Considerations for oscilloscope measurements of electrical and optical PAM4 signals

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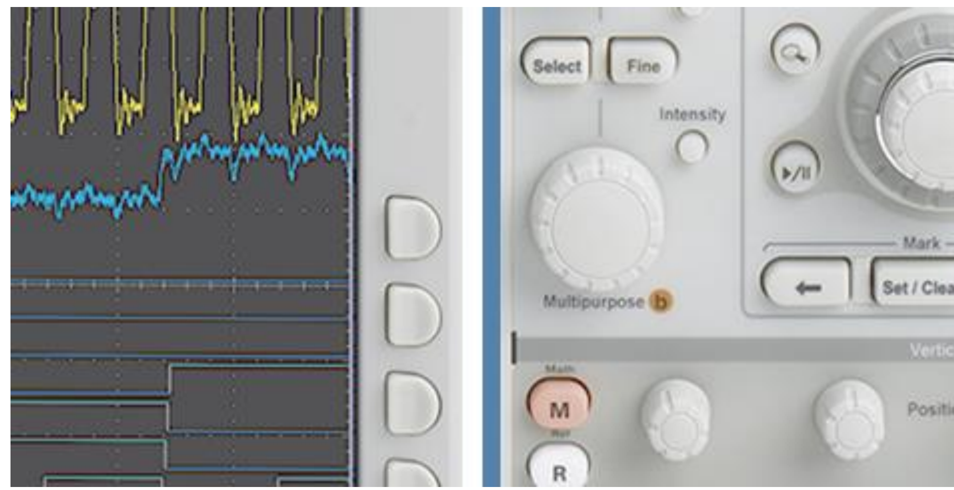

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Considerations for oscilloscope measurements of electrical and optical PAM4 signals

- Sampling oscilloscopes: modes of operation with respective features/limitations
- Real-time oscilloscopes: modes of operation with respective features/limitations
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Oscilloscopes: signal constraints vs. depth of analysis: basic eye capture on Sampling*

Two acquisition types are possible on a *sampling** oscilloscope:

1. Capture with no decomposition of statistical properties

   e.g. capture of the eye diagram.
   - No need for Pattern Trigger (Pattern Lock);
   - No possibility of SW DSP (no SW equalization possible).
   - Works on any pattern or traffic, incl. PRBS31
   - BW controllable as a 4th order Bessel-Thomson from ~40% to 100% of BW_{MAX} ; this is a valid filter for all components of the signal

*Equivalent time sampling oscilloscope

Oscilloscopes: signal constraints vs. depth of analysis: pattern capture on Sampling

… two acquisition types are possible on a *sampling* oscilloscope:

2. Capture with separation and decomposition of statistical properties
   - Repetitive pattern and Pattern Lock or (Pattern Trigger) are necessary
   - Realistic pattern length: PRBS15 in several minutes
     (so ok for design, for manufacturing, shorter would be better)
     Note that for statistical analysis, many passes of the pattern must be analyzed – capture of just repeat of pattern won't allow collection of statistical behavior
   - Jitter components decomposed and measured (RJ, DDJ, RN, DDN, ...)*
   - HW filter as in 1. remains
   - Correlated** information (the waveform w/o random noise/jitter) has correct spectrum and can be exported as a waveform;
     can also be equalized in a SW CTLE/FFE/DFE etc.
   - Uncorrelated information (RJ, RN, PJ, PN, etc.) known only in distribution, not as a true time-step vector. Spectral shaping based on assumptions (e.g. RN is white, thus will be limited in certain way by e.g. an CTLE).

*Random Jitter, Data Dependent Jitter, etc.   ***correlated* to the pattern

Basic facts for Sampling Oscilloscopes

- Excellent noise performance (e.g. 600 uV_{RMS} for 33 GHz of BW)
- Excellent bandwidth at low cost (BW>80 GHz)
- Optical plug-ins available for most signals' needs
- Trigger signal necessary (a CR, or a Clock e.g. from the signal source)
- Clock recovery behavior (PLL Loop BW, etc.) in HW of the clock recovery (CR)

Oscilloscopes: signal constraints vs. depth of analysis: pattern capture on Real Time

Two acquisition types are possible on a real-time oscilloscope:

3. Capture with no decomposition of statistical properties
   - e.g. capture a segment of the pattern, or 1 repeat of it.
   - Works on any pattern or traffic, incl. PRBS31
   - Jitter / Noise decomposition not possible (not enough data for good analysis from 1 repeat of a waveform)
   - BW controllable fully; DSP processing (SW equalizers) fully available

Oscilloscopes: signal constraints vs. depth of analysis: pattern capture on Real Time

… two acquisition types are possible on a real-time oscilloscope:

4. Capture with decomposition of signal components
   - capture many (e.g. 100) repeats of the pattern
   – Repetitive pattern with length ca. < PRBS21 is necessary*
   – For statistical analysis a repetitive waveform that can be digitized completely about 100 times is highly desirable:
     Jitter components decomposed and measured (RJ, DDJ, RN, DDN, ...)
   – BW controllable fully; DSP processing (SW equalizers) fully available
   – Noise performance

*necessary for high quality of result; random data partially analyzed

Equalization capabilities of oscilloscopes

- Two acquisition modes for sampling oscilloscopes:
  - Basic Eye Diagrams:
    - No restrictions on pattern length (includes live traffic)
    - Simple clock triggering
    - Limited analysis of statistical properties
    - No post processing (no SW equalization)

  - Pattern Locked analysis
    - Requires repetitive pattern and Pattern Trigger
    - More accurate analysis of signal properties
    - Realistic pattern length: PRBS15 is viable, test time driven by pattern length
    - Allows variety of SW equalization tools
- Real Time oscilloscopes
  - Can acquire and process any waveform without pattern length and triggering restrictions
  - For statistical analysis and equalization, repetitive waveforms with multiple observations highly desirable

Basic facts for Real-Time Oscilloscopes

- Good noise performance (e.g. 1200 uV_{RMS} for 33 GHz of BW)
- Trigger signal not needed
- Clock recovery available in SW (highly flexible)

Measurement bandwidth requirements for electrical and optical signals

- An example of proposal for bandwith required for oscilloscope measurements of PAM4 signals follows.
  The goal of proposal is to receive feedback; not final numbers

Measurement bandwidth requirements for electrical and optical signals

- What changes are needed for PAM4 vs. NRZ signaling?
- Current requirements:
  - 120D.3.1 CDAUI-8 transmitter characteristics
    A test system with a fourth-order Bessel-Thomson low-pass response with 33 GHz 3 dB bandwidth is to be used for all transmitter signal measurements, unless otherwise specified.
  - Several other places in Clause 120 list the same requirement
- NRZ optical signals historically measured 4th Order Bessel-Thomson response with electrical bandwidth at 0.75 * Symbol_Rate, (effective optical 3dB BW ~ 1.02 * Symbol_Rate).

NRZ:				
Symbol rate			25.78125	[GBd]
today's electrical B-T filter			33	[GHz]
optical ref. receiver (defined at 0.75x SRf)			19.33594	[GHz]
Equivalent optical BW			26.29688	[GHz]

What is the proper bandwidth for PAM4 waveform analysis optical signals

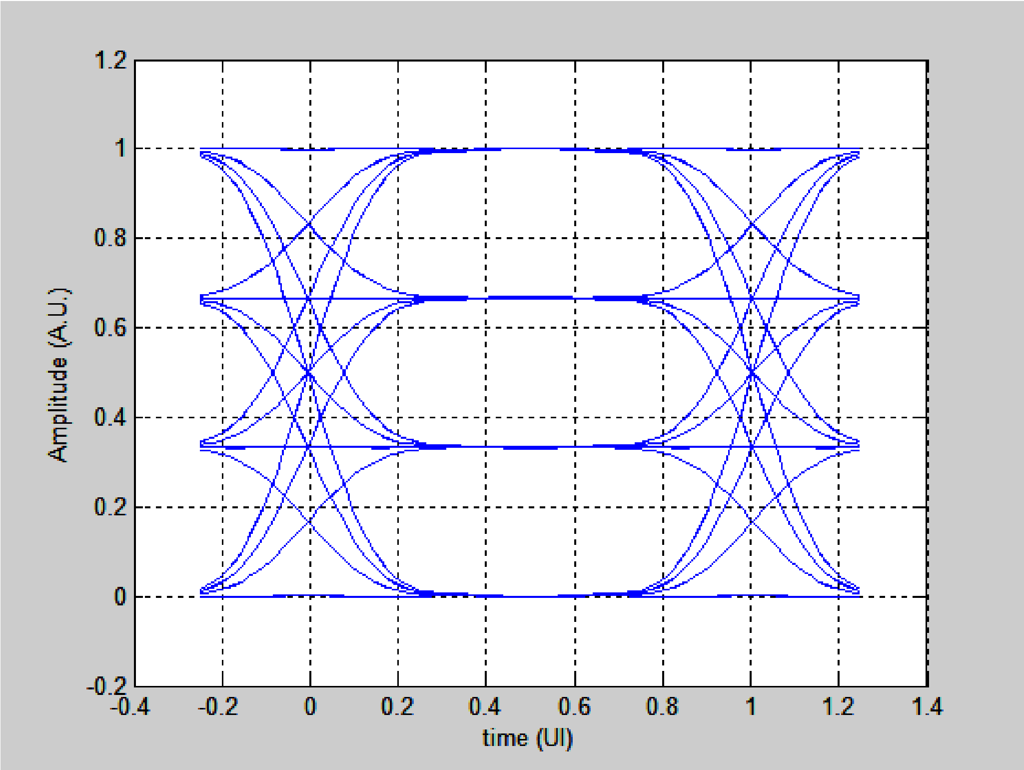
- What are the essential signal properties that must be observed to provide confidence that a signal will yield an operable link
- What is the proper observation BW to measure those properties?
- Is the 33 GHz (3 dB B-T bandwidth) appropriate for electrical signals?
- What Optical Reference Receiver (ORR) bandwidth should be used for PAM4 NRZ at
  - 26.5625 GBd
  - 54.29 GBd
- What is the measure of goodness of a reference receiver? (for either electrical or optical)

Recommend continued use of Bessel-Thomson design

- Best time domain response (constant group delay in pass band yields best flatness of step response)
- Consider a bandwidth that yields comparable vertical eye closure to that of legacy PAM2 NRZ
- This is a general recommendation applicable to an eye mask test or other measurements.
  - Acknowledging that measurements are still being defined, with a possibility of closed eyes
- Can existing optical reference receivers be leveraged for 802.3 bs?
  - 802.3ba, 802.3 bm: 19.34 GHz
  - 32xFibre Channel : 21 GHz

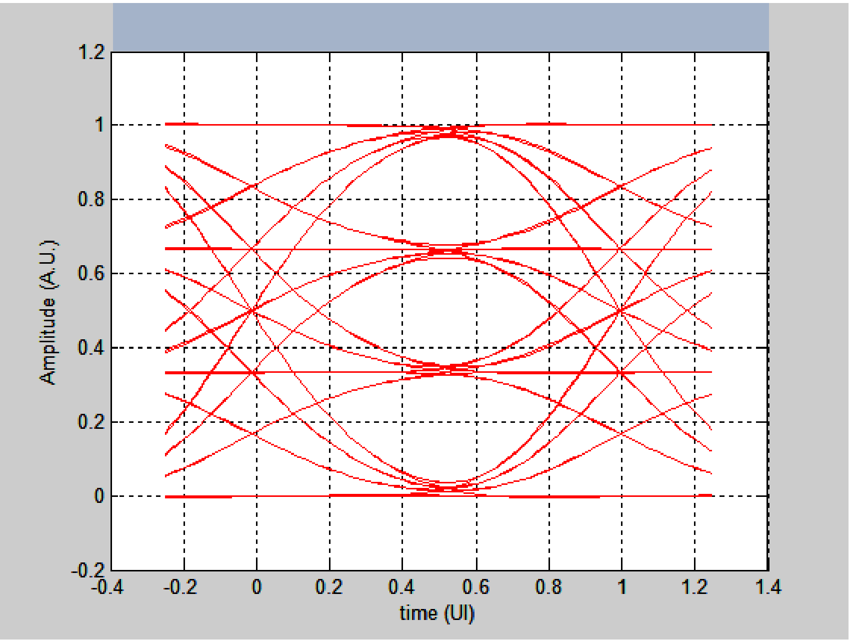
The impact of the measurement bandwidth on the PAM4 NRZ signal: test signal

- A “very fast” signal (rise-time = 0.1 * UI) representing an extremely fast DUT is filtered in simulation through several 4th-order Bessel-Thompson filters
- The very fast signal eye diagram:



The evaluation of the impact of the test equipment

- The eye diagrams exhibit horizontal eye closure and vertical eye closure
- Example: for test equipment with BW of 0.6 * Symbol_rate_frequency (this is optical BW at 0.75*Sym.r.f) the measured signal is significantly impacted in both the horizontal eye closure and vertical eye closure



- Horizontal eye closure not comparable to that of PAM2 NRZ, so …
- Using vertical eye closure

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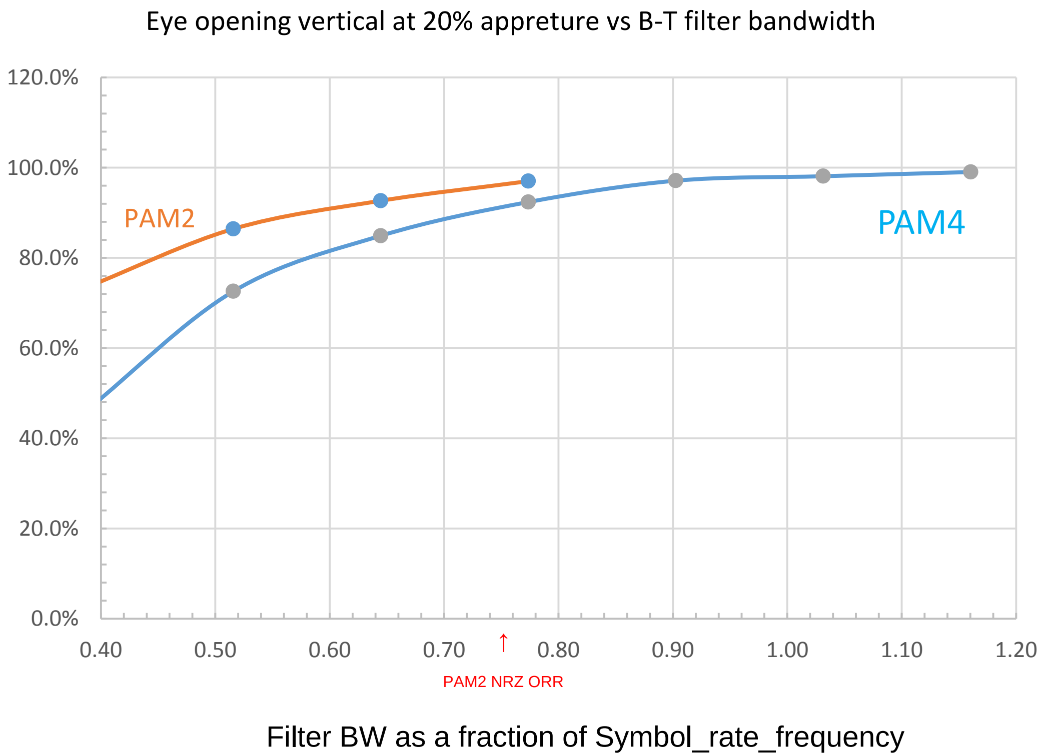
Comparison of the relative eye closure of PAM2 and PAM4 NRZ vs. relative Reference Receiver Bandwidth

- Vertical eye closure is worse on PAM4 than on PAM2



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Tentative proposal

- If there are no other constrains on the bandwidth of the oscilloscope used for measuring of PAM4 signals, here is an example table of results:

PAM4 NRZ:		
Symbol rate	26	[GHz]
electrical B-T filter	37.95	[GHz]
Optical filter (0.75x)	22.425	[GHz]

PAM2 NRZ: (legacy)		
Symbol rate	25.78125	[GHz]
electrical B-T filter	33	[GHz]
Optical filter (0.75x)	19.33594	[GHz]

We propse to finalize the methodology and the numbers in both the SM ad hoc and in the Electrical ad hoc

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End.

- Thank you.