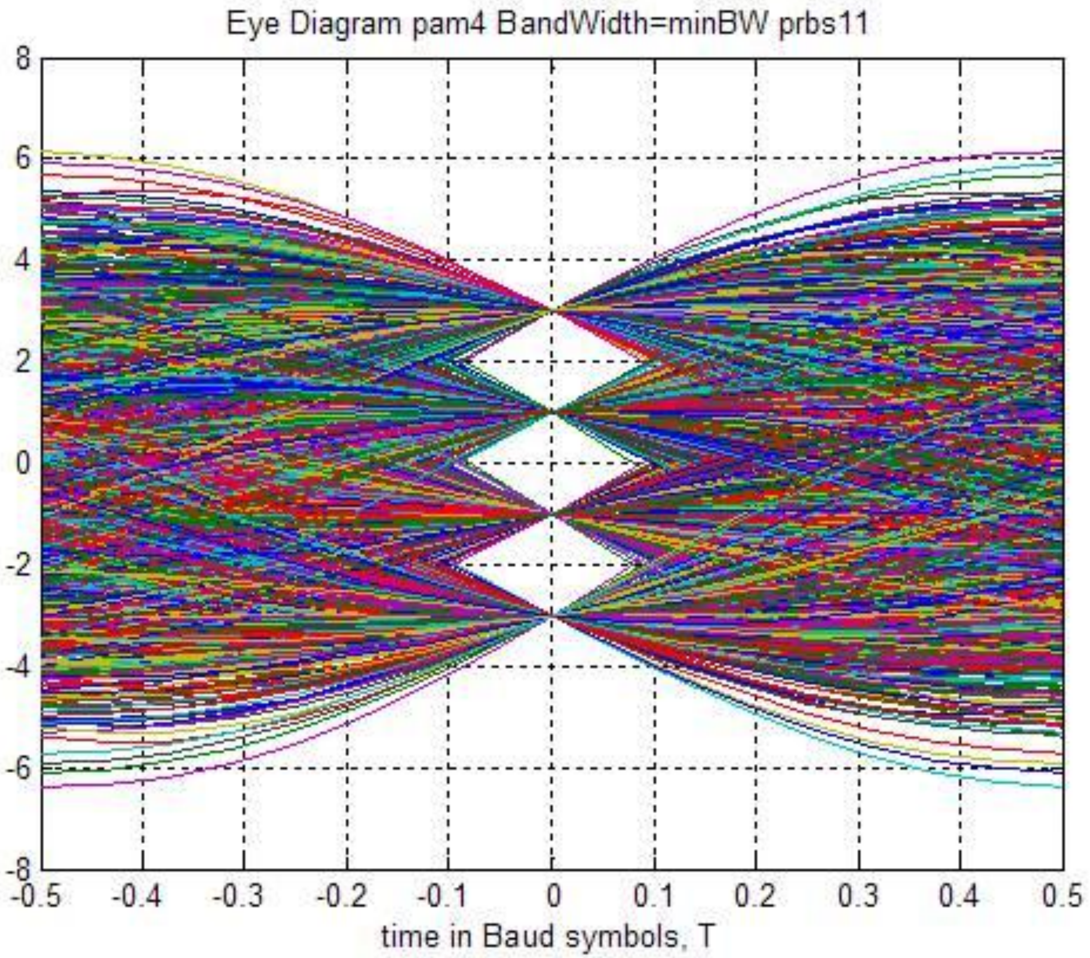
- A Raised Cosine with twice the minimum bandwidth is used
  - I.e., a 26 GHz analog BW is used for a 26Gbps raw rate
- This is a common textbook example of a 'full response' Nyquist criteria function
- The horizontal eye is the commonly expected +/- 0.5T



- For 26 Gbps, this requires well controlled analog response out to Fs = 26 GHz
  - Phase must be close to 'matched filter phase' to achieve constructive aliasing
  - Amplitudes must effect the desired ratio of the raised cosine curve
  - And requires useful SNR out to 26 GHz
  - Not generally feasible

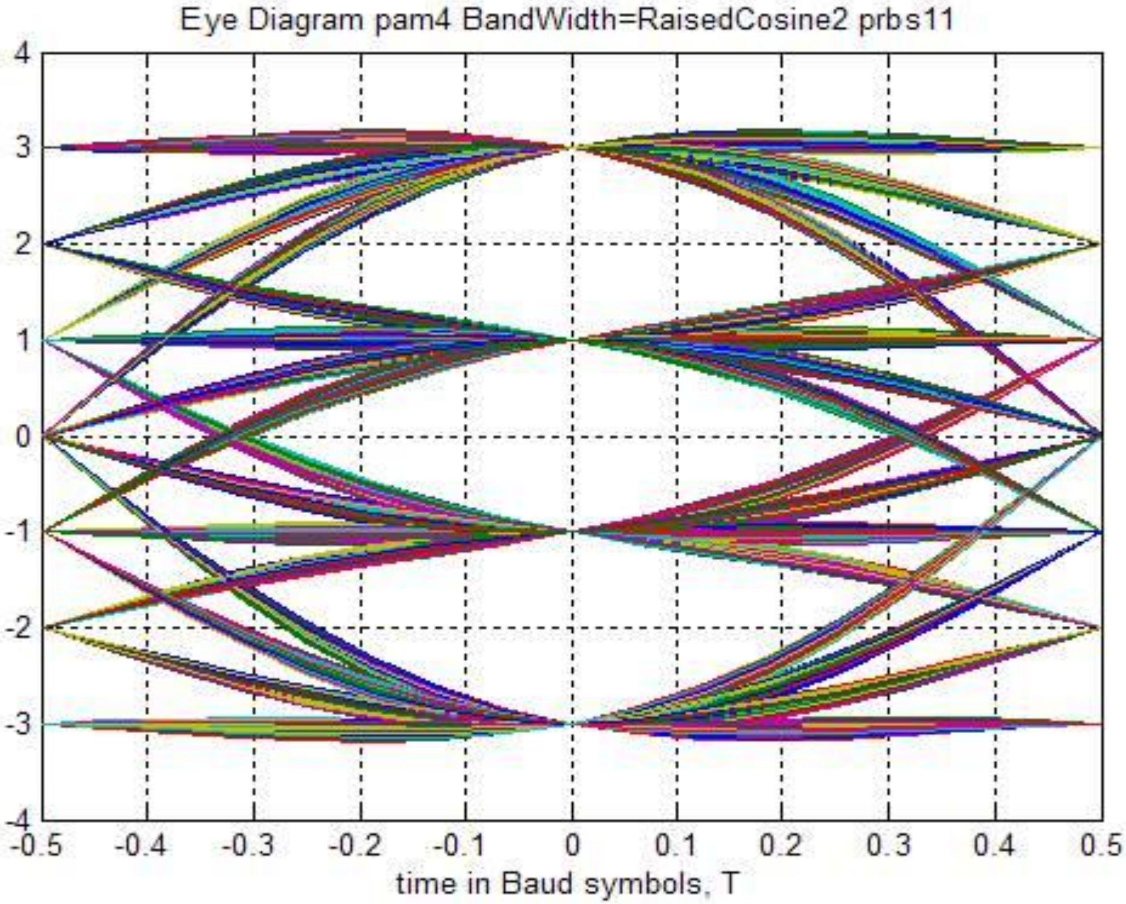
PAM-4 with Minimum BandWidth (no DFE)

- With minimum Bandwidth response the PAM-4 horizontal eye opening is about +/- 0.085 T
  - Analog BW is 6.5 GHz for 26 Gbps raw data rate
- But the Baud period T for PAM-4 is twice that of NRZ at the same user data rate
- So the horizontal eye opening in absolute time is approximately the same for min BW PAM-4 as for min BW NRZ
  - 0.17 vs 0.18 T of NRZ



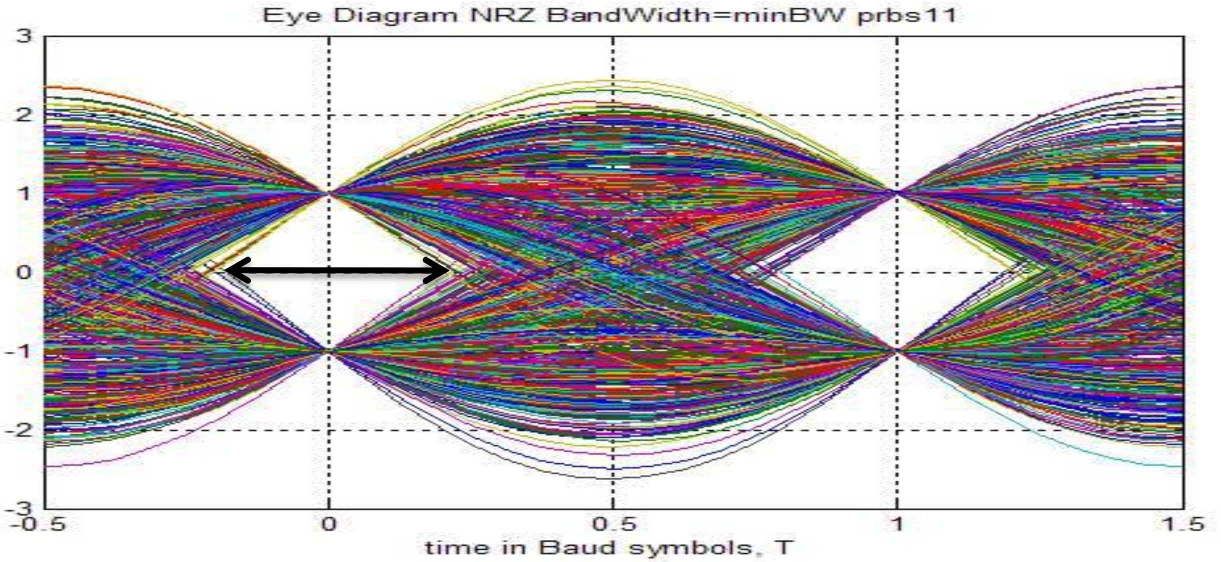
PAM-4 with Raised Cosine (no DFE)

- With Raised Cosine response the PAM-4 horizontal eye opening increases to +/- 0.3T for the central eye and to +/- 0.23T for the outer eyes
  - Analog BW of 13 GHz is used here for 26 Gbps raw data rate

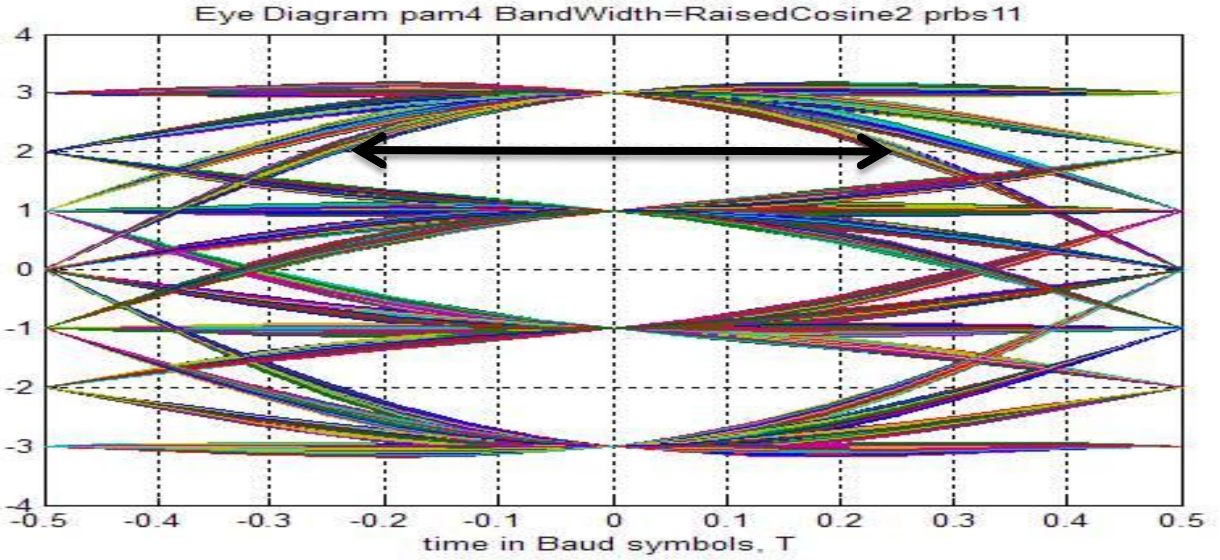


Compare Eyes with equal 13GHz Analog Bandwidth

- NRZ and PAM-4 are compared with equal fixed 13GHz analog BW
- So the NRZ is ‘minimum BW’ while the PAM-4 is the ‘raised cosine’ BW
- The NRZ plot is adjusted for equal physical time scale, so two periods shown
- The horizontal eye opening of PAM-4 is 2.5x wider in time than the NRZ opening

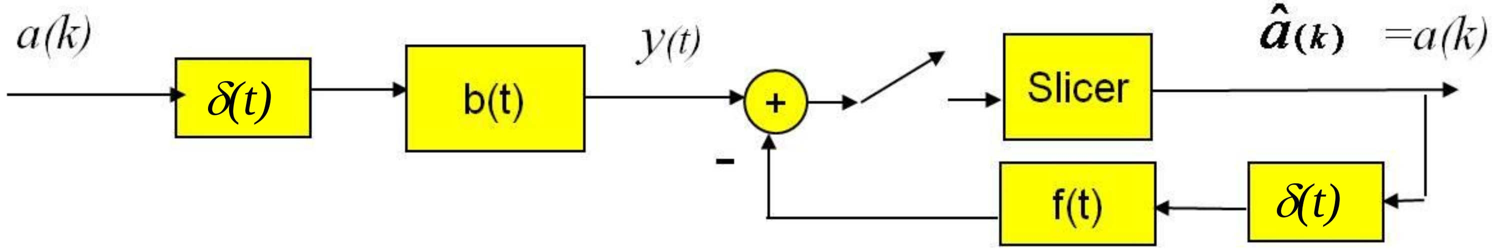


Eye Diagram NRZ BandWidth=minBW prbs11



Eye Diagram pam4 BandWidth=RaisedCosine2 prbs11

Extended Analog Bandwidth with DFE

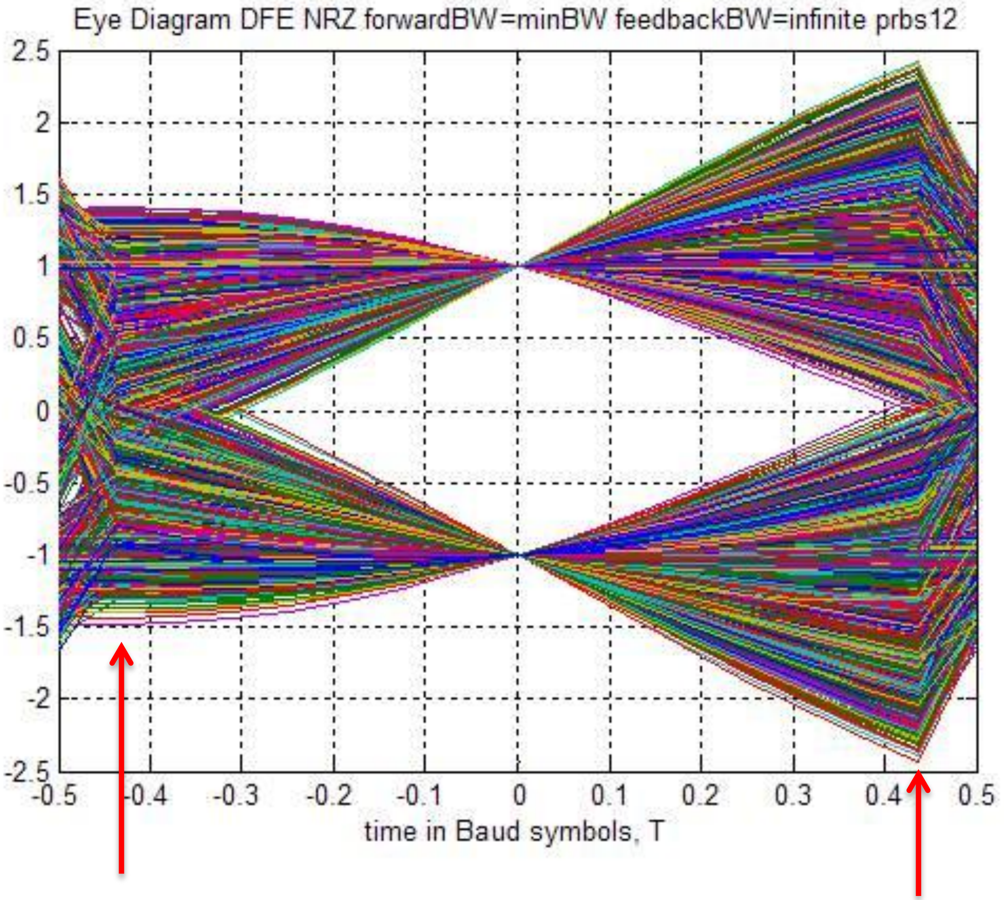


b(t) sampled at kT yields the normal DFE sequence {1, b1, b2, …}
f(t) sampled at kT yields the normal FBF sequence {0, b1, b2, …}

- **Consider the case of a DFE, either analog (shown) or with ‘Digital Feedback’**
- **The Feed Forward path has its own amount of ‘excess bandwidth’**
  - **We will continue with the two cases of ‘minimum BW’ and ‘raised cosine’**
- **For analog decision Feedback, there is an analog feedback transfer function f(t) with its own ‘excess BW’**
  - **Note that there is a real ‘simulatable’ eye for the analog DFE, but all the ‘balooned and non-periodic’ eyes presented were synthetic eyes and do no exist as shown in any real simulation (NRZ half rate parallel analog signal processing?)**
  - **For convenience we show the feedback applied as an infinite BW but finite time analog ramp at the ‘edge’ of the eye (vs. the center of the eye)**
- **Digital DFE implementation ‘Eye’ can not exist in a simple time domain simulation**
  - **We create a ‘synthetic eye’ where each ‘time shift’ represents an independent experiment run with a different ‘sample time jitter,’ and plot them ‘like a waveform’**

NRZ with Minimum BandWidth Forward and ~Infinite BW Feedback DFE

- The forward path here is minimum BW, so about 13 GHz
- The DFE feedback path here is 'near infinite' BW with a fast ramp centered on the edge of the eye
- The horizontal eye opening is asymmetric - 0.29T to +0.39T
- Performance with asymmetric left-right eyes is dominated by the 'worst case', which here is the 'early shift' (left)
  - Sometimes the horizontal width of (.29+.39)=0.68 is used, while performance is closer to 2*.29 = 0.58

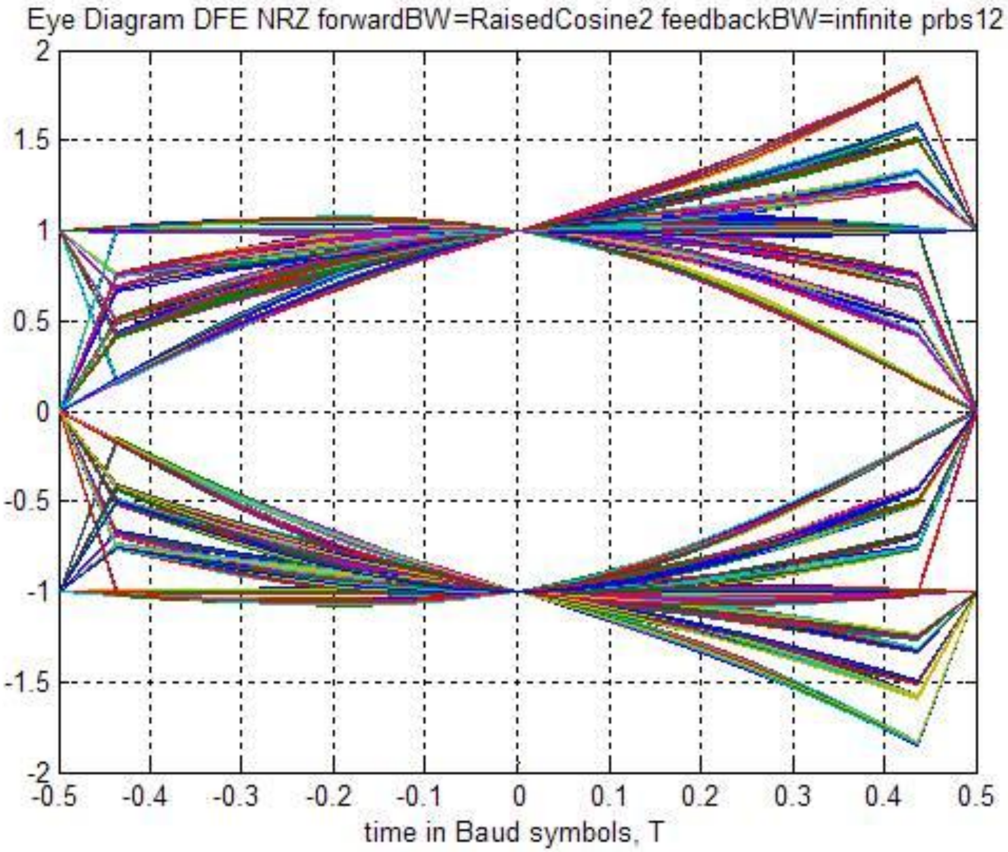


FeedBack is fully settled here

FeedBack starts ramping here

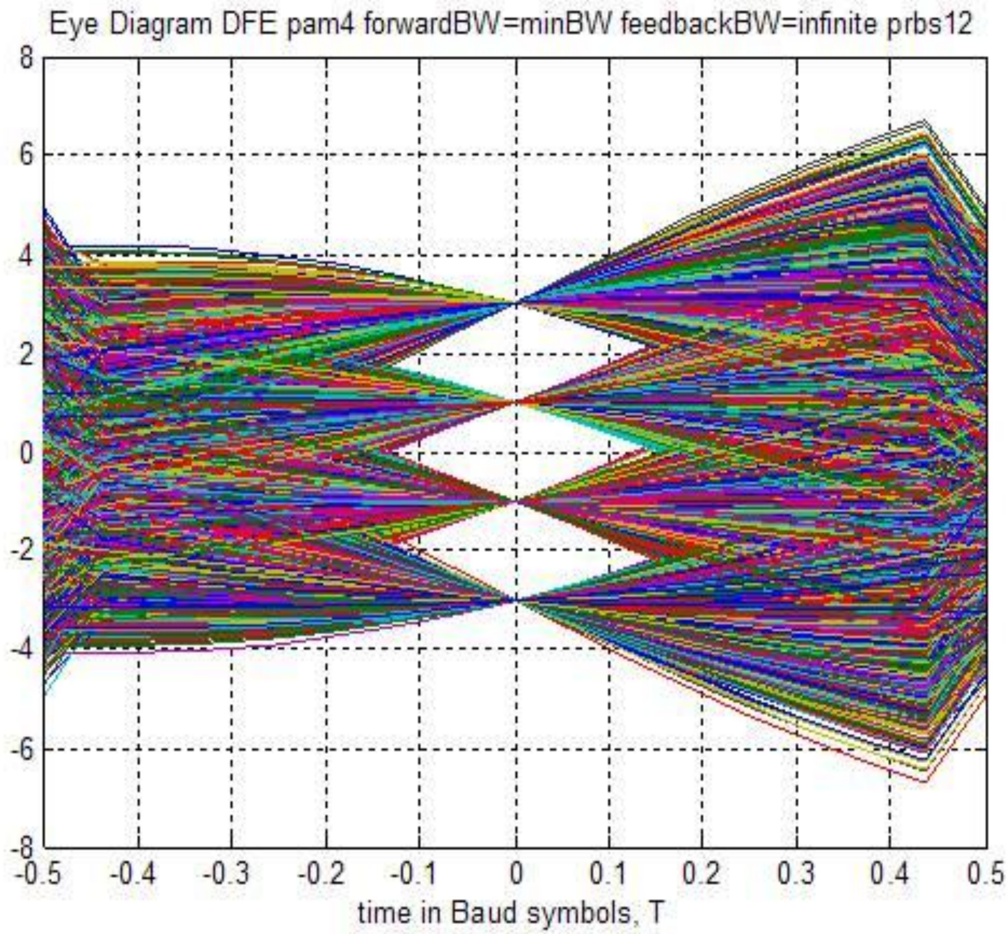
NRZ with Raised Cosine Forward and ~Infinite BW Feedback DFE

- The forward path here is full Raised Cosine, so 26 GHz analog forward BW
- The DFE feedback path here is ‘near infinite’ BW with a fast ramp centered on the edge of the eye
- The horizontal eye opening remains the ideal +/- 0.5T



PAM-4 with Minimum BandWidth Forward and ~Infinite BW Feedback DFE

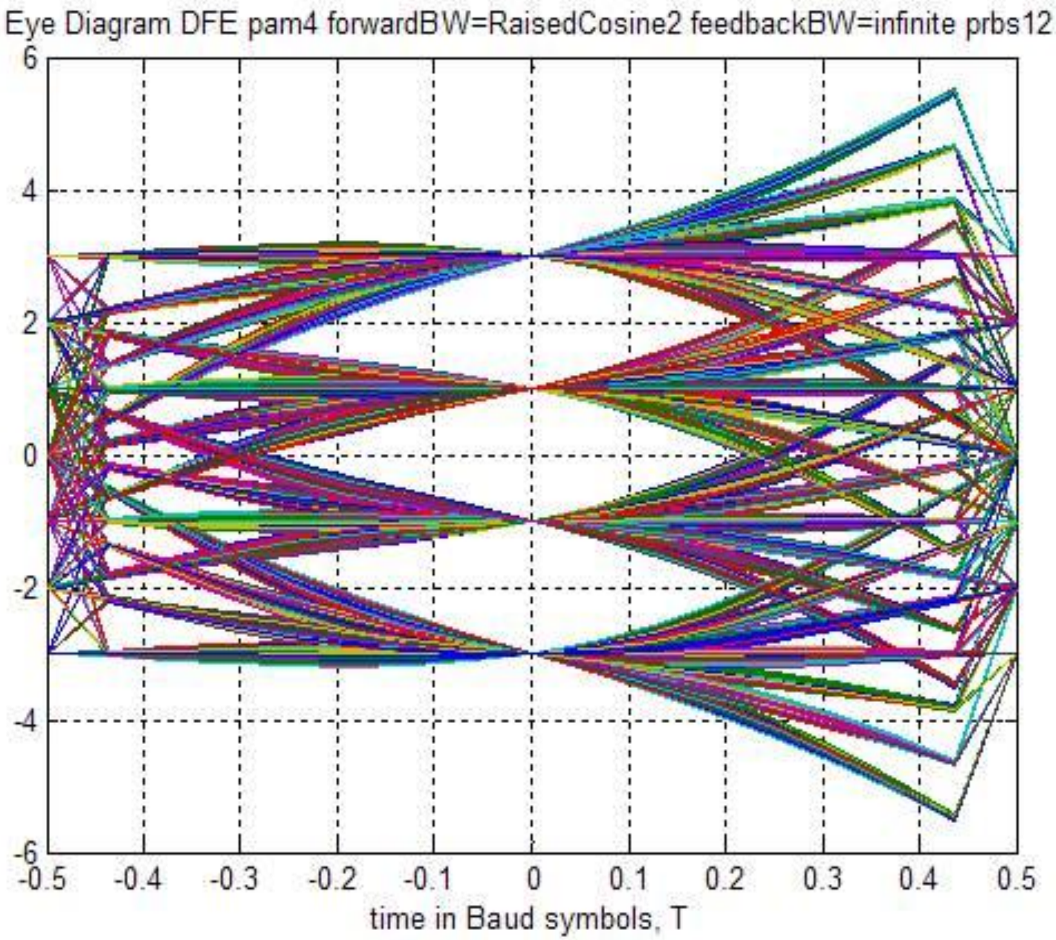
- The forward path here is minimum BW, so about 6.5 GHz
- The DFE feedback path here is ‘near infinite’ BW with a fast ramp centered on the edge of the eye
- The horizontal eye opening is asymmetric
  - 0.10T to +0.12T



PAM-4 with Raised Cosine Forward and ~Infinite BW Feedback DFE

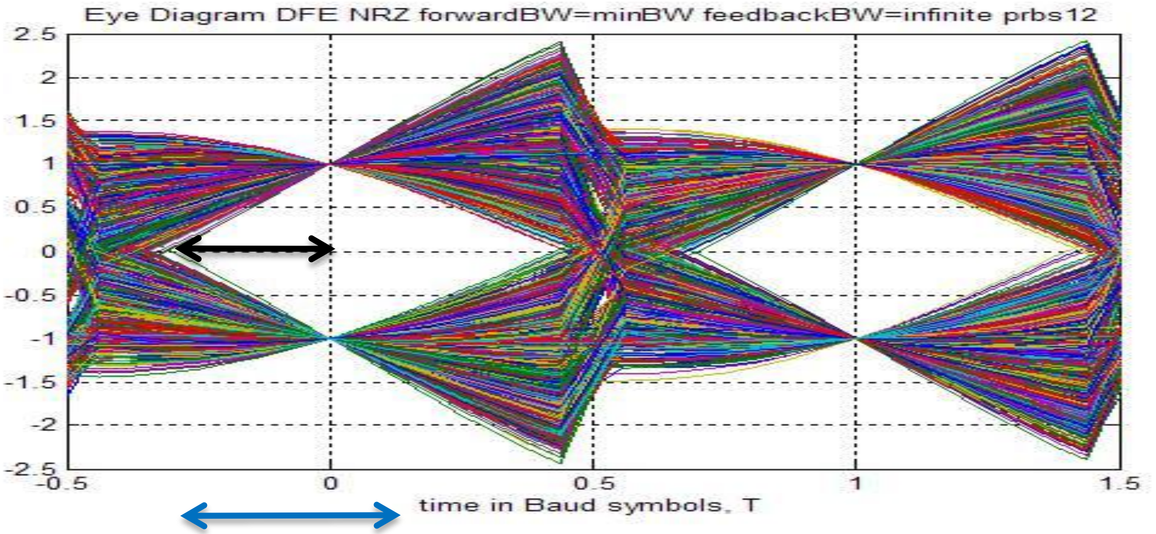
- The forward path here is minimum BW, so about 13 GHz
- The DFE feedback path here is ‘near infinite’ BW with a fast ramp centered on the edge of the eye
- The horizontal eye openings here are bounded by

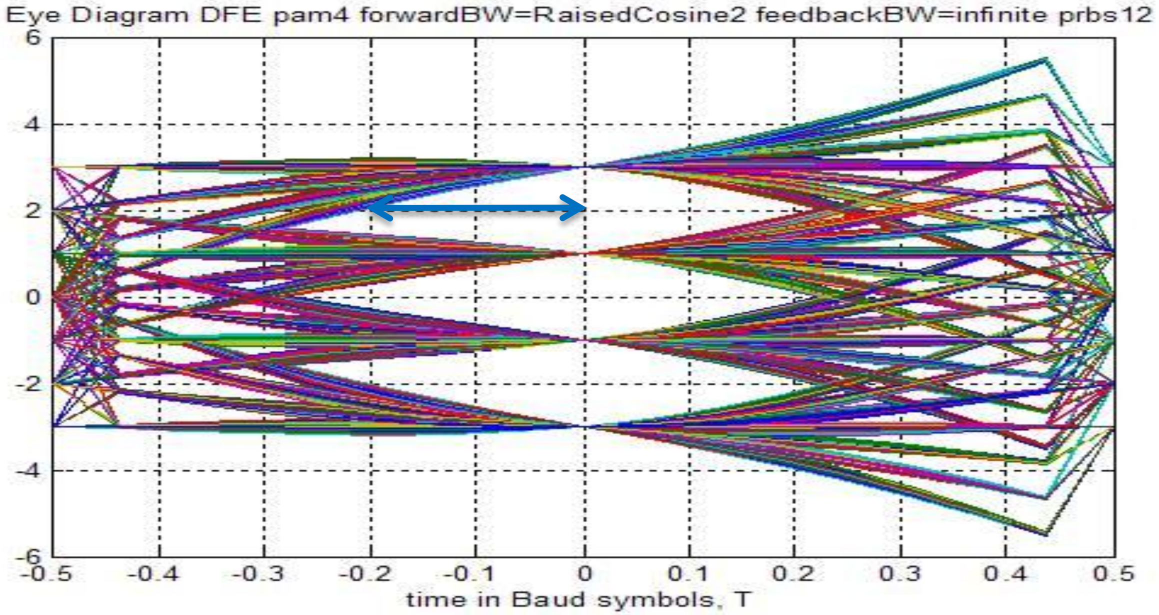
- 0.2T to +0.22T



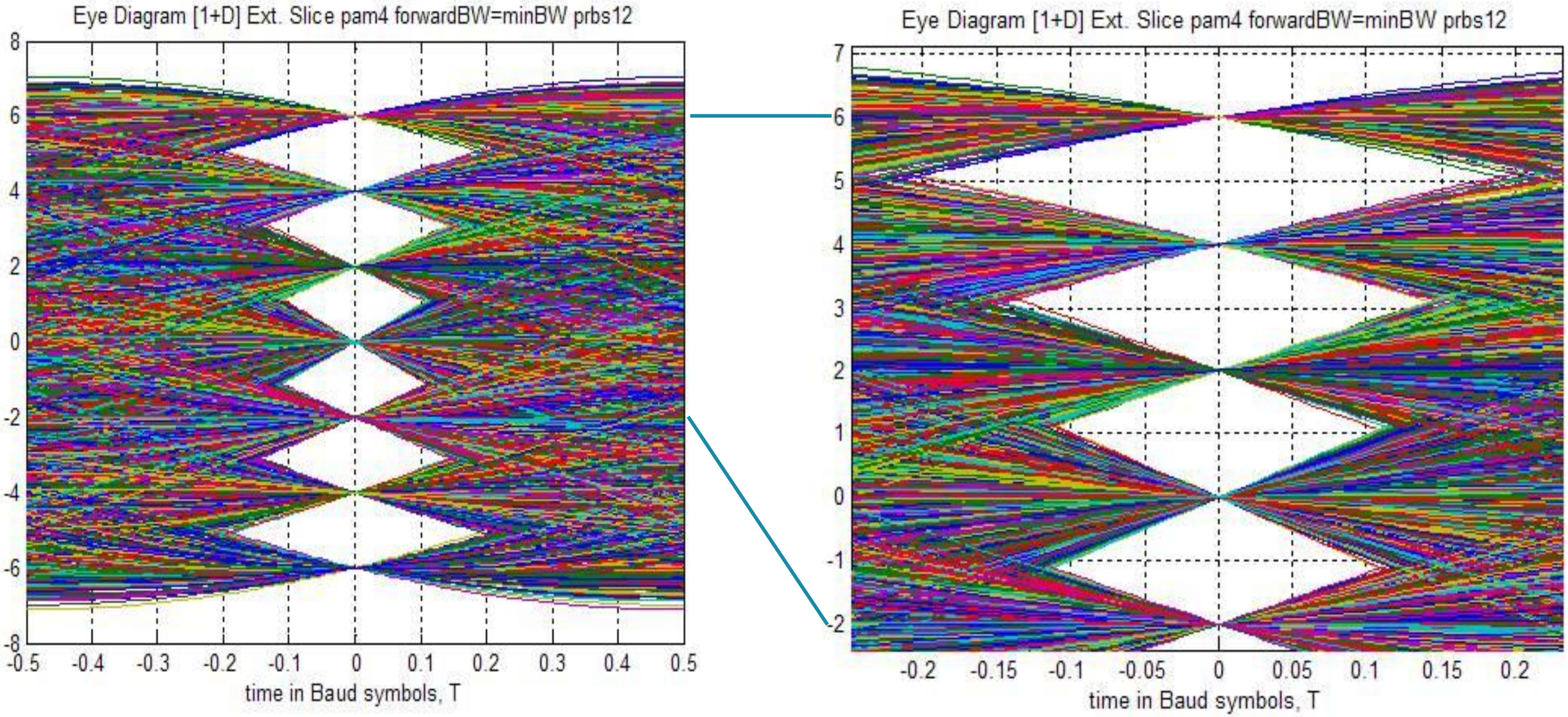
Equal 13GHz forward Analog Bandwidth with DFE

- NRZ and PAM-4 are compared with equal fixed 13GHz analog BW
- So the NRZ is ‘minimum BW’ while the PAM-4 is the ‘raised cosine’ BW
- The NRZ plot is adjusted for equal physical time scale, so two periods shown
- The horizontal eye margin of PAM-4 is 38% wider in real time than the NRZ





Partial Response Eye; (1+D) w/ PAM-4 minBW



- **Partial Response target (1+D) with PAM-4 minimum BW eye diagram at the 'Extended Slicer' (zoomed in figure on the right) has +/- 0.1 T_Baud horizontal eye opening**
  - **Better performance than a simple PAM-4 minimum BW slicer (+/- 0.085 T)**
  - **The same asymptotic performance as PAM-4 DFE (-0.1T to +0.12T)**

On Static Time Shift and Different Forms of ‘Jitters’

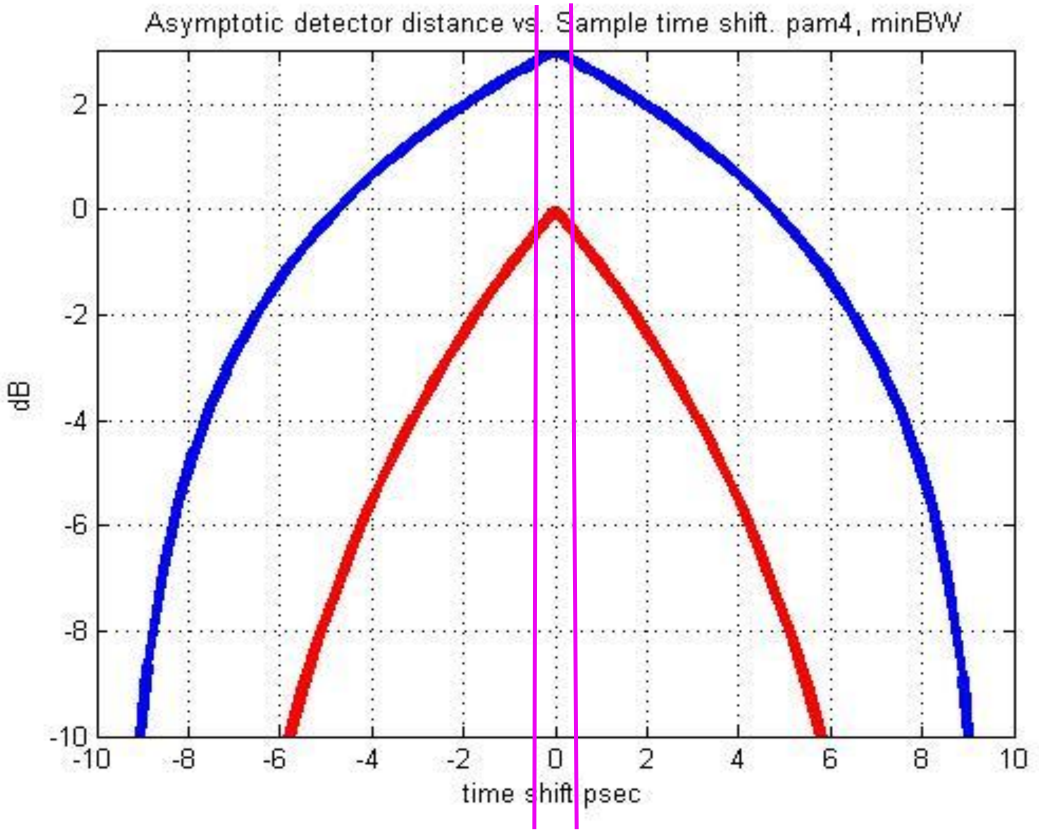
- The previous results are for the special case of ‘static’ time shifts and simple ‘slicer’ decision elements (ignoring error propagation of DFEs)
  - These results can well predict performance in certain lower frequency ‘jitters’, whether Random or Deterministic IF
    - Jitter energy is above the maximum reasonable ‘tracking BW’ of CDR
    - AND Jitter energy is low enough frequency that the non-linear distortions of ‘shifting clock edges’ is small enough to ignore
      - In general ‘moving clock edges’ is NOT a Linear Time Invariant system
      - E.g., the same jitter at TX and RX would have different effects
  - Random (Gaussian) Jitter (RJ) from oscillators are normally low frequency dominated, so performance can be accurately predicted
- Deterministic Jitter (DJ) means a deterministic but non equally spaced clocking time sequence in the TX and/or the RX
  - Sine Jitter (SJ) is a special case of DJ where the deterministic pattern of shifts in clock edges follows a sampled sine wave ‘sequence’
- The performance in RJ or DJ (of SJ) with ‘higher frequency’ energy where non-linear distortions are not negligible is not predicted from any ‘time shift’ results
  - Rather, the non-linear distortions are typically simulated, hopefully with long enough simulations to accurately predict performance to 1e-12

Timing Error Sensitivity and Advanced Detectors

- Its useful to define a timing error sensitivity function ‘g’ that maps a systems
  - BER= g(time_shift)
  - The function ‘g’ depends on all the other system variables including all impairments, such as noises, mis-equalization, non-linearities, HF jitters, etc.
  - The function ‘g’ is often found through a combination of simulations at different time shifts and modeling / extrapolation
    - For NO FEC systems, model the tails of impairment pdf and ‘extrapolate’ slicer BER
    - For FEC systems, model / extrapolate ‘FEC mapping’ of BER input to output
- For the simple (divide and conquer) case of studying timing sensitivity with no other noises, its useful to study the ‘detector distance’ (distance to error) as a function of time shift
  - For Slicers and DFEs (ignoring practical analog feedback settling and error propagation) this distance (in dB) = 20*$\log_{10}$(1- deviation_towards_slice_error)
    - The ‘asymptotic distance’ (dominates at low BER) replaces an ensemble of such deviations with the worst case value
  - For MLSD, e.g., for the simple Partial Response (1+D) channel described in http://www.ieee802.org/3/bj/public/sep11/dabiri_01_0911.pdf, the asymptotic detector distance is found by finding the largest amplitude inner product of an actual sample error sequence (due to time shift) and a supported error event (from an alternate fooling coded sequence)

Detector Distance (to error) vs. Time Shift for PR (1+D)

- **Asymptotic detector distance (worst case pattern) vs. time-shift in psec for simple Partial Response target (1+D)**
- **Blue = Maximum Likelihood Sequence Detector PAM-4**
  - **3dB gain over 'slicer'**
- **Red = extended slicer PAM-4**
- **The MLSD performance is 3db better with 'no time shift' and is about 2 times less sensitive (in dB) to 'time shift' in areas of interest**
- **The sequence detector performance can be approached with many 'sub-optimal' but simpler architectures**



Recent Task Force simulations* with Random Gaussian Jitter rms = 0.35 psec

Many modern systems w/FEC achieve net BER <= BER(1*σ static time shift)

* http://www.ieee802.org/3/bj/public/sep11/meghelli_01a_0911.pdf

Summary

- The width of the horizontal eye has been a proxy for ‘jitter tolerance’ and jitter requirements
- Excess analog BW is well known to play a large role in Timing Recovery, so its not surprising to see that it plays an equally large role in ‘horizontal eye opening’ and jitter tolerance
- For non-DFE slicer systems (or DFE with very small taps), the PAM-4 horizontal eye opening is approximate the same fraction of a bit period (not Baud period) as NRZ even when the analog BW of the NRZ system is twice that of the PAM-4 system
- DFE systems don’t always have ‘true eyes’, but we can still create synthetic plots that show the performance vs. ‘static sample time shift’ (aka ‘jitter’)
- For DFE systems the horizontal opening is generally asymmetric, and performance will be dominated by the ‘worst side.’
- With infinite Analog Bandwidth’ in the DFE feedback,
  - If both system’s forward analog bandwidths are their own min BW, then PAM-4 has 31% narrower horizontal eye opening in time than NRZ, but
  - If forward analog bandwidths are equal in GHz, then PAM-4 has a 38% wider horizontal eye.
- ‘Jitter sensitivity’ and ‘Detector Distance’ vs. time shift were introduced to understand performance of more complicated detectors.
- The simple Partial Response (1+D) PAM-4 channel with MLSD was shown to not only have 3dB larger detector distance with no time shift, but to also only lose about half as much (in dB) due to time shift as a slicer