PAM-4 vs. duobinary modulation @25 Gb/s

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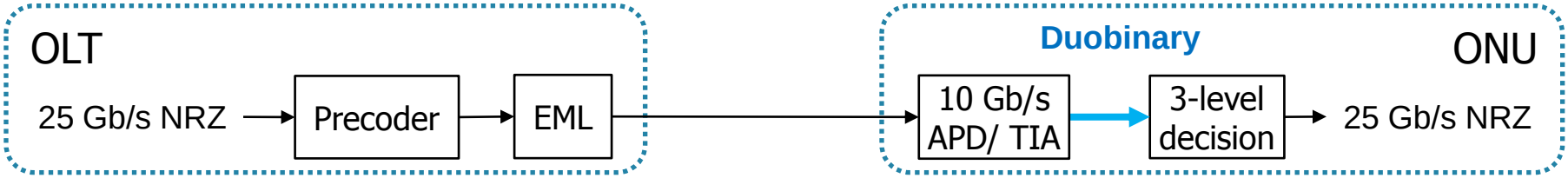
Scope

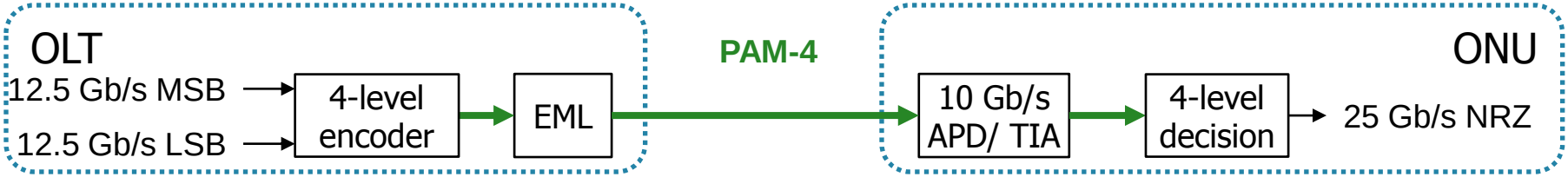
"Apples-to-apples" comparison

- 25 Gb/s into a low-cost 10 Gb/s ONU receiver, ≈ 7 GHz bandwidth (practical NRZ receiver bandwidth ≈ 0.7*R).
- 25 Gb/s NRZ requires ≈ 17.5 GHz bandwidth and is not workable into a 10 Gb/s receiver.
- Receiver-encoded duobinary ideal receiver bandwidth ≈ 0.27*R = 7 GHz. A 10 Gb/s NRZ receiver is ideal.
- PAM-4 is half the baud rate of NRZ, so ideally requires ≈ 9 GHz. There will be lower noise but additional signal distortion out of a 10 Gb/s NRZ receiver.

Receiver-encoded duobinary (as described in ngepon_1114_harstead_01.pdf)



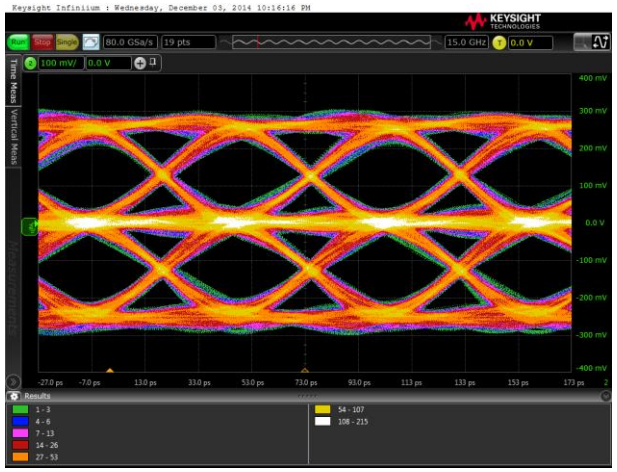
PAM-4



Theory: modulation penalty (vertical eye)

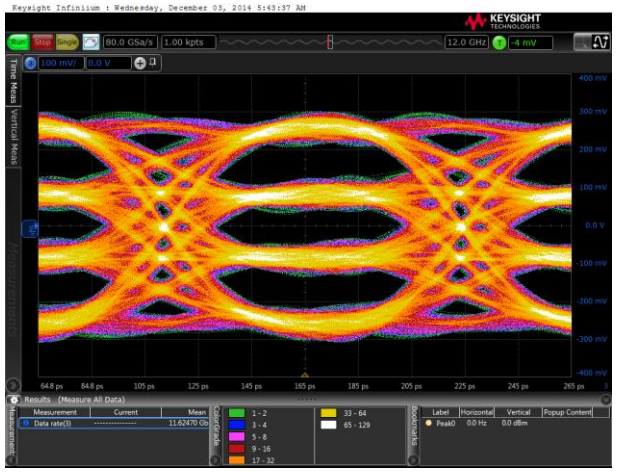
Ideal PAM-M modulation penalty MP = 10*log10(M-1)

C. Cole, "Ideal SNR Penalties", contribution to IEEE 802.3 400 Gb/s Ethernet Task Force, September 2014



Duobinary 3-level signal (M=3)

- MP = 3 dB



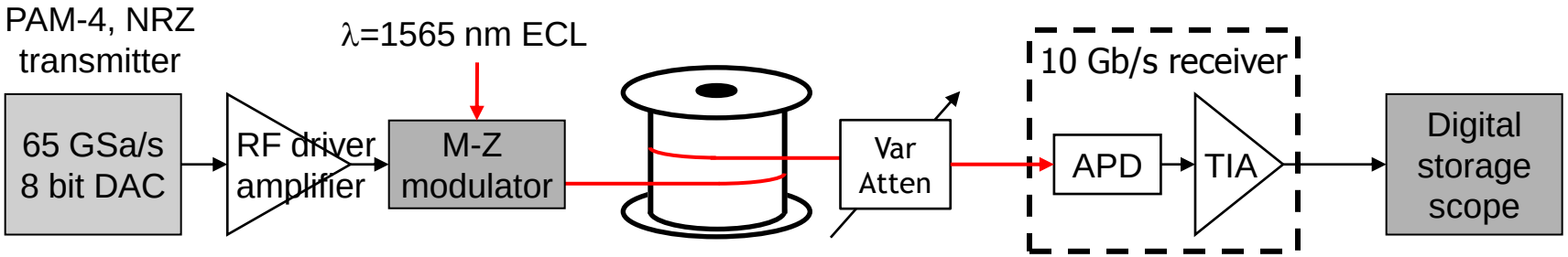
PAM-4 4-level signal (M=4)

- MP = 4.8 dB

- We expect a 1.8 dB advantage for duobinary
- Due to the non-ideal receiver bandwidth for PAM-4, the actual advantage may be larger

Experimental comparison

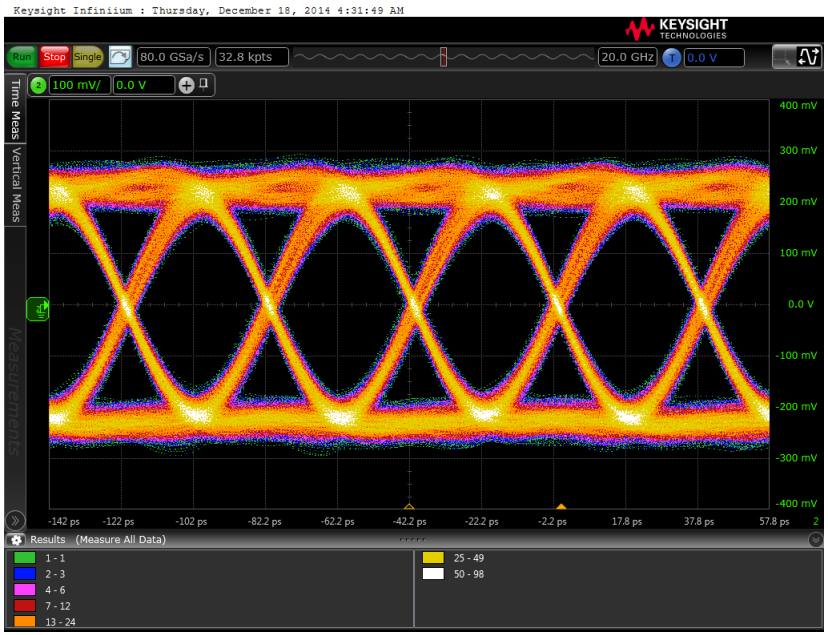
Compare duobinary and PAM-4 using the exact same experimental setup



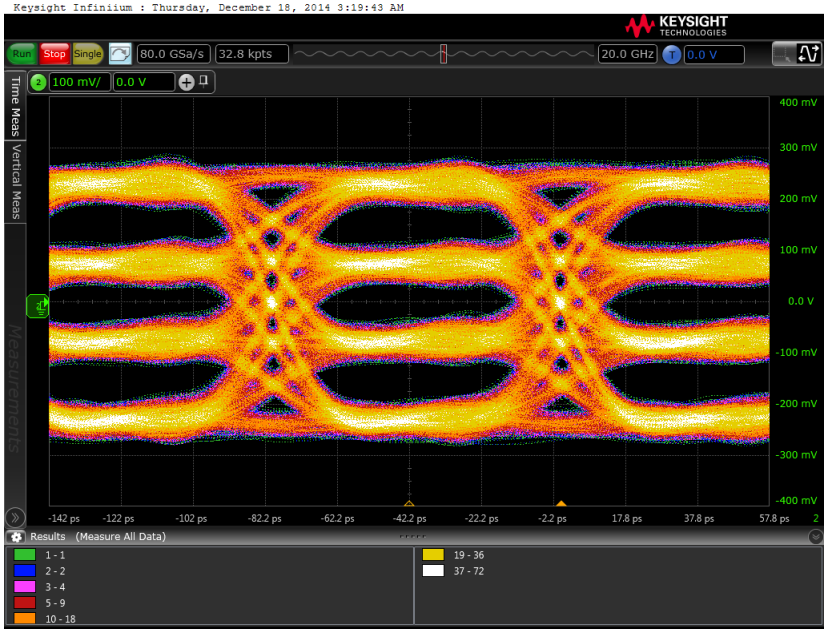
Transmitter

- For receiver-encoded duobinary, a conventional 25 Gb/s NRZ signal is transmitted
- For PAM-4, two data streams of 12.5 Gb/s each are combined to create a 4-level 12.5 Gbaud driving signal

Electrical eye diagrams at the output of the DAC



25 Gb/s NRZ

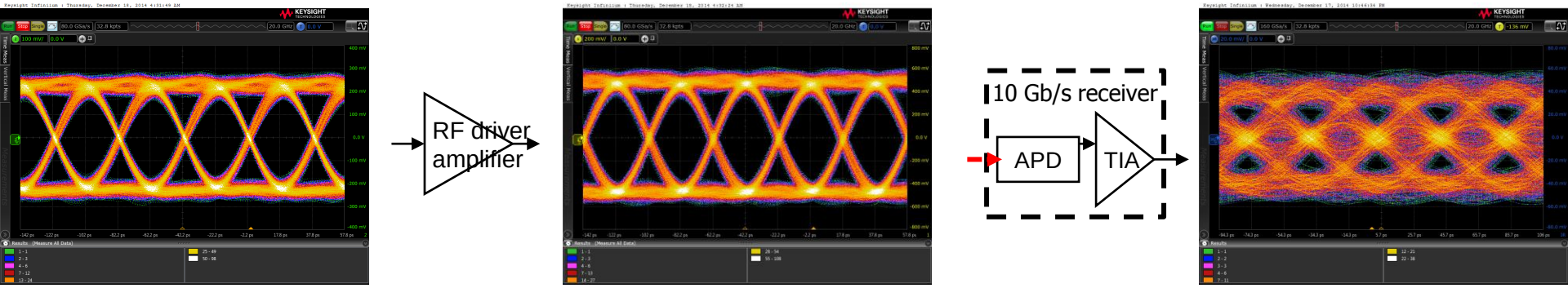


12.5 Gbaud PAM-4

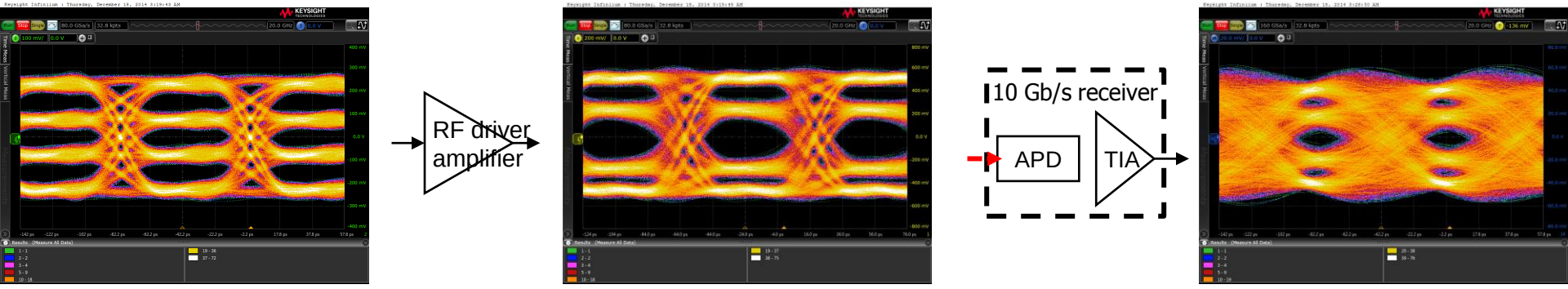
Transmitter linearity

Electrical eye diagrams for NRZ and PAM-4 before and after the RF driver amplifier at maximum driving voltage swing, and after the 10 Gb/s receiver.

- 25 Gb/s NRZ: negligible signal distortion. Transmitter linearity is not an issue.

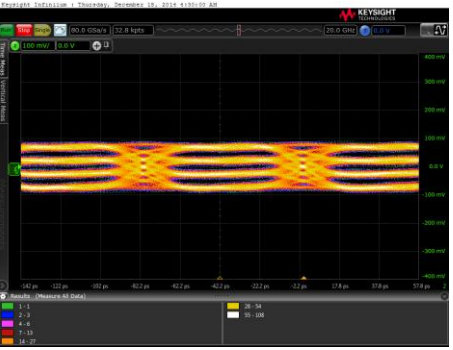


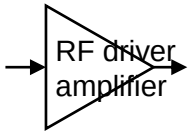
- PAM-4 eyes are distorted. PAM-4 requires a linear transmitter response.

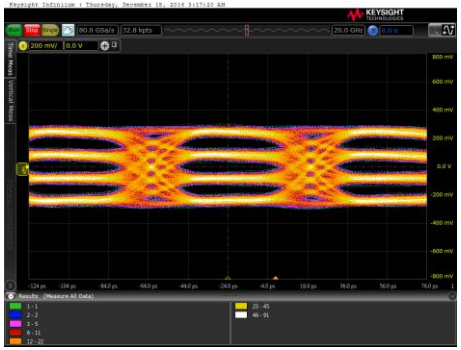


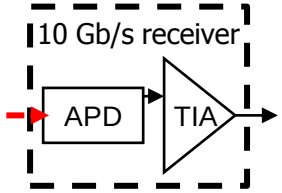
Achieving a linear PAM-4 transmitter

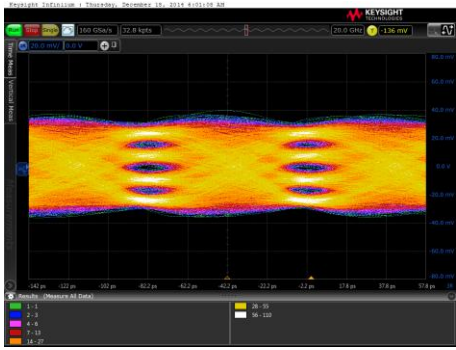
- Reduced driving signal swing to stay in linear regime.
- But this will reduce the modulation extinction ratio (ER) and lead to a penalty.



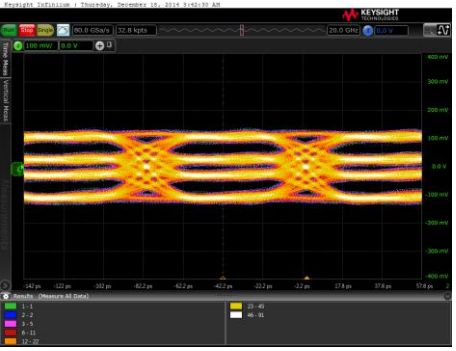


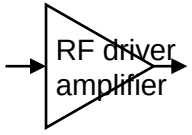


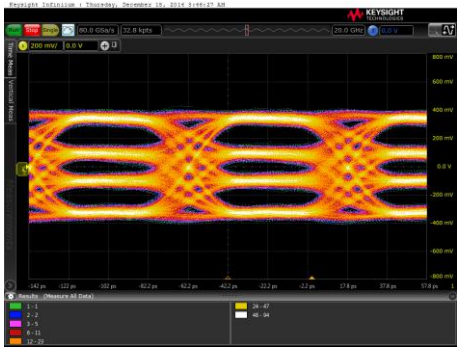


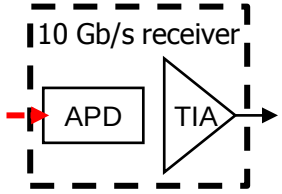


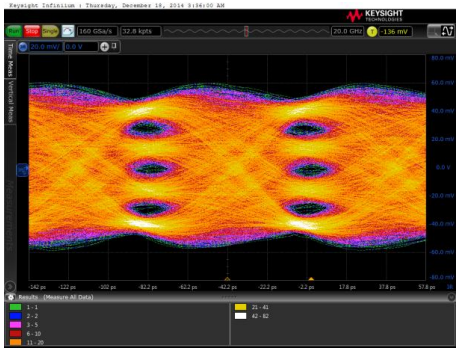
- Drive harder and add pre-distortion-- which adds some noise
- Optimal combination of drive swing plus pre-distortion to minimize penalty.
- Will become even more important for EML (more non-linear than M-Z modulator)







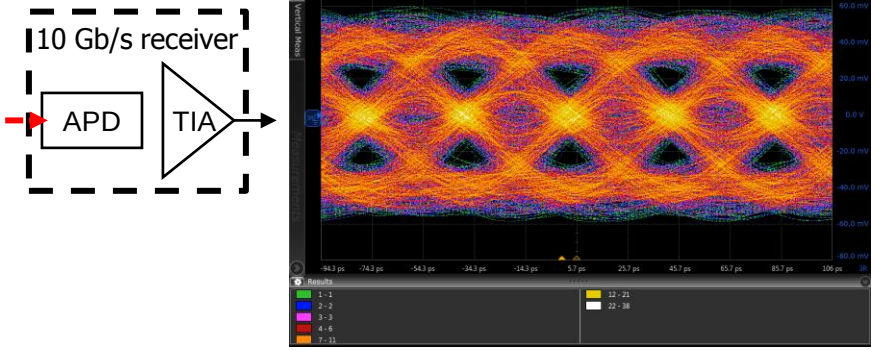




Measured back-to-back receiver penalty

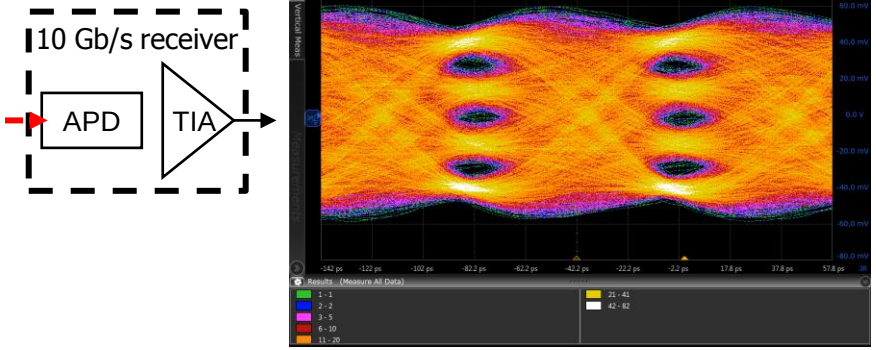
Received eye diagrams (shown at -18 dBm)

Receiver-encoded duobinary



Receiver sensitivity @10^{-3}
BER = -24.9 dBm

PAM-4, optimized transmitter



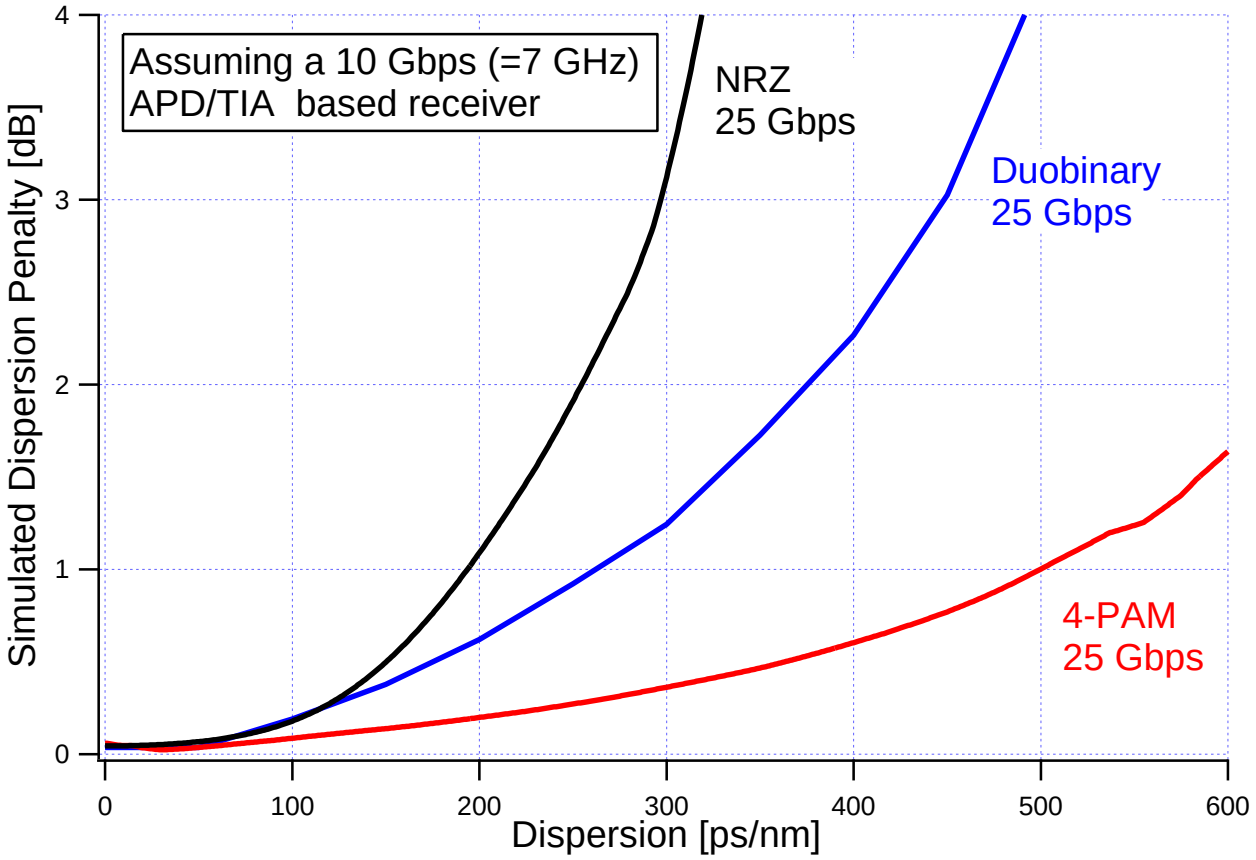
Receiver sensitivity @10^{-3}
BER = -21.5 dBm

The 3.4 dB empirical advantage for duobinary is larger than the theoretical 1.8 dB.

Probable causes:

- Noise penalty associated with pre-distortion to optimize the PAM-4 eye.
- Any latent uncompensated non linear signal distortions at the transmitter
- Non-optimized receiver bandwidth for PAM-4 produces some additional signal distortion

Dispersion tolerance (simulated)



- PAM-4, with a bit interval 2x longer than duobinary, achieves ≈1.8 better dispersion tolerance.

Noise contributions, laser linewidth and non-linearities were not taken into account in the simulation.

Duobinary dispersion penalty relative to PAM-4 @20 km	
O-band (130 ps/nm maximum)	+0.2 dB
1600 nm (415 ps/km)	+1.8 dB

Summary

"Apples-to-apples" comparison: 25 Gb/s into the same low-cost 10 Gb/s receiver

Relative optical performance		Duobinary Relative penalty	PAM-4 Relative penalty
Measured back-to-back optical penalty			+3.4 dB
Simulated dispersion penalty at 20 km	O-band	+0.2	
	1600 nm	+1.8	
Total optical penalty at 20 km	**O-band**		**+3.2**
	1600 nm		**+1.6**

We conclude that receiver-encoded duobinary has about a 1.6 to 3.2 dB performance advantage over PAM-4, depending on transmission wavelength

Future work

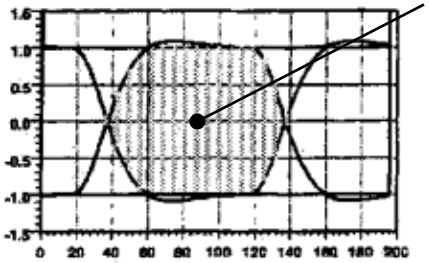
- Empirical dispersion tolerance
- 25 Gb/s NRZ
  - A higher bandwidth receiver will be required, e.g. 25 Gb/s 100GBASE-ER4 (17.5 GHz).
- PAM-4, duobinary comparison at 40 Gb/s
  - Using the same 25 Gb/s receiver as above, it will be possible to optimize the receiver bandwidth for both PAM-4 (≈14 GHz) and duobinary (≈11 GHz).
- Comparison with transmitter-encoded duobinary
  - Has been proposed for upstream to allow 10 Gb/s transmitter in the ONU.
  - Transmitter linearity will be a factor, although not expected to be as critical for a 3-level signal as for a 4-level signal.
- Pre-distortion of 25 Gb/s PAM-4 to compensate for signal distortion due to limited 10 Gb/s receiver bandwidth. Any possible gain?

Backup

Optimizing ISI to create a duobinary signal

Figures from E. Säckinger, Broadband Circuits for Optical Fiber Communication, 2005

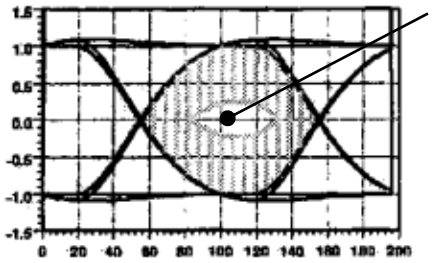
Low signal distortion, but too much noise



NRZ eye

$BW_{3dB} = \frac{4}{3}B$

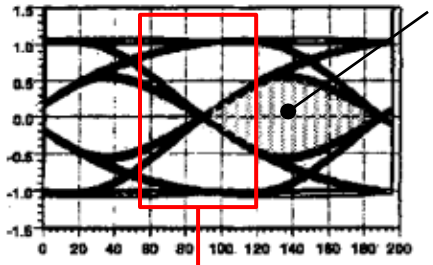
Optimum



NRZ eye

$BW_{3dB} = \frac{2}{3}B$

Low noise but too much ISI



NRZ eye

$BW_{3dB} = \frac{1}{3}B$

But at this bandwidth, ISI creates a duobinary eye!