Does PAM-4 or NRZ Require an Intra-Baud Clipping Penalty?

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OUTLINE

- **Definition of ‘Intra-Baud’ Peak**
- **History motivating the Question**
- **Mathematical Model and Result**
- **Conclusions and Comments**

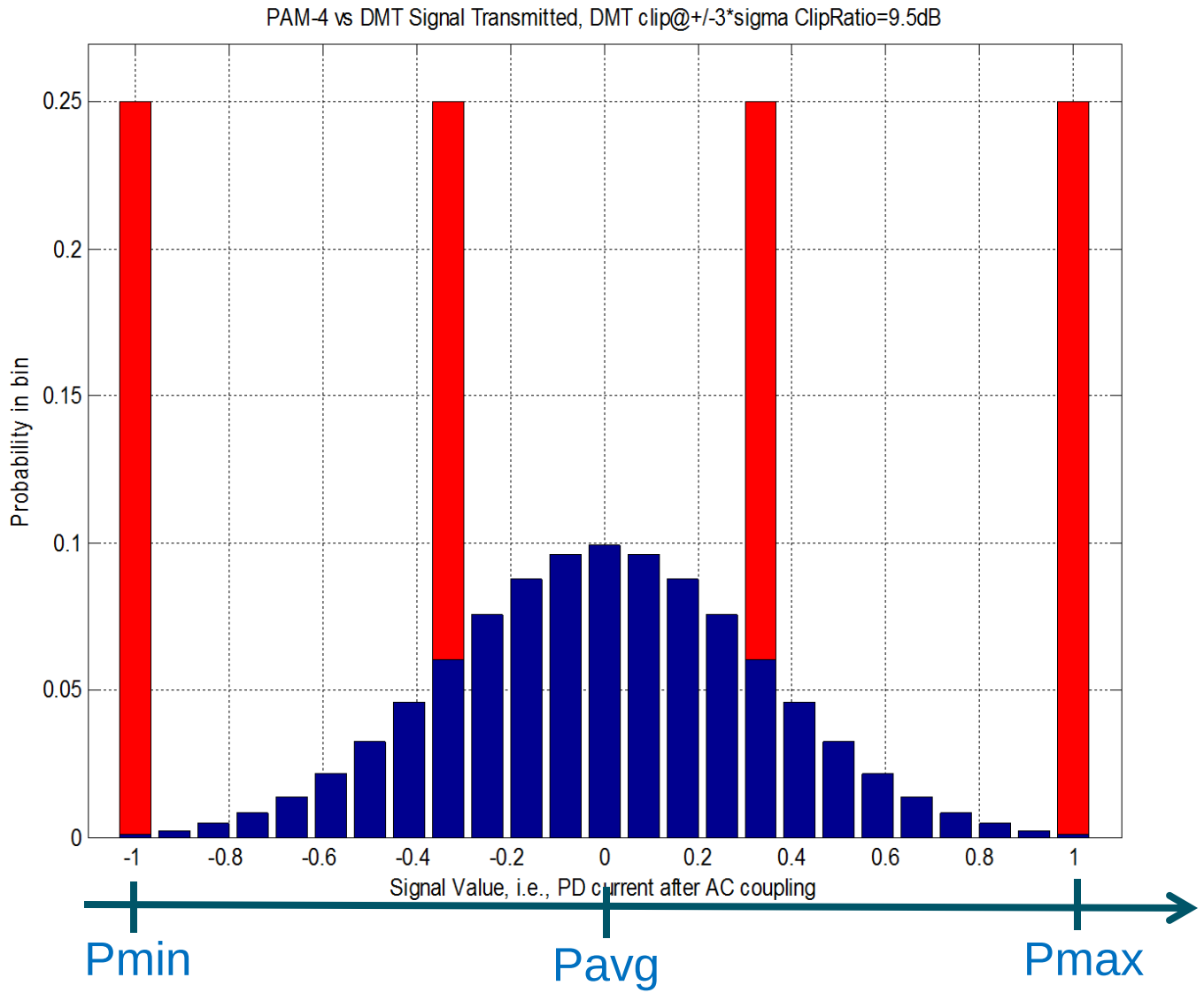
DEFINITION OF ‘INTRA-BAUD PEAK’

- **Some previous presentations have calculated and shown Peak to Average Power Ratio (PAPR) based on Baud Rate TX signals**
  - E.g., a visual comparison of the ‘TX DAC’ output histograms for PAM-4 (with no TX pre-emphasis or other filtering) and for DMT (with 3σ clipping) is in http://www.ieee802.org/3/bs/public/14_07/bliss_3bs_01_0714.pdf
  - These results do not include any consideration for the electrical characteristics of the TX ‘DAC’, for the electrical ‘transmission line’, etc.

PAPR OF DMT VS. PAM-4 TX *Baud Samples Only*

Taken from

http://www.ieee802.org/3/bs/public/14_07/bliss_3bs_01_0714.pdf



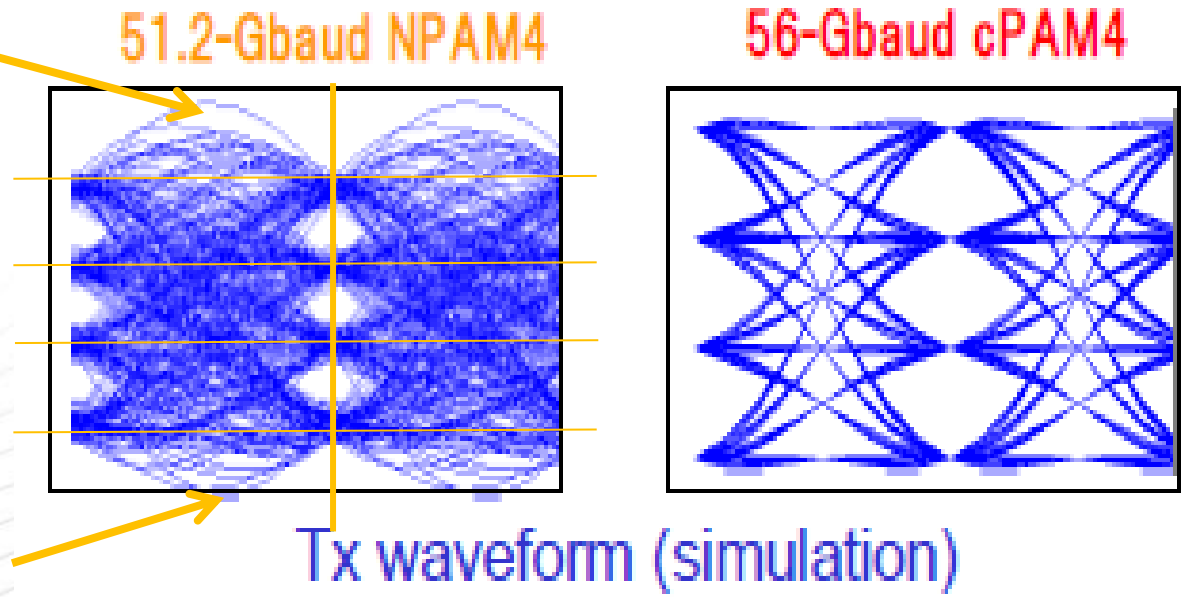
- **Red = PAM-4 probability**
- **Blue = DMT example with moderate clipping at +/- 3*sigma**
  - 'Clipping ratio' = 9.5dB
- **Mean time to 'clipping' is about 370 Bauds, so average more than one clip per Block of N=512 Baud samples.**
  - Many blocks will have multiple clippings
- **The 'Signal Variance' (which is communication theory TX power) is 7 dB lower than that of PAM-4**
- **Note that the laser has the same peak-peak power range and equal average laser power**

DEFINITION OF 'INTRA-BAUD' PEAK, FOR NYQUIST TX SHAPING

- **Recent interest in "What happens when certain digital filtering is applied between the PAM-4 data and the TX DAC?"**
- **E.g., for 'Nyquist TX shaping (filtering)' in http://www.ieee802.org/3/bs/public/14_09/hirari_3bs_01_0914.pdf**

WB:

N== Nyquist PAM-4



WB:

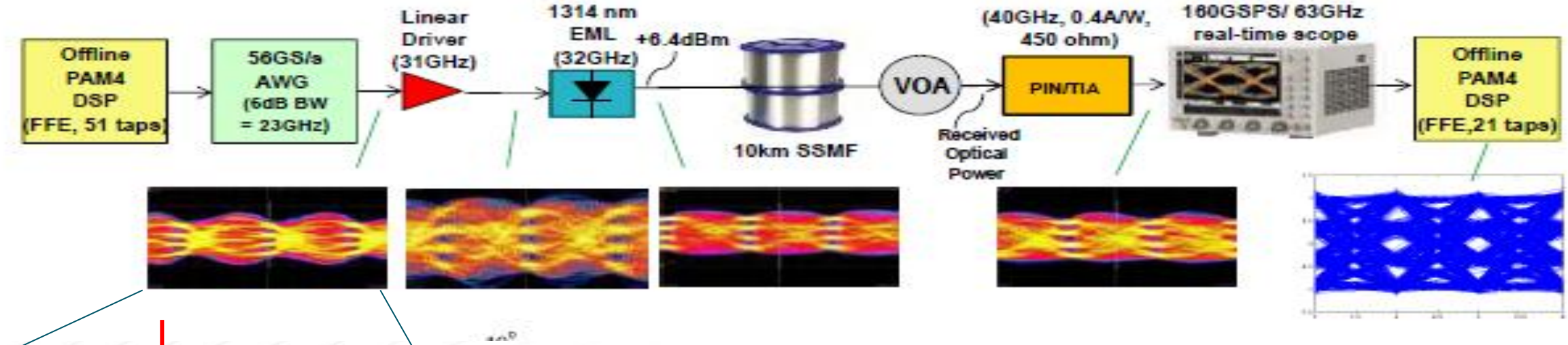
C== Conventional PAM-4

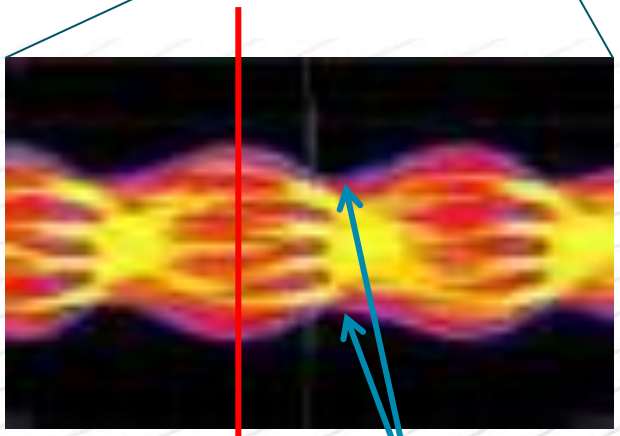
No large peak values

- **Large peak occurs between Baud sample times (where eye is ~open) == 'Intra-Baud'**
- **The discussion questions should be, "Does this cost the SNR budget?" and "Do all PAM-4 systems have this?" and "Do NRZ systems have this?"**

‘PEAKING’ FOR TX LOW FREQUENCY DE-EMPHASIS

- **E.g., for TX de-emphasis** http://www.ieee802.org/3/bs/public/14_079/way_3bs_01_0914.pdf
  - 51-tap TX FFE .





Baud sample

Intra-Baud samples have lower peak envelope, due to the de-emphasis

WB: This is normal TX de-emphasis, where the peak still occurs at the Baud sample (at the ~ eye opening). Traditional TX de-emphasis must cut low frequency signal, which leads to the ‘envelope dips’ between Baud samples

HISTORY OF THE QUESTION

- **E-mail threads discussing 'peaking', e.g.,**

From: Chris Cole [mailto:chris.cole@FINISAR.COM]
Sent: Wednesday, October 01, 2014 3:05 AM
To: STDS-802-3-400G@LISTSERV.IEEE.ORG
Subject: Re: [STDS-802-3-400G] IEEE P802.3bs 400 Gb/s Ethernet SMF Ad Hoc conference call draft agenda

Hi Winston,

For Case 1, it is difficult if not impossible to define most optical parameters since the eyes are severely closed. This includes peaking. This is not a useful or realistic example and .bs is unlikely to consider transmitters with such severe bandwidth limit.

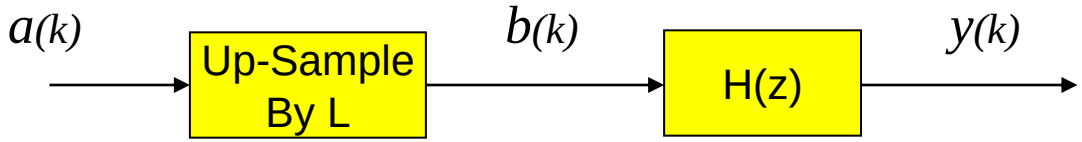
For Case 2a, the EML optical eye image is shown below magnified to a more useful viewing size, as the original thumbnail image makes it difficult to see what's going on. It is now clear that the blue outer waveform lines are beyond the 11 and 00 eye levels. Further, what the colors do not show are the tails of the distribution. The TX OMA penalty to accommodate this transmitter optical waveform is less than Case 2b examples, but is not negligible, and should be accounted for in complete link budget analysis.

To avoid this penalty requires broad excess bandwidth, as is possible using 50G components for 50G PAM-4. and appropriate pulse shaping for example Bessel. Similarly, many years from now, when we have 100G components, we could eliminate this from 100G PAM-4 waveforms. *Until then, all practical 100G PAM-4 approaches will have some level of peaking unless severe clipping is acceptable.*

Chris

- **Has an extra penalty been applied to PAM-4 based on 'Intra-Baud peaking'? Or?**
  - In addition to the well known 'loss' (higher required SNR) required of PAM-4 vs.NRZ

PEAK ENVELOPE 'BETWEEN THE BAUDS', MODEL



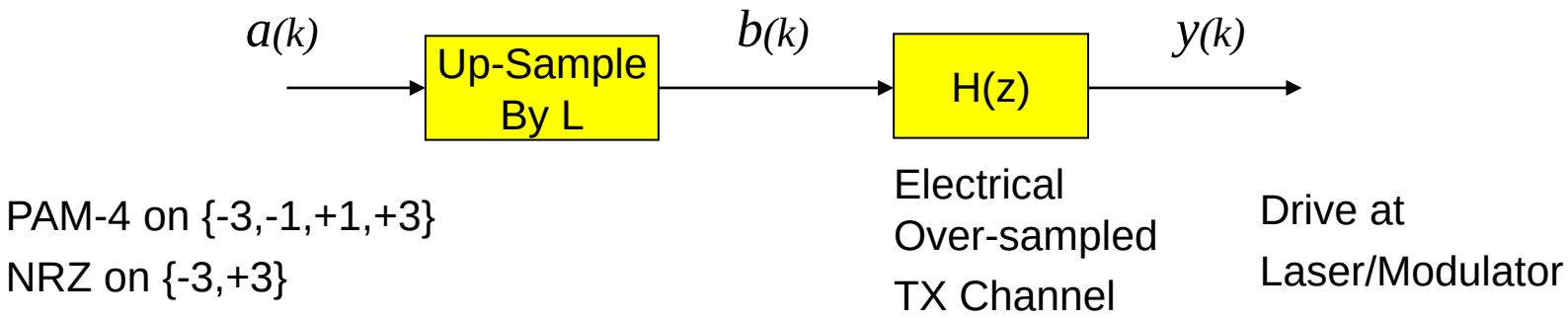
PAM-4 on {-3,-1,+1,+3}
NRZ on {-3,+3}

Electrical TX Channel

Drive at Laser/Modulator

- **Without loss of generality we can model the continuous time (analog) domain with an oversampled discrete time system**
  - Here model the TX electrical filter with the L times oversampled response *h(k)*
- **Consider NRZ and PAM-4 with identical peak Baud rate values**
- **Without loss of generality, we can consider DC free systems**
  - We're only interested in the Peak-to-Peak envelope, which is independent of DC here

PEAK ENVELOPE 'BETWEEN THE BAUDS', MATHEMATICS



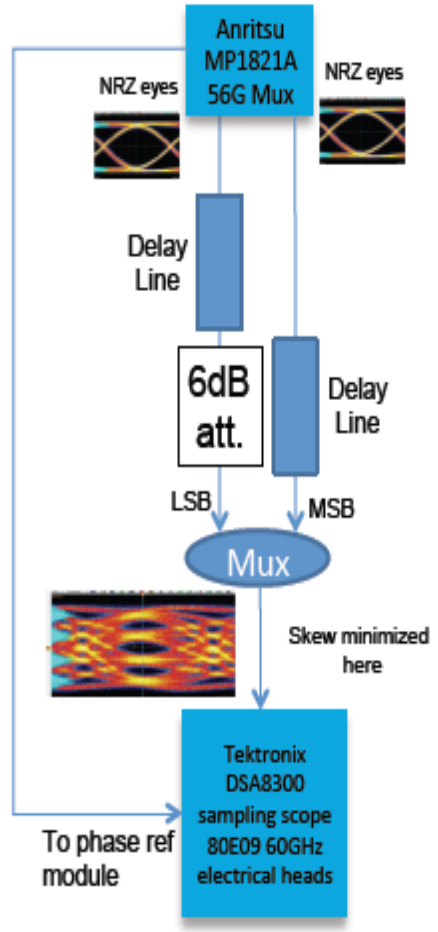
- **THEOREM: For any oversampled time value 'k' (any 1 of L over-sampled phases and any Baud time), an input sequence *{ a(k) }* which maximizes or minimizes *y(k)* can be composed of only the maximum and minimum values of the alphabet of *a(k)***
- **PROOF:** Examine the convolution equation. For any over-sampling phase 'p', the over-sampled *h(k)* can be reduced to Baud rate by summing each group of L coefficients with the same up-sampled values *a(k),* so the problem is reduced to Baud rate *h_p(k).* This is now the well known bang-bang control problem. The single sample *y(k)* is maximized by choosing the sign of *a(k)* to match the sign of the appropriate *h_p(k).* To minimize *y(k),* the sign is chosen opposite. If *h_p(k)* has a zero coefficient, then *{a(k)}* is not unique, but is still maximized or minimized with only max and min values of *a(k).* **QED**
- **CORRALARY: NRZ and PAM-4 (and any PAM-M) with the same peak-to-peak drive have exactly the same peak values (envelopes) for all possible TX electrical filters *h(k)***

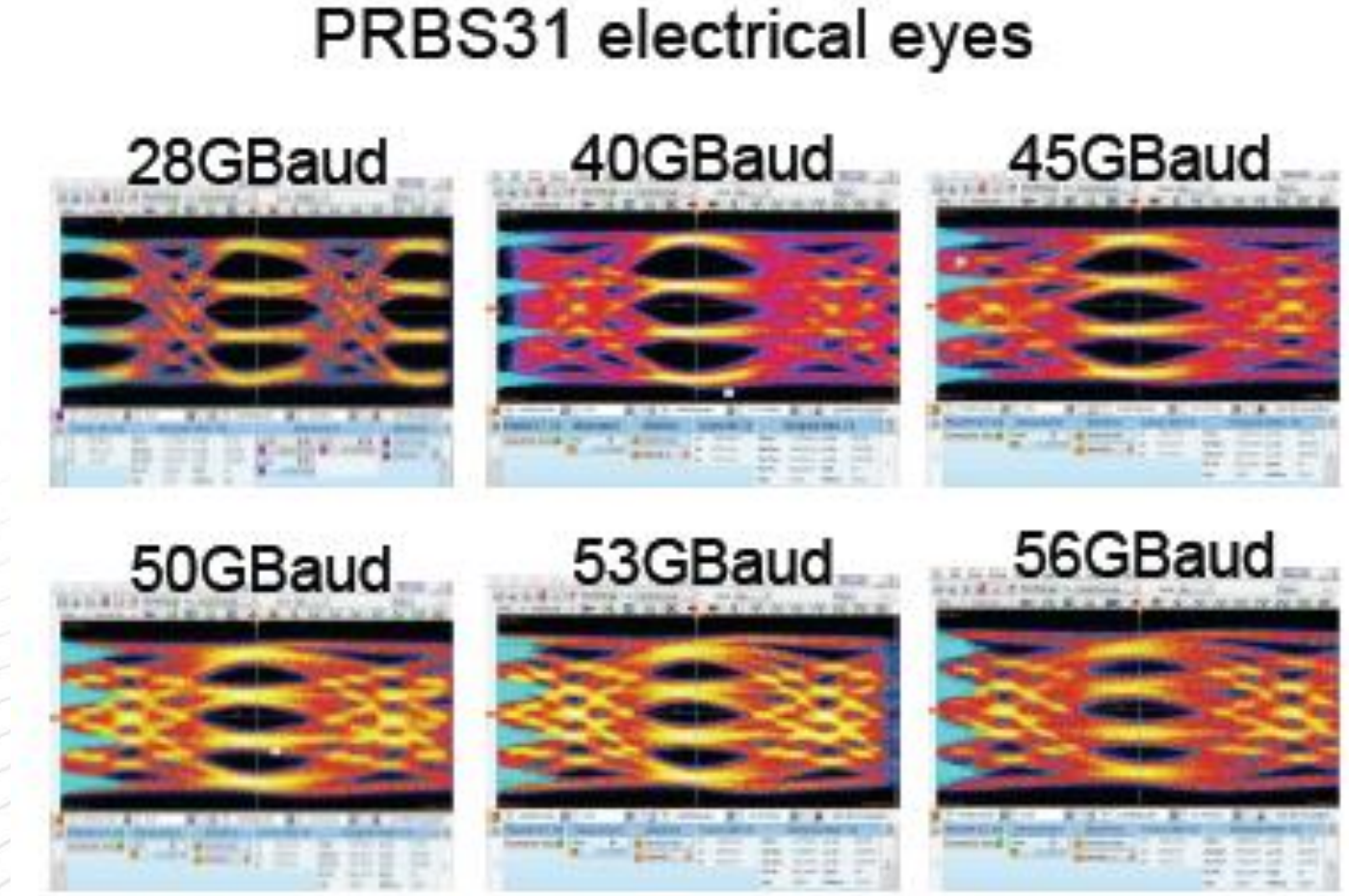
PEAK ENVELOPE, PRACTICAL TX FILTERS

- **The lowest cost TX is a simple Baud rate PAM with the simplest electrical filter, which is to use the ‘natural analog’ as is**
  - This works fine!
  - No 6+ bit TX DAC is required
  - E.g., one or two real poles in the S-domain produces simple exponential rise and fall ‘shapes’, so NO OVERSHOOTs (no matter how low the BW)
  - This is a ‘normal TX’ for many Baud rate modems. It maximizes energy onto the line given a peak limited TX.
- **Some ‘pushed transmission lines’, e.g., running at twice their designed Baud rate, can show ringing and overshoot problems**
  - E.g., from electrical transmission line reflections producing ‘peaks’, or
  - E.g., Peaking from package inductance, etc.
  - This is not a desirable situation to drive optics, just as it isn’t desirable in copper backplanes, etc.

‘PEAKING’ FOR NORMAL BAUD RATE PAM-4

- **Experimental lab equipment setup for ‘straight’ Baud rate PAM-4 in http://www.ieee802.org/3/bs/public/14_09/mazzini_3bs_01_0914.pdf**





WB; little or no intra-Baud peaking from this experiment run with lab equipment at 112Gbps PAM-4.

CONCLUSIONS AND COMMENTS

- **Peak TX waveform envelope for PAM-4 is identical to NRZ at the same Baud rate (so e.g., 100Gbps PAM-4 has the same envelope as 50Gbps NRZ)**
  - For the same linear system response
- **Systems with specified TX FFEs need to account for 'peaking' in their budgets**
  - Nyquist shaping TXs, or traditional TX de-emphasis FFEs
  - Just as was included in the budget for TX De-emphasis with NRZ
  - This author's preference is for simple straight PAM transmissions with no TX FFE shaping
- **All systems will strive for good transmission line behavior between electrical TX and the 'optical load'**
  - Just as was done for NRZ. It pays to make your transmission lines 'decent' for your Baud rate.
  - Bad transmission lines create Insertion Loss Deviation (ILD), which makes equalization difficult, and which makes a 'peak problem' similar to those shown here
  - We have one presentation, where even with lab equipment the transmit waveform looks good.
- **Any ultimate / residual transmission line 'problems' must be dealt with**
  - For any modulation system, including NRZ
- **So, does PAM-4 or NRZ Require an Intra-Baud Clipping Penalty?**
  - Not generically for simple Baud rate straight PAM transmission. Only poor transmission lines would create a penalty

Thank you