6.3.2 PAM-4 modulation.

Place holder

6.3.4 PAM-4 vs. duobinary modulation.

Back-to-back comparison, 25 Gb/s

Comparing duobinary's 3-level signal to PAM-4's 4 level signal, duobinary's larger vertical eye dimension results in an ideal 1.8 dB modulation advantage. For the same bit rate R, each signal has an optimal receiver bandwidth: approximately 0.27R for receiver-encoded duobinary and 0.35R for PAM-4. The wider bandwidth of the PAM-4 receiver will result in about a 1 dB receiver noise penalty. This ideally gives duobinary a 2.8 dB advantage when considering optimized receiver bandwidths.

In PON systems, ONU cost must be minimized. In the downstream direction, an ideal NG-EPON receiver would be based on high-volume low-cost 10 Gb/s APDs, as used in 10G EPON ONUs today. 10 Gb/s APDs have about 7 GHz bandwidth, which is ideal for 25 Gb/s receiver-encoded duobinary. 25 Gb/s PAM-4 ideally requires about 9 GHz receiver bandwidth, but 7 GHz can yield good results. (25 Gb/s NRZ requires about 17.5 GHz, and is therefore unworkable with a 7 GHz receiver).

An empirical comparison [REF] at 25 Gb/s transmission into a 7 GHz APD, using the exact same set-up for receiver-encoded duobinary and for PAM-4 modulations, has been performed. In this case, with an identical receiver, there is no receiver noise penalty for the PAM-4 signal, and we would expect to see only the 1.8 dB modulation penalty. In fact, the measured receiver sensitivities (@10^{-3} BER) for duobinary and PAM-4 were -24.9 and -21.5 dBm respectively, a 3.4 dB penalty. The observed eye diagrams are shown in Figure 1.

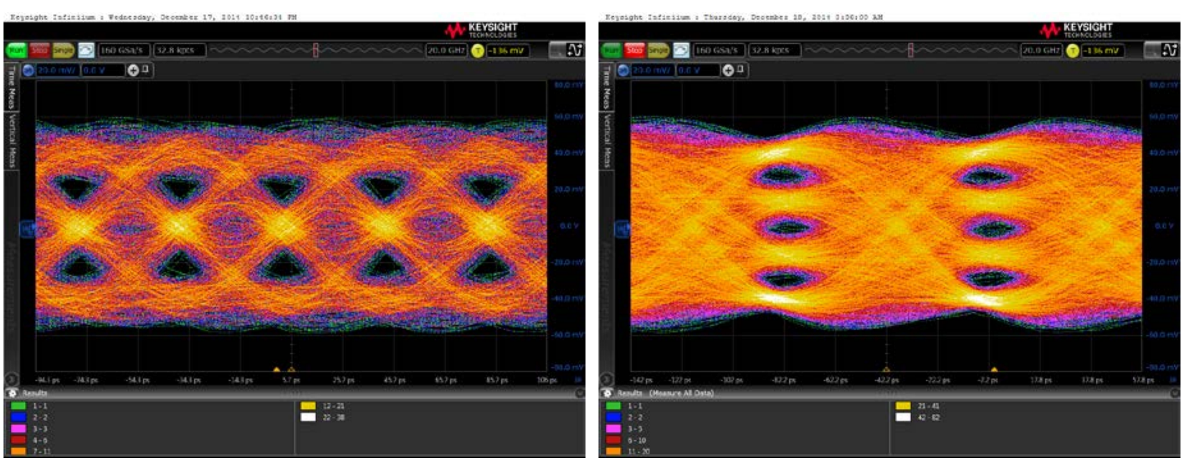

Figure 1. Received eye diagrams (shown at -18 dBm) for duobinary and for PAM-4.

The additional 1.6 dB penalty can be explained by the following:

- The PAM-4 signal is sensitive to transmitter non-linearity. Pre-distortion was used to mitigate this effect, however at the cost of some transmitter noise penalty.

- Any latent uncompensated non-linear signal distortions at the transmitter,
- Non-optimized receiver bandwidth for PAM-4 produces some additional signal distortion.

20 km transmission, 25 Gb/s

PAM-4 has half the baud rate as duobinary, which should lead to superior dispersion tolerance. Simulations [REF], again for 25 Gb/s into a 7 GHz APD receiver, has shown that PAM-4 achieves about 1.8x better dispersion tolerance (see Figure 2). For 20 km transmission, this gives about a 0.2 dB and 1.8 dB advantage to PAM-4 when transmitting in the O-band and at 1600 nm respectively.

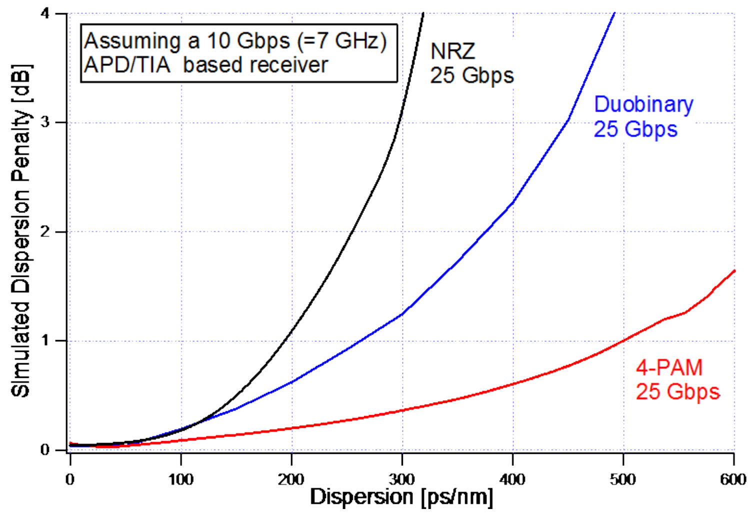

Figure 2. Simulated dispersion tolerance for duobinary and for PAM-4.

Combining this with the back-to-back performance, it is concluded that receiver-encoded duobinary has about a 3.2 dB and 1.6 dB performance advantage over PAM-4 when transmitting in the O-band and at 1600 nm respectively, which bookends the full range of likely wavelengths to be considered for NG-EPON.

40 Gb/s

For 40 Gb/s, an APD receiver with >>7 GHz bandwidth will be required. A 25 Gb/s 100GBASE-ER4 receiver is a likely candidate. In this case the receiver bandwidth can be optimized for both duobinary and for PAM-4. The relative increase in receiver noise for PAM-4 (due to wider PAM-4 receiver bandwidth vs. duobinary) should be more than offset by reduced signal distortion. In which case the back-to-back advantage for duobinary would be expected to be less than the observed 3.4 dB and closer to the ideal 2.8 dB.

[REF] V. Houtsma, D. van Veen, E. Harstead, “PAM-4 vs. duobinary modulation @25 Gb/s”, ngepon_0115_houtsma_01.pdf, Jan. 2015.