PAM4 signals for 400 Gbps: acquisition for measurement and signal processing

V1.00

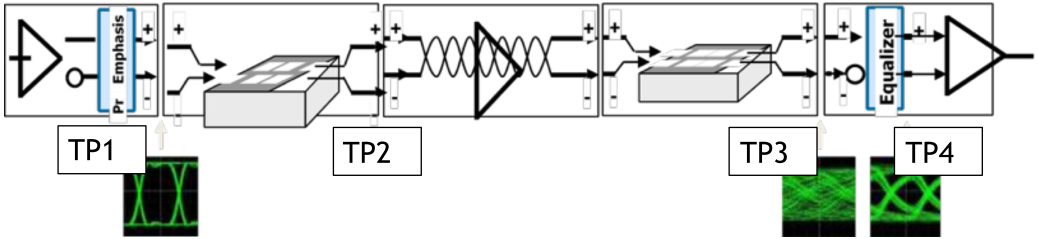
Introduction, content

High speed serial data links are in the process in increasing line speeds from 25 Gb/s to 50 Gb/s and higher. This is being implemented largely by moving from PAM2 NRZ signaling to PAM4 NRZ signaling. We consider the following aspects of measurement methodology addressing this change:

1. Measurement bandwidth considerations for measurement of performance and of compliance of PAM4 transmitters
2. Impact of PAM4 clock recovery system on measurement
3. Receiver equalization methodology for measurements on equalized PAM4 links

Measurement bandwidth considerations for measurement of performance and of compliance of PAM4 transmitters

- Measurement of a transmitter for compliance for interoperability requires standardization of both the methodology and the performance of the measurement equipment.
- For practical concerns TP2 is the typical measurement point for electrical systems.



Bandwidth requirements for testing of PAM4 signal: 4x25G electrical: “Ideal” PAM4 Tx, unlim BW Scope

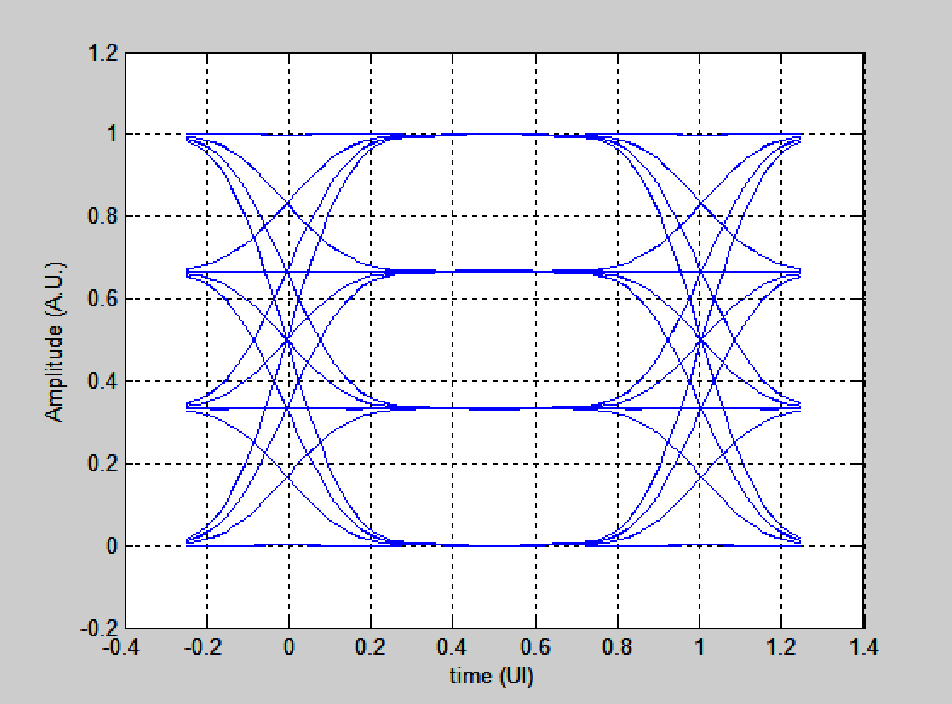


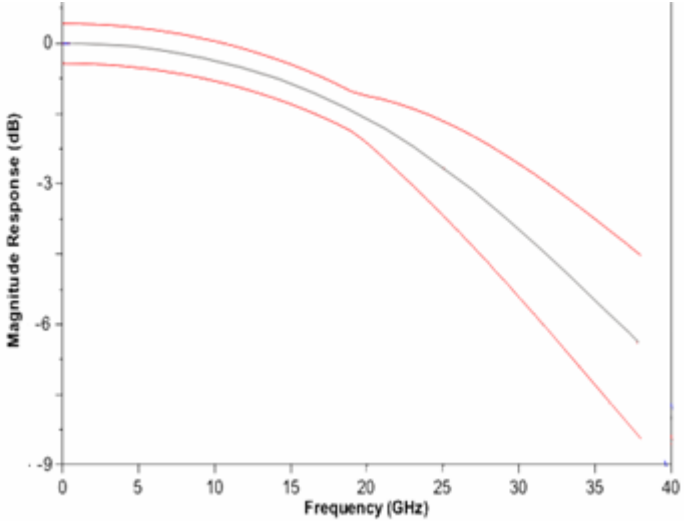
Figure 3 Eye diagram of a unrealistically fast step ran through a 4th order Bessel-Thompson filter (t_r = 10% UI)

Bandwidth requirements for testing of PAM4 signal: 4x25G electrical: BT smooth roll-off

- Traditionally the test equipment bandwidth for the evaluation of the transmitter is a matter of great dispute. Vendors were tempted to recommend as correct the bandwidth that they just achieved in their latest tools; the justification typically being that <n>th harmonic is the key requirement.
- Optical industry has a settled methodology:

$$H(y) = \frac{105}{105 + 105y + 45y^2 + 10y^3 + y^4}$$

$$y = 2.14p; p = \frac{j\omega}{\omega_r}; \omega_r = 2\pi f_r; f_r = 0.75 f_s$$

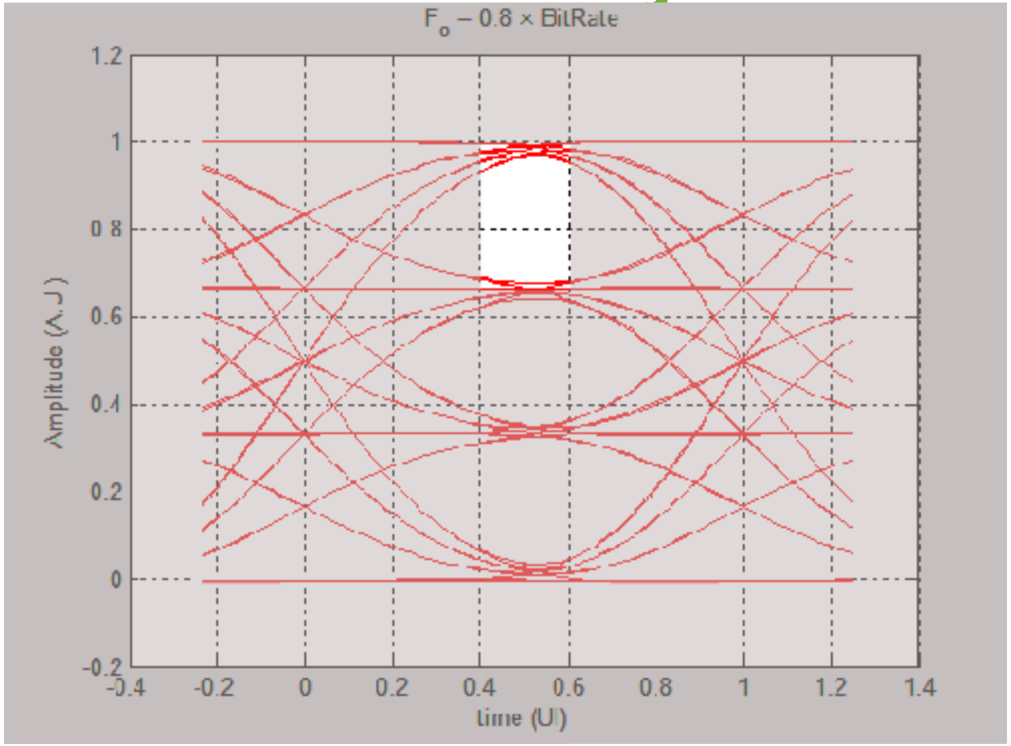


Moving from PAM2 NRZ to PAM4 NRZ: electrical: smooth roll-off… at what frequency?

- 100G PAM2 Electrical precedent is 33 GHz for 25.78125 Gb/s
This is not necessarily the best choice but it appears to be a good enough for PAM2.
- What does that say for PAM4 ?
- Postulate: if PAM2 has certain eye closure, and this worked out for the industry, then similar eye closure will work out at PAM4 as well.

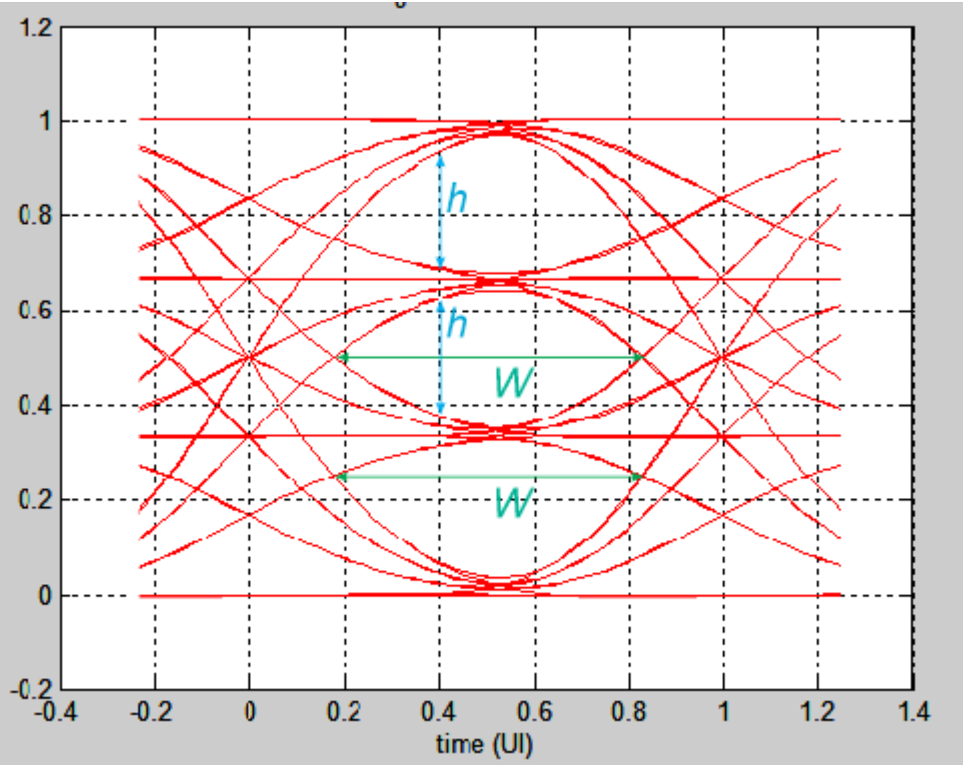
Vertical Eye Closure (due to measurement tool) as a measure of measurement fidelity

- Vertical eye opening would be a poor choice of DUT transmitter evaluation (in equalizing links), and the standards recognized that - what matters it how equalizable the signal is. However it still is a valid tool for evaluating the measurement equipment: the closure due to the measurement eats into the equalization budget.
- Vertical eye closure in a 20 % aperture shown on the right



Closure of which eye

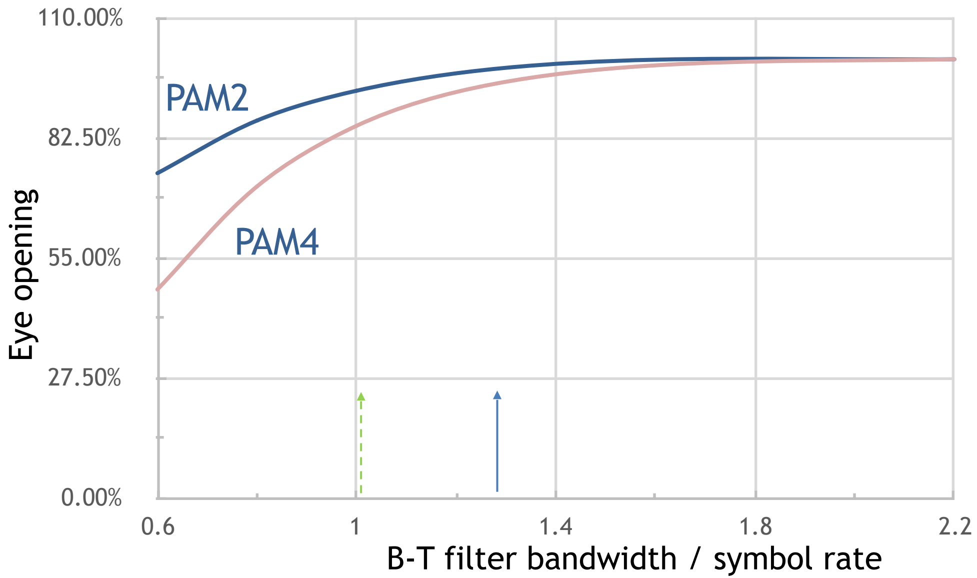
- There are two distinct eye shapes in the PAM4 signal: the central eye and the top and bottom eyes (one shape mirrored). Somewhat unintuitive their closures are the same.
- All data is expressed in % of full *inner* eye for PAM4
- The signal source used has transition time = 10% UI



Vertical eye closure as a f(BW/fs) PAM2 and PAM4

- "Traditional" optical eye measurement methodology (green, dashed arrow) experiences ~7 % of vertical eye closure (due to the measurement system's bandwidth) on PAM2.
- To match these results in PAM4, the bandwidth of optical measurement systems needs to increase to 1.24x symbol rate.
- But the bandwidth of the PAM4 electrical measurement system would need to increase 1.52x SR.

Eye opening vertical at 20% aperture vs B-T filter bandwidth



Do we really need to increase the bandwidth to 1.5 x Symbol Rate?

- Table on the right shows that nearly a 50% increase in bandwidth would be necessary to match the fidelity of the PAM2 measurement

search for where PAM4 equals PAM2, electrical			
electrical: same closure as 33 GHz/ 25.78125 - 2% closure			
BW/fs	vert. eye opening		opening
	PAM4el	PAM2el	delta
[-]	[-]	[-]	[-]
1.28	95%	98%	3.1%
1.3	95.0%	97.9%	2.7%
1.4	96.5%	98.5%	1.2%
1.48	97.3%	98.9%	0.4%
1.52	97.7%	99.1%	0.0%

BW/fs	BW [GHz]	B-T tail
	e.g. for 25.78G	GHz
[-]	26 GBd:	
1.28	33.28	50
1.3	33.8	51
1.4	36.4	55
1.48	38.48	58
1.52	39.52	59

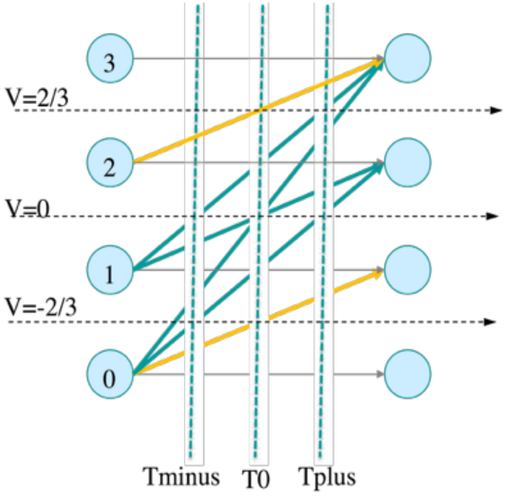
On the left: Practical Consideration - Scope BW? example based on the BW of 33 MHz for PAM2 25.781 GBd

Recommendations for measurement bandwidth for PAM4

- For electrical measurements, moving from PAM2 to PAM4 increase the bandwidth only slightly…. so recommendation is…
  1.3 times the symbol rate. At 5% the vertical closure (PAM4) is larger than that experienced today for PAM2 (which is 2% with 33 GHz measurement on 25.781 GBd) but still smaller than in optical systems today (optical eye closure is about 7%).
- For optical systems keep the vertical error in check by increasing the bandwidth to 1.24 times the symbol rate (for closure increase from ~ 6% to ~ 7%)
- PAM4 Bandwidth - BT roll off to 1.5* BW. Not an easy task, especially for 53 GBd.

2. Impact of PAM4 signaling on clock recovery

- 6 rising edges, 6 falling edges, 4 non trans
- 16 options
- PAM4 Transition density (td) is 12/16 = 75%



Possible PAM4 phase detectors

- Simplest: 1 detector: 0V crossing; allow all edges that cross to be counted
- More complicated: 1 detector: 0V crossing; Restrict data to symmetric data, i.e. 03--30 or 12--21 transitions
- Even more complicated: 3 detectors: -2/3, 0, 2/3
- Full detect: 5 detectors: -2/3, -1/3, 0, 1/3, 2/3

Receiver technology

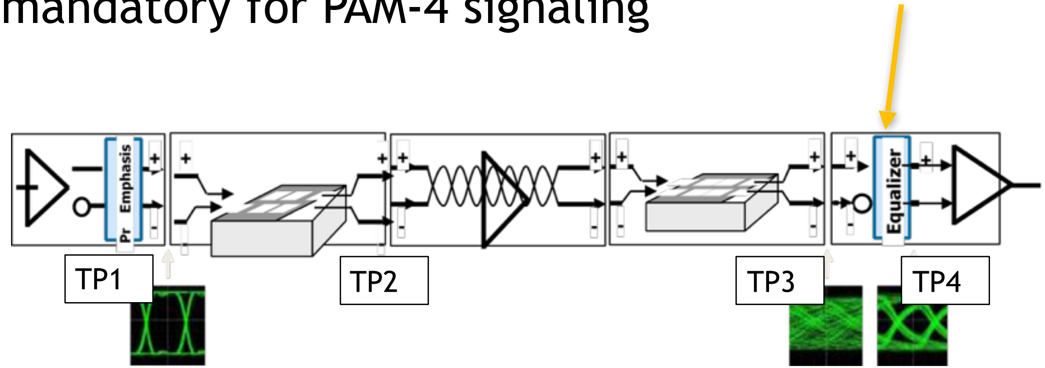
- DSP CDR receiver: use voltage samples (1UI time spaced). Can use all transitions as information and essentially ignores edge timing, and require processing time for CDR updates, so the PLL Loop bandwidth is sub-MHz.
- On the other hand an analog receiver can evaluate edge timing and allows 10 MHz PLL loop… but it is difficult to evaluate multiple thresholds/transitions.

Technology directly impacts the measurement

- Since the PLL loop bandwidth (and jitter tracking, etc.) is so severely impacted by the technology used in the receiver (DSP vs analog loop), an explicit requirement has to be made in the standard whether support one, the other, or most likely both

3. Receiver equalization methodology for measurements on equalized PAM4 links

- Among the challenges of effectively designing and measuring PAM-4 components and systems, stressed eyes at the receiver end are often severely impaired and closed, making digital data recovery and direct analysis of the eye parameters unfeasible. Therefore, receiver equalization is usually mandatory for PAM-4 signaling



Bandwidth requirements in links and receiver equalization

- A question with regard to the test of equalizing links is this: does the presence of the equalizer in the receiver relax the requirement on the performance of the test equipment?
- i.e., if the receiver is equalizing, does that mean that the transmitter doesn't have to be performed with high bandwidth?
- Our answer to this question is "no" – the transmitter performance needs to be evaluated for impact on possibly unusual equalization on possibly very short links. Understanding what the transmitter really is doing remains the key to interoperability.

Equalizing setup for PAM4

Today's PAM4 systems use the same setup as PAM2 systems

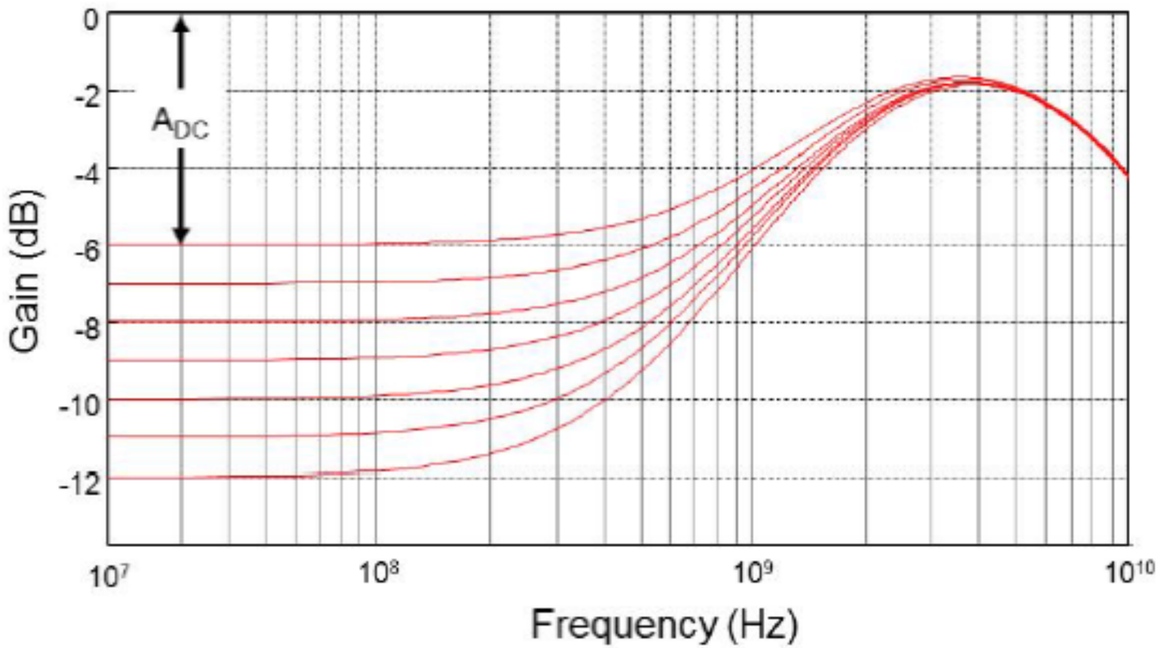
- Linear equalizer: Continuous time linear equalizer (CTLE), feed forward equalizer (FFE)
- Nonlinear equalizer: Decision feedback equalizer (DFE)

With some of the linear equalization possibly present in the transmitter.

In principle, established NRZ linear equalizer methodologies still apply for PAM-4 …

Example of linear equalier

For illustration see the behavioral CTLE for PCI Express Gen-3 (8 GT/s) (as per PCIe SIG)



DFE for PAM4

- The nonlinear equalizers, of which we currently use DFE in serial data measurement considerations, require a new design and implementation to extend support to PAM-4 signaling.
- Instead of attempting to invert the channel like the linear methods do, DFE estimates post-cursor ISI by making bit decisions on received symbols and subtracting from the next measurement.
  The subtracted values are of two levels on PAM2 but of four on PAM4.

$$z_k = y_k - \sum_{i=1}^{n} w_i \tilde{d}_{k-i}$$

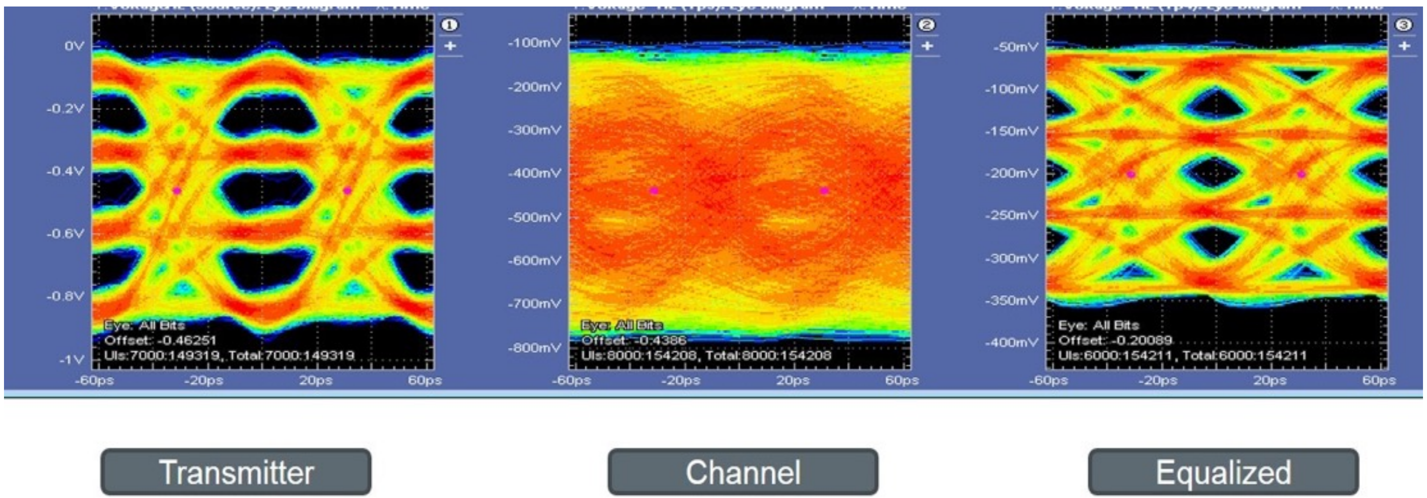
where y_k is measured amplitude, $\{w_i\}$ is DFE tap values, and $\widetilde{d}_k$ the bit value extracted by the DFE decision algorithm.

DFE for PAM4

- In the end the PAM-4 aware DFE algorithm enables ISI removal without noise amplification just as it does in PAM2, so contributing to the interpretation and assessment of PAM-4 signals with complex transition and leveling schemes.
- Furthermore, to compensate for changing ISI, DFE parameters are often adaptively determined based on the newest incoming data stream. In our PAM-4 DFE design, a least-square optimization was performed to determine the optimal DFE tap values.

Example of an equalized PAM4 signal

- Here is an example of a channel effect and receiver equalization for a 25 GBd PAM-4 waveform



Signal source: Tek PPG3202; medium length backplane; oscilloscope: Tek DPO77004SX

Software processing of the PAM4 data

- Post-capture, the waveform was clock-recovered in SW and equalization was performed in SW.

Note: SW clock recovery on PAM4 easily supports the super-set of the likely PAM4 clock recovery methodologies. This includes the set-ability of PLL Loop BW to either DSP-like or to analog-like frequency.

Signal analysis and clock recovery: Tek DPOJET software package. Equalization, channel emulation: Tek SDLA software package.

Software processing of the PAM4 data

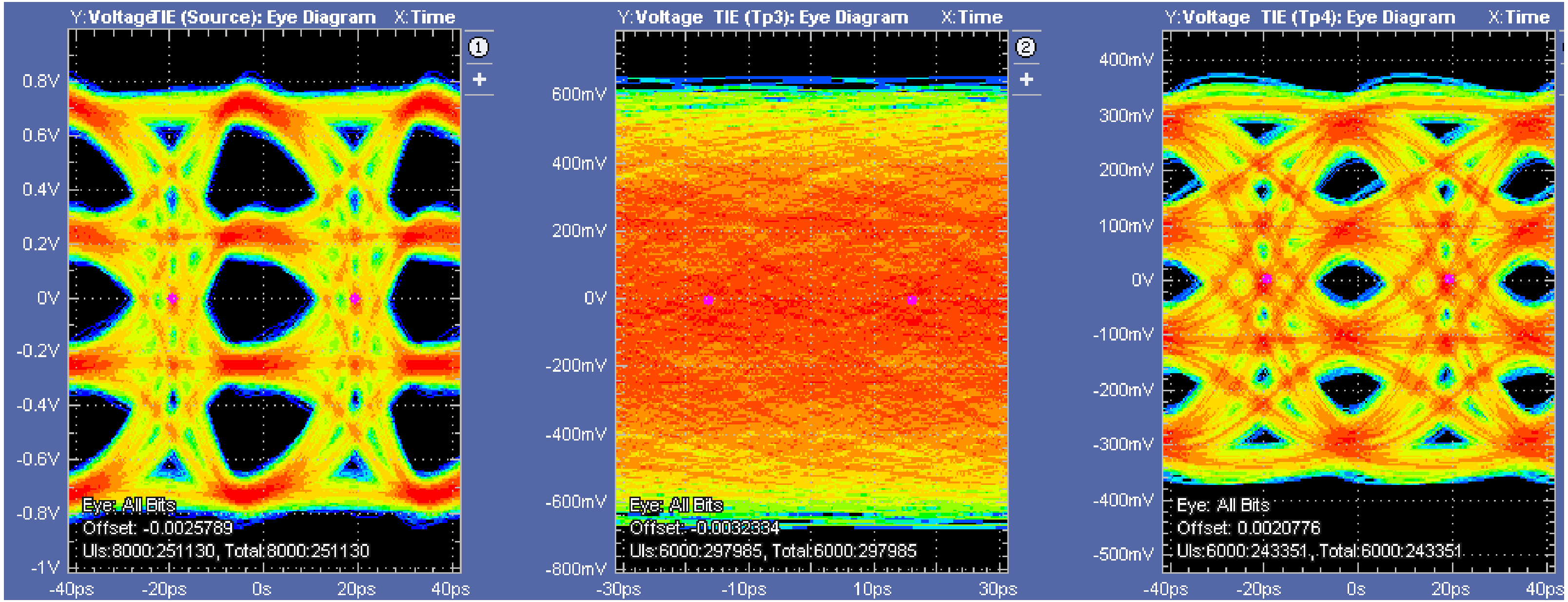


Figure 11. Before channel, after channel and after Rx eye diagrams without Rx DFE.

Software processing of the PAM4 data

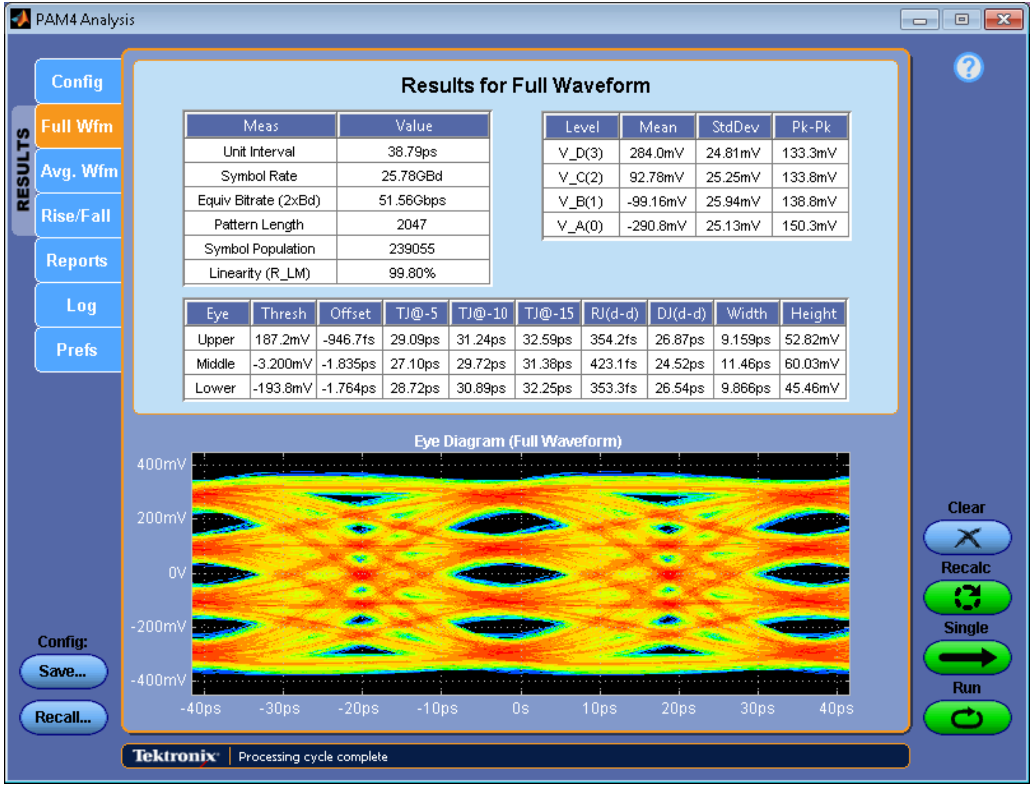


Figure 12. Analysis results when Rx DFE is not used.

Software processing of the PAM4 data

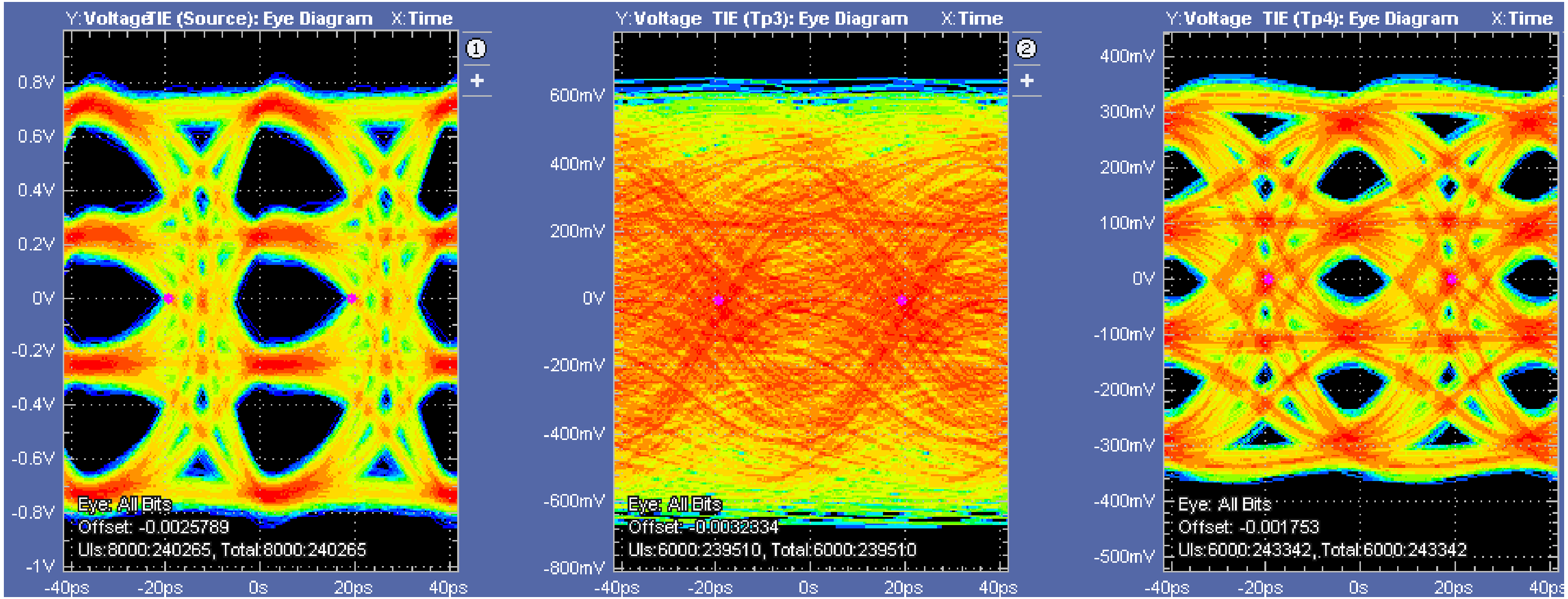
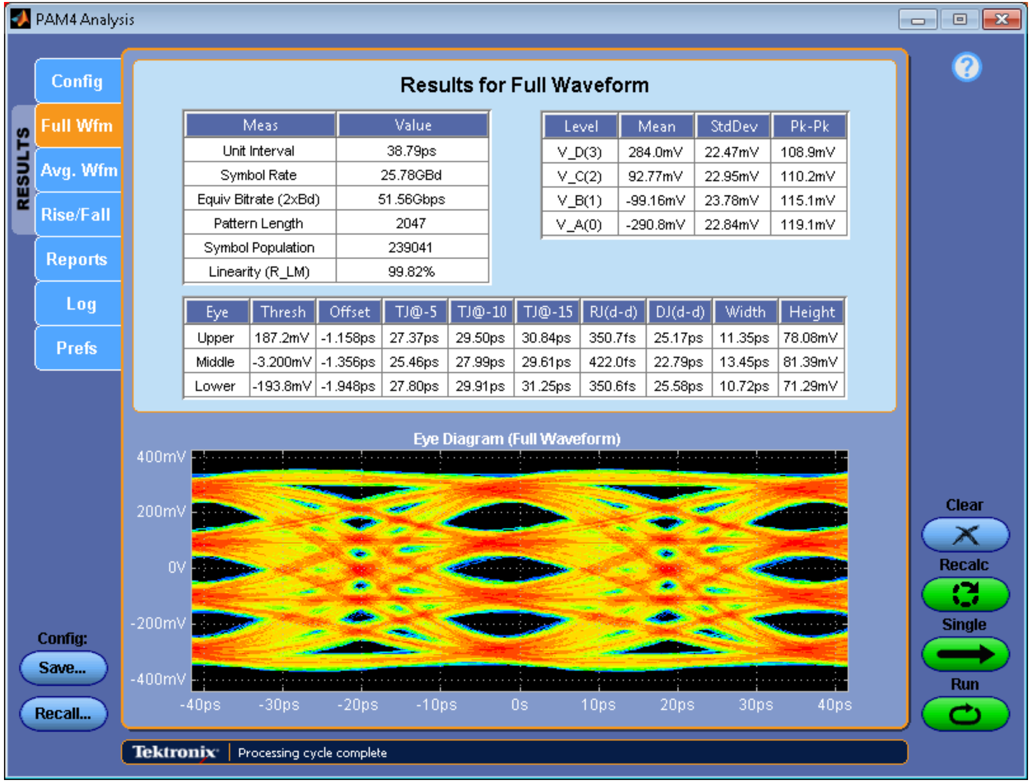


Figure 13. Before channel, after channel and after Rx eye diagrams with Rx DFE.

Software processing of the PAM4 data



Meas	Value
Unit Interval	38.79ps
Symbol Rate	25.78GBd
Equiv Bitrate (2xBd)	51.56Gbps
Pattern Length	2047
Symbol Population	239041
Linearity (R_LM)	99.82%

Level	Mean	StdDev	Pk-Pk
V_D(3)	284.0mV	22.47mV	108.9mV
V_C(2)	92.77mV	22.95mV	110.2mV
V_B(1)	-99.16mV	23.78mV	115.1mV
V_A(0)	-290.8mV	22.84mV	119.1mV

Eye	Thresh	Offset	TJ@-5	TJ@-10	TJ@-15	RJ(d-d)	DJ(d-d)	Width	Height
Upper	187.2mV	-1.158ps	27.37ps	29.50ps	30.84ps	350.7fs	25.17ps	11.35ps	78.08mV
Middle	-3.200mV	-1.356ps	25.46ps	27.99ps	29.61ps	422.0fs	22.79ps	13.45ps	81.39mV
Lower	-193.8mV	-1.948ps	27.80ps	29.91ps	31.25ps	350.6fs	25.58ps	10.72ps	71.29mV

Figure 14. Analysis results when Rx DFE is used.

Results summary of software processing of the PAM4 data

	Width (ps)		Height (mV)	
	No DFE	With DFE	No DFE	With DFE
Upper	9.156	11.35	52.82	78.08
Middle	11.46	13.45	60.03	81.39
Lower	9.866	10.72	45.46	71.29

- In summary equalization is bringing the same advantages to PAM4 as it does to PAM2 signals, and signal analysis measurement tools are available to support the measurements.

Conclusions

- We considered the impact of measurement tools' bandwidth on the fidelity of measurement of PAM4 signal; we've compared this to PAM2, and we recommend bandwidth for electrical measurement on PAM4.
- We presented an overview of the features of PAM4 signal on clock recovery methodology: the measurement jitter tracking is dependent on the technology of the receiver.
- And finally we've presented an example of equalization of PAM4 signal – acquired live signal – in the oscilloscope toolset, and demonstrated that the equalization methodology used in PAM2 is a good toolset for measurement equalization in PAM4.

Thank you!

QUESTIONS?

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