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NRZ, PAM4 and Duobinary Modulation Schemes for 10G Serial Ethernet

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Introduction

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- Different Modulation Schemes for 10G Backplanes
  - NRZ
  - Duobinary: Use channel as part of equalizer
    - It has been used in disk drive applications for years
  - PAM4: Reduce baud rate by using multi-level signaling
    - It has been used for years in Modems
- Spectrum
- Required RX Equalizer Boost
- Eye Opening
- Complexity and Required Power
  - Transmitter
  - Receiver
- Crosstalk Sensitivity
- Summary/Conclusion

Spectrum

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- **PAM4 and Duobinary have**
  - ✓ **the same spectrum for |f|<1/2T**
  - ✓ **Different sensitivity to Xtalk**

NRZ

$$S_{NRZ}(f) = 10 * \log 10(\text{abs}(\text{sinc}^2(Tf)))$$

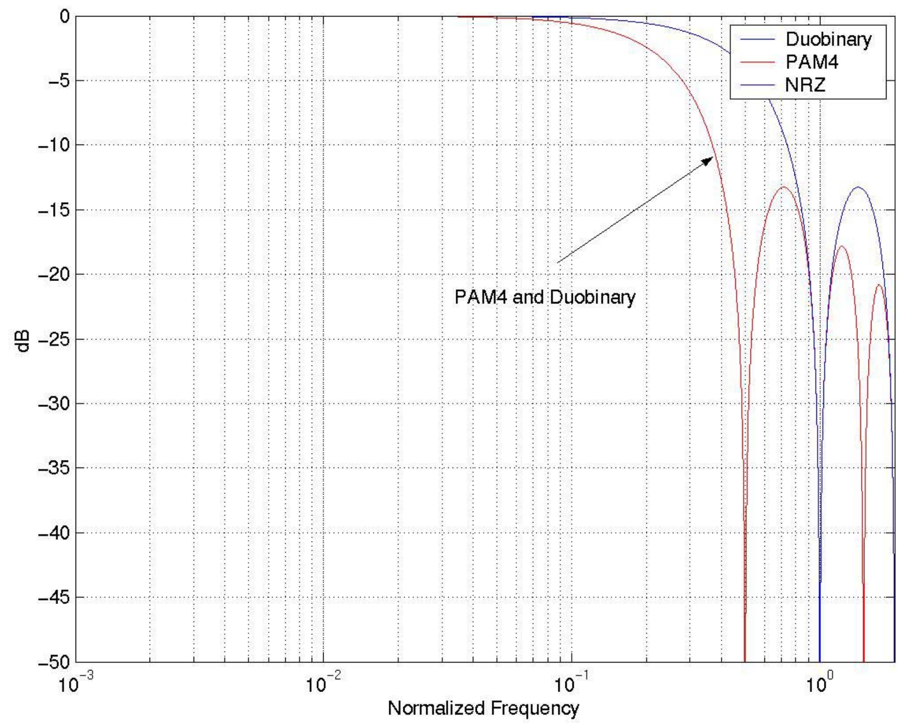
PAM4

$$S_{PAM4}(f) = 10 * \log 10(\text{abs}(\text{sinc}^2(2Tf)))$$

Duobinary

$$S_{Duobinary}(f) = 10 * \log 10(\text{abs}(\text{sinc}(TF)\frac{1+\exp(-j2\pi fT)}{2})^2)$$

$$= S_{PAM4}(f) \quad |f| < \frac{1}{2T}$$



Block Diagrams and Equalization

NRZ/PAM4 Signaling

Duobinary Signaling

Ideal Equalizer (Zero Forcing)

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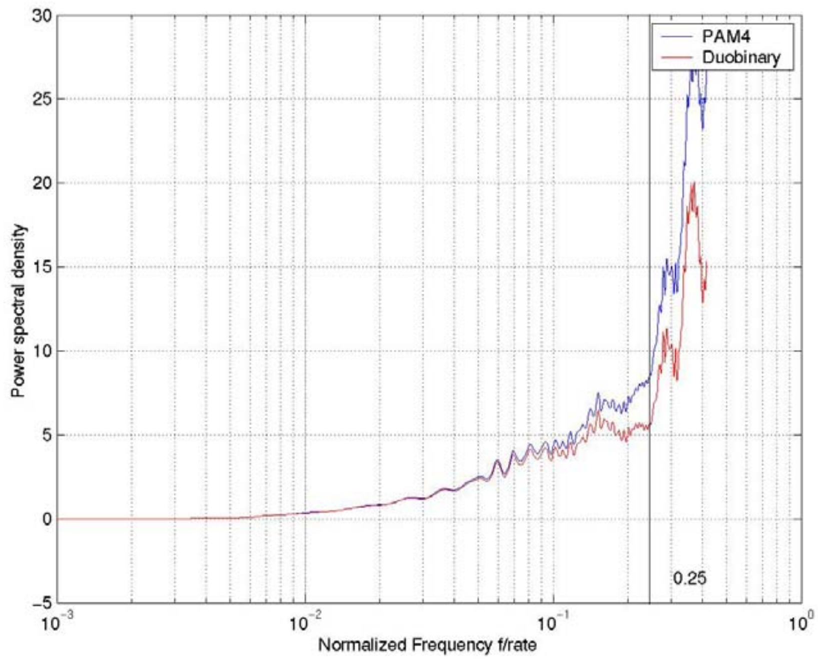

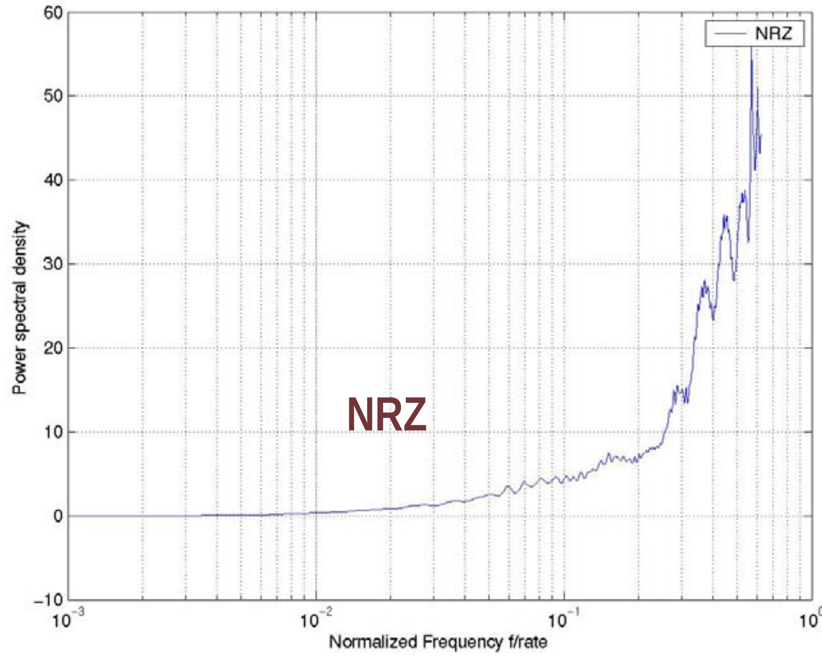

- PAM4 needs about 3 dB more equalization around 0.25R frequency
- PAM4 eye opening will be 2/3 of Duobinary for a fixed maximum signal level

Perfect Equalization (or Perfect Transmitter Eye Diagrams)

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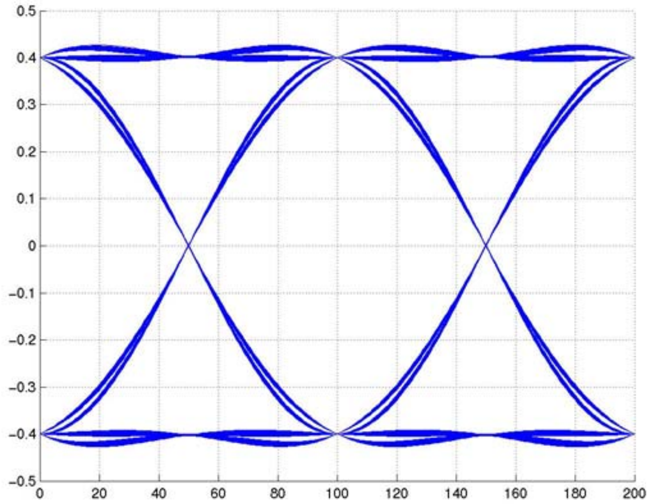
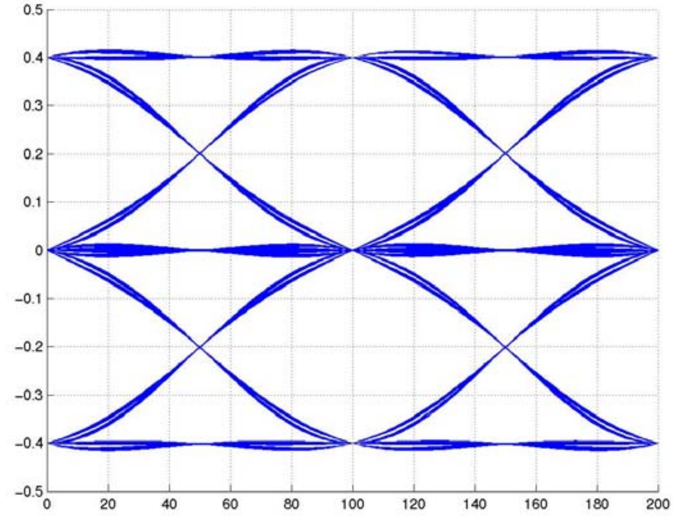
NRZ

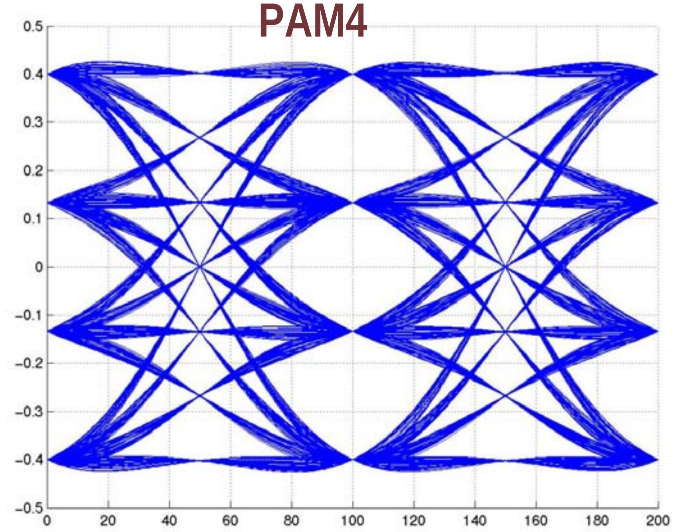


Duobinary



- For perfect equalization PAM4 has 0.66 of horizontal eye opening compared to NRZ and Duobinary.
- In terms of absolute value, if we take into account TX RJ/DJ, all will have the same horizontal eye opening.

PAM4



Optimized Duobinary Linear Receiver Equalizer

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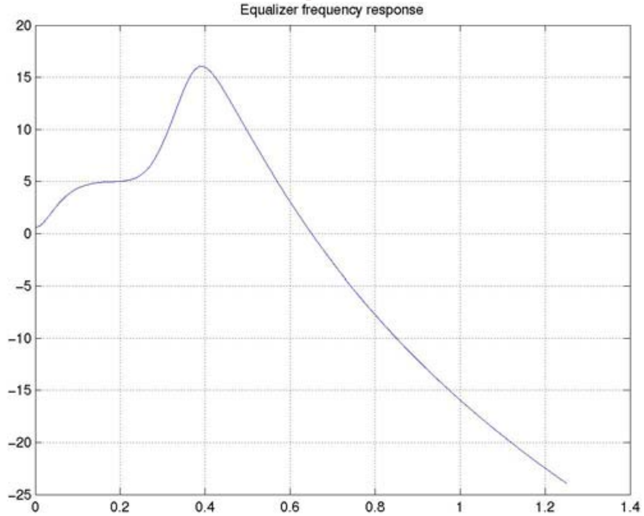
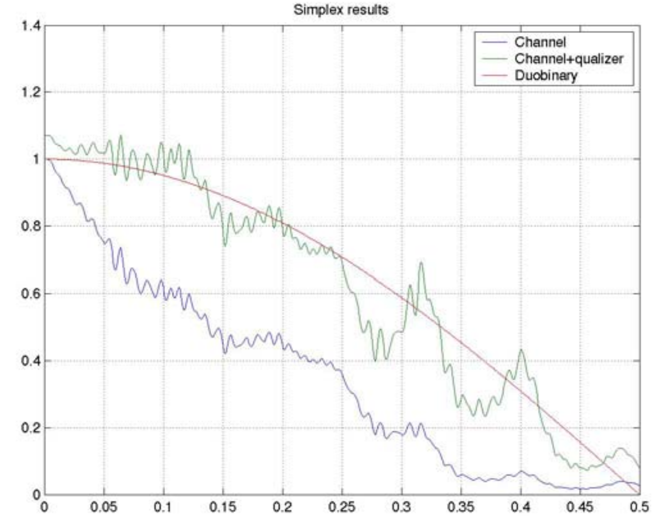
Equalizer

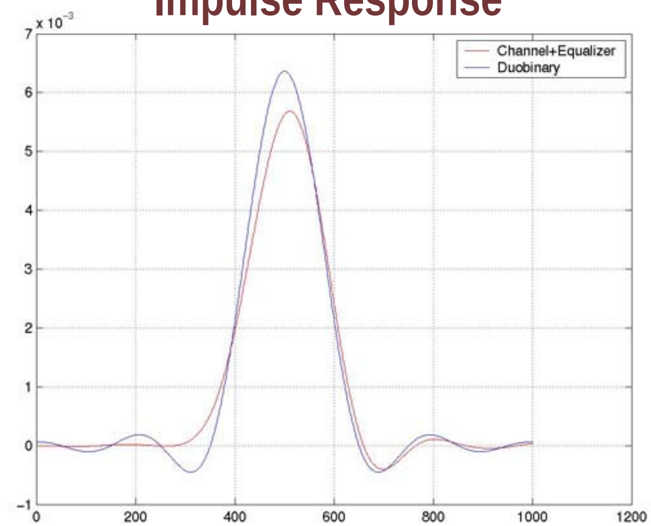


Channel+Equalizer



With linear equalizer and reasonable boost, channel has been equalized to have a duobinary characteristic.

Impulse Response



Eye Diagrams(34” Tyco XAUI Backplane)

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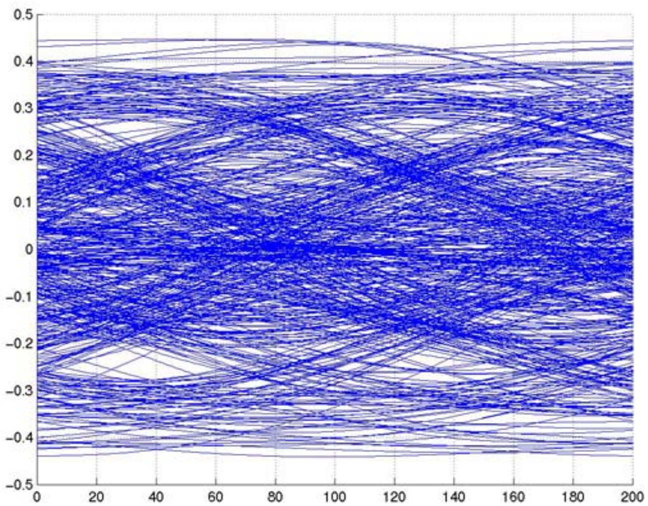
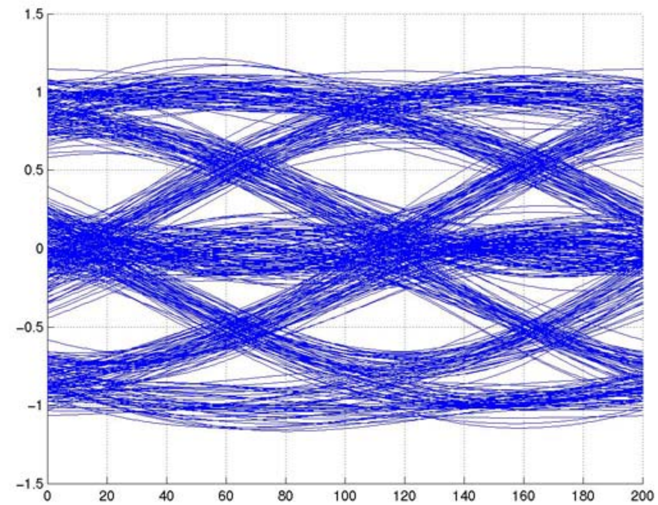
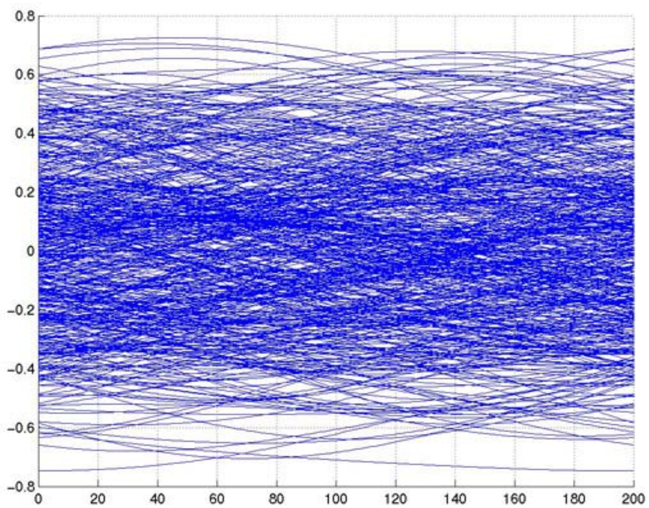
Channel Output | **Equalizer Output**

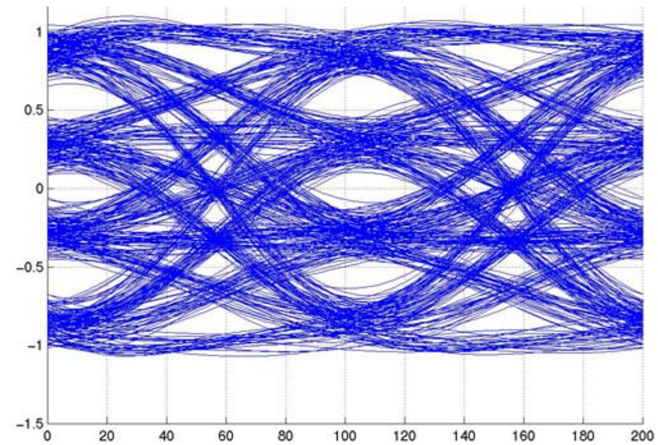
Duobinary





PAM4





Better Channel (34" BP trace at bottom of Backplane)

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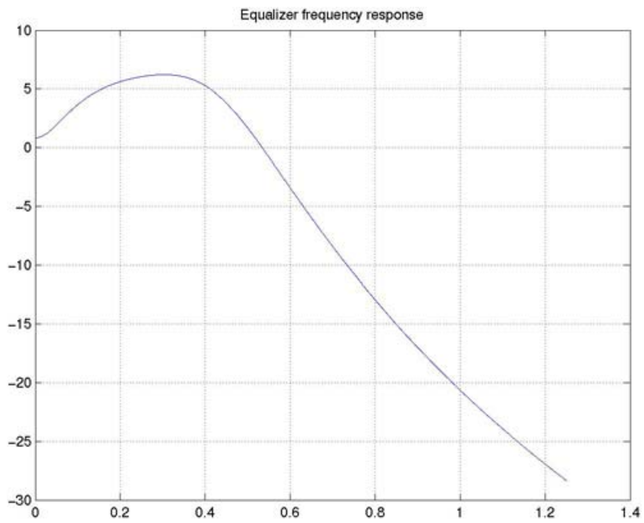
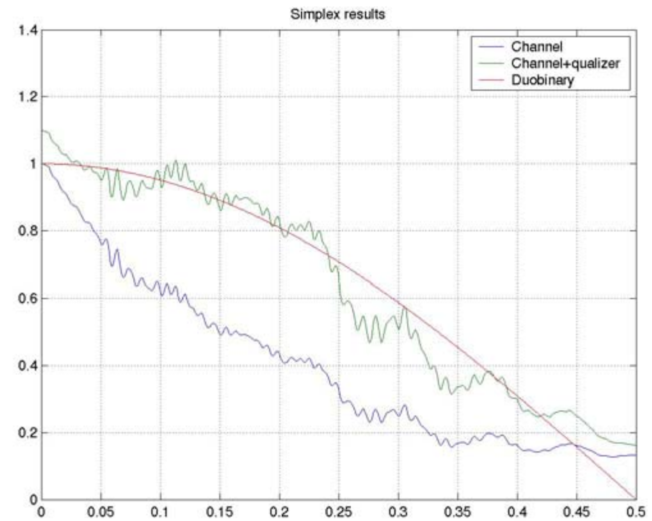
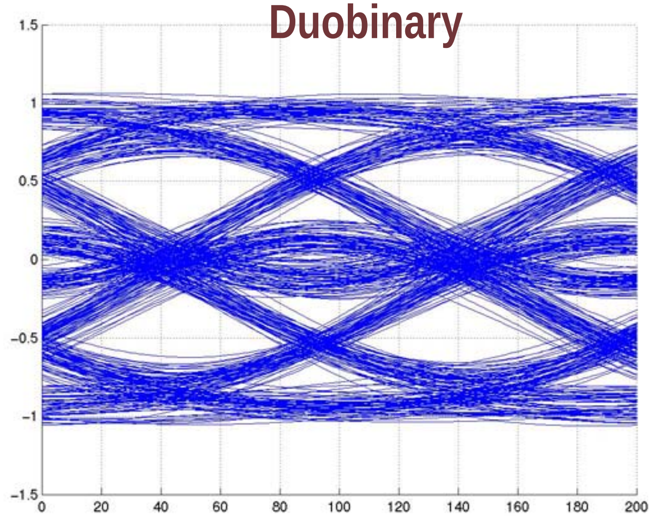
Equalizer



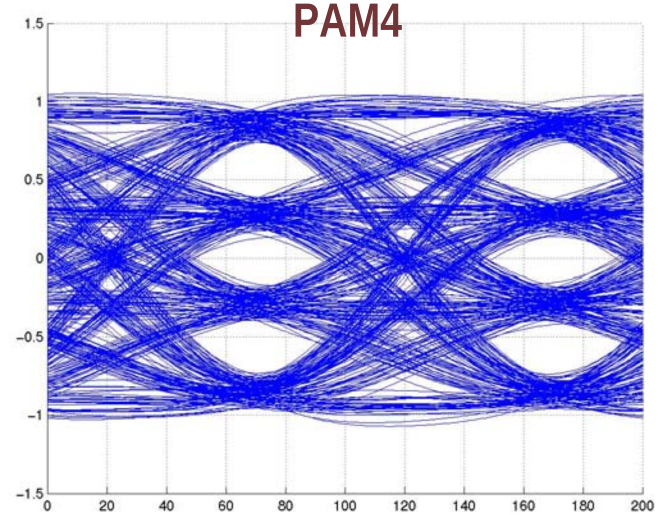
Channel + Equalizer



Duobinary



PAM4



Eye Opening(summary)

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- Horizontal (Usually dominant factor due to CDR jitter)
  - Duobinary does not have all transitions, better horizontal eye opening compared to PAM4 and the same as NRZ
  - PAM4 worse than NRZ

- Vertical (For noisy environment with small CDR jitter)
  - PAM4 has 0.33 of NRZ eye opening
  - Duobinary has 0.5 of NRZ eye opening

✓ Duobinary has better horizontal and vertical eye opening compared to PAM4.

Tx Block Diagrams (No Pre-emphasis)

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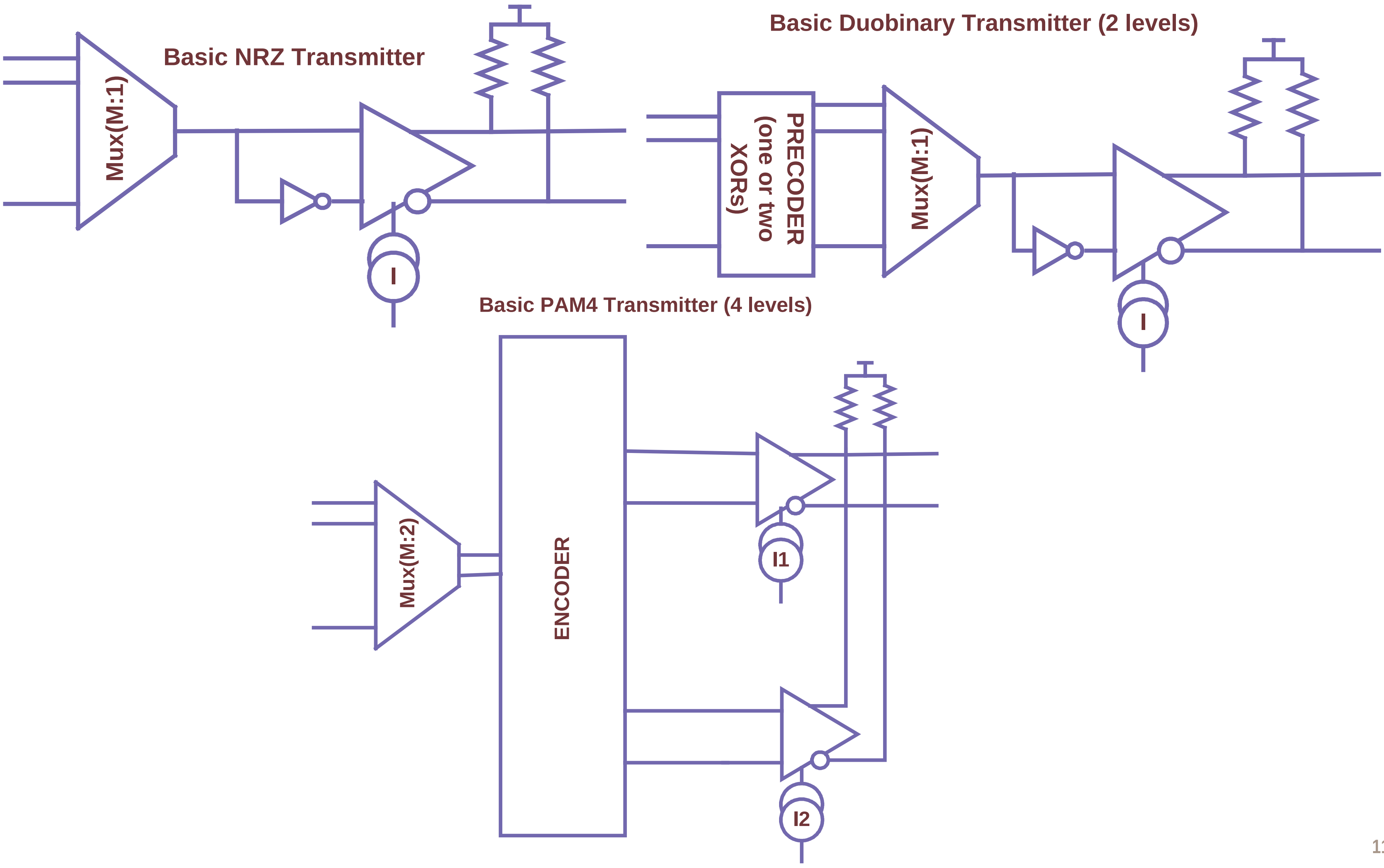

Transmitter Complexity with No Pre-emphasis

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- PAM4
  - Half speed drivers of NRZ
    - Same current density and higher current => wider transistors (ex. 3 times)
    - Same Current density and equal current => same total size transistors, but 9 dB degradation in vertical eye opening
  - Twice number of drivers as of NRZ
  - Due to lower speed, the drivers before the last stage could be smaller size compared to NRZ, but they need to drive larger transistors (more capacitive load) which results in larger sizes.
- Duobinary
  - Same speed driver as NRZ
  - Driver size twice of NRZ (or lose 6dB vertical eye opening)
  - Only needs a simple logic for XOR and maybe differential encoder

✓ Since today's technology is able to work at 10Gbs bit rate, the Difference in TX complexity is not significant. Silicon devices working at 10G are already in production.

TX Power to obtain the same Eye opening

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- DC Power
  - PAM4 needs three times current as NRZ and higher supply voltage
    - Needs about 3*1.8/1.2 = 4.5 times power as NRZ
  - Duobinary TX needs twice current as NRZ
- Logic AC Switching Power
  - Only a small part of PAM4 mux (2-bit encoder) works at lower speed
  - That small part of logic needs more gates.
  - Duobinary does not need much more logic gates than NRZ and can be done at low speed prior to mux.
  - NRZ, PAM4 and Duobinary use almost the same power for logic gates.

✓ PAM4 needs more power than NRZ and Duobinary.

Duobinary DFE Receiver

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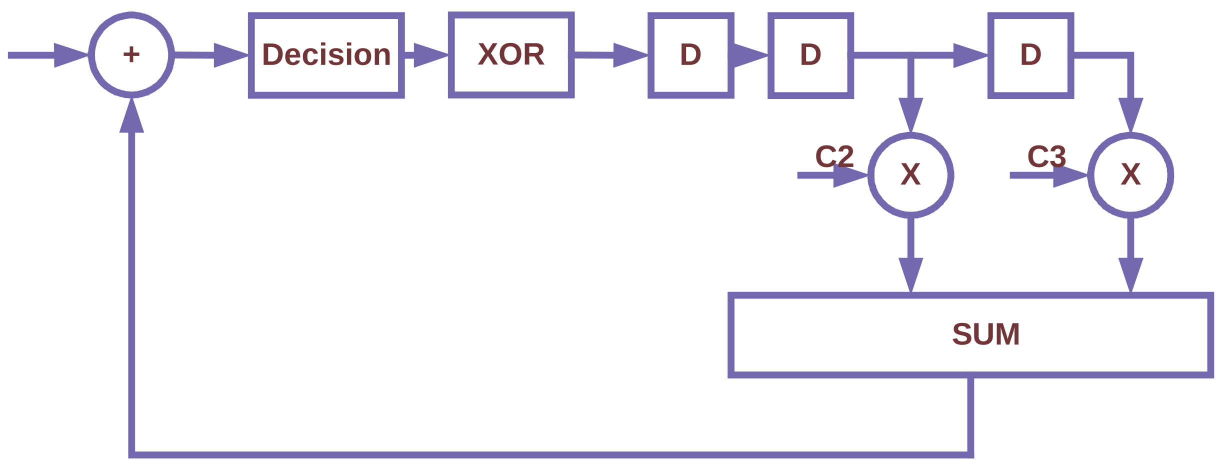
- Duobinary
  - Needs two slicers for signal detection (up to 5 if LMS adaptation is used)
  - Simple DFE as NRZ
    - Only binary multiplication (sign times coefficient) is required (use XOR)
  - Same baud rate as in NRZ, but 10G DFE implementations have been demonstrated.



PAM4 DFE Receiver

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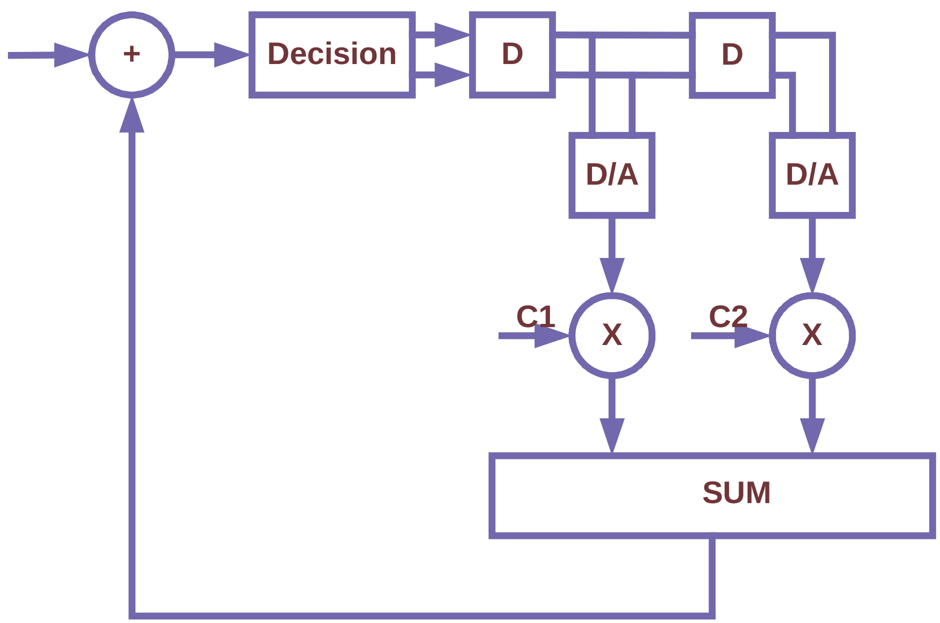
- PAM4
  - Needs 3 slicers (up to 7 if LMS adaptation is used)
  - Complex DFE with **high speed** 2-bit D/A and tap control mechanism
    - 4-level symmetric multiplication is required
    - Very challenging at 5 Gbaud/s
  - Half baud rate of NRZ



Cross-talk

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- PAM4
  - Less margin compared to NRZ (-9.5 dB) and Duobinary (-3.5 dB)
  - Lower bandwidth and crosstalk enhancement compared to NRZ (3 to 6 dB)
- Duobinary
  - Margin better than PAM4 because of larger vertical eye opening , but worse than NRZ
  - Less Crosstalk enhancement compared to PAM4 and NRZ

✓ Duobinary is less sensitive to crosstalk compared to PAM4 due to better amplitude margin and lower boost requirement

✓ Duobinary is comparable to NRZ due to less RX boost requirement

Summary

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Modulation Scheme	TX Complexity	TX Power	Rx Complexity	Xtalk margin	Horizontal EOP	Vertical EOP
NRZ	Low	1 1	Low	0 dB	1	1
PAM4	Moderate	4.5 (3) 1	High	-3 to -6 dB	0.66	0.33
Duobinary	Low	2 1	Moderate	-3 to 0 dB	1	0.5

Jitter dominant system

Conclusion

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Duobinary has potential advantages compared to NRZ and PAM4 for 10G serial backplanes. Compared to PAM4:

- Duobinary and PAM4 have the same spectral content.
- Duobinary utilizes the copper channel as part of equalizer.
- Duoinary has better horizontal and vertical eye opening compared to PAM4.
- Duobinary is less sensitive to crosstalk compared to PAM4 and comparable with NRZ.
- PAM4 receiver is much more complex than NRZ and duobinary.

Additional Slides

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Required Equalization

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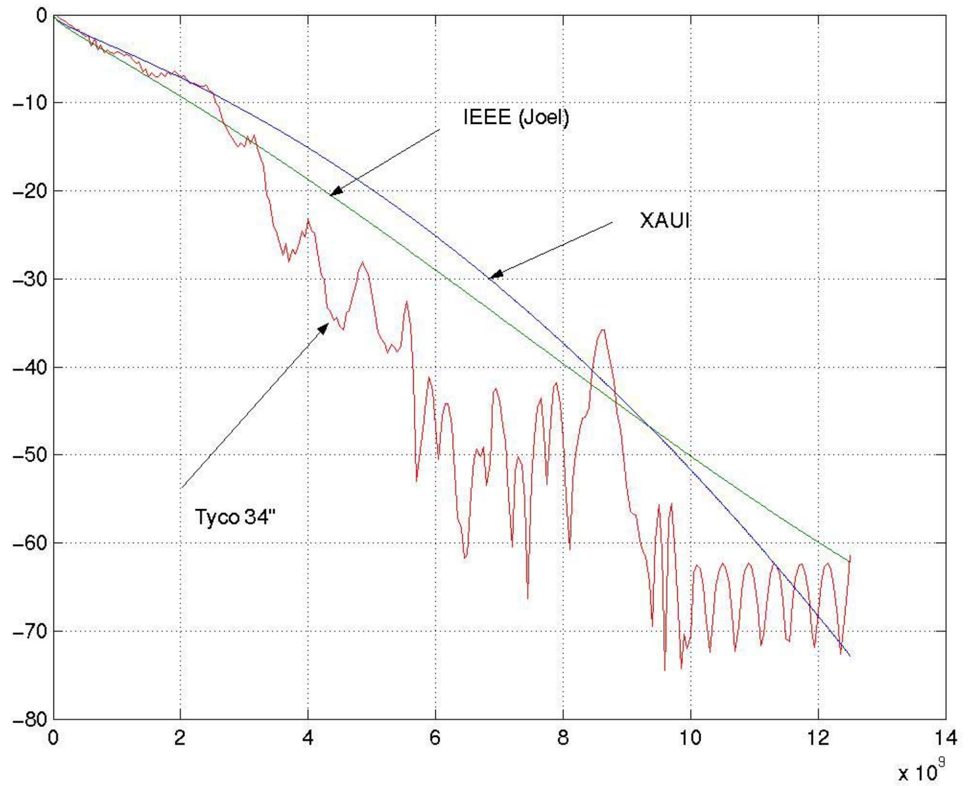
- Duobinary
  - Use the channel as part of equalizer
  - Baud Rate is the same as NRZ
  - Null at half data rate
  - Do not need to equalize out channel completely
- PAM4
  - Baud Rate is ½ that of NRZ
  - Null at half the data rate
  - Channel Needs to be equalized completely up to quarter bit rate
- NRZ
  - Null at data rate
  - Channel needs to be equalized up to half bit rate


IEEE (Joel)
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Tyco 34"
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