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Crosstalk and Receiver Equalization for 10G Serial Ethernet

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Agenda

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Requested by many system vendors and IEEE Task Force for further duobinary contributions on crosstalk and equalization.

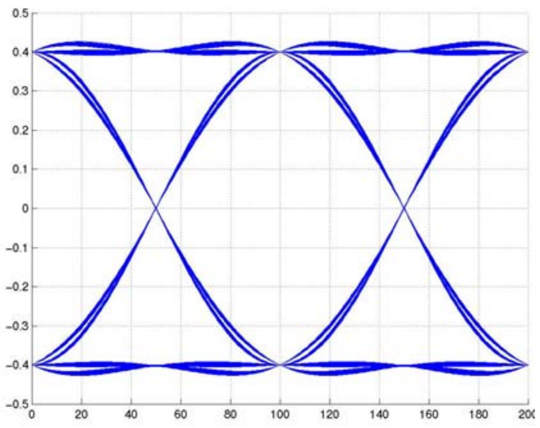
- Summary of May 2004 presentation on NRZ vs. PAM4 vs. Duobinary
- Introduction to duobinary
- Simulation model used for crosstalk
- Optimum FSE receiver
- Crosstalk enhancement for NRZ / PAM4 / Duobinary
- Possible application of DFE to reduce crosstalk enhancement
- Summary/Conclusion

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

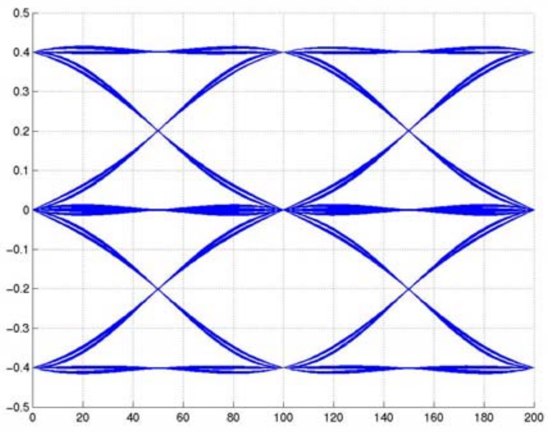
- Duobinary and PAM4 have same spectral content
- Duobinary utilizes the copper channel as part of the equalizer
- Duobinary has better eye opening compared to PAM4
- Duobinary has greater crosstalk immunity
- PAM4 receiver is more complex than NRZ and Duobinary
- PAM4 requires more power

Ideal Data Eyes

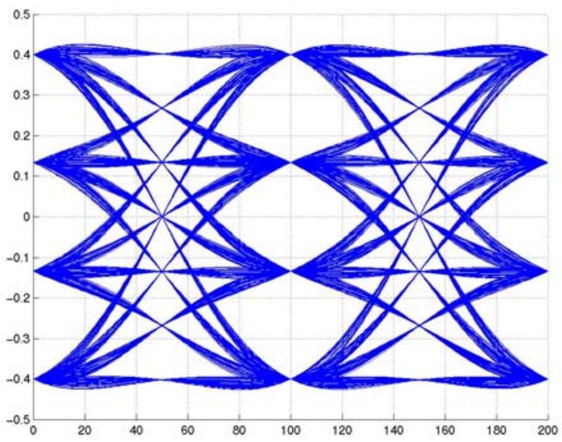
NRZ
Two level signaling



Duobinary
Three level signaling



PAM4
Four level signaling



Duobinary Signaling Basics

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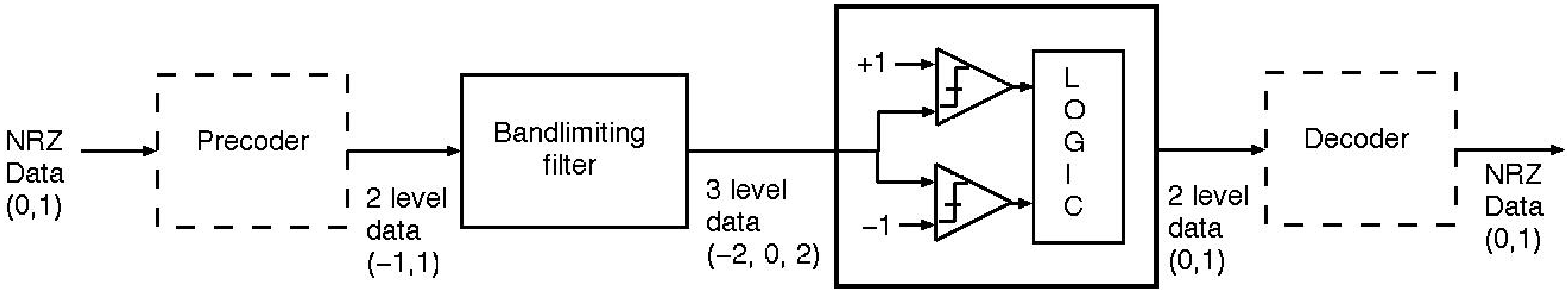

- ✓ Key concept: band-limiting filter creates controlled ISI between symbols resulting in conversion of 2 level signal to a 3 level signal
- NRZ data can be precoded at the TX or decoded at the RX, but not both. Decoding can suffer from error propagation so precoding is used.
- Precoding enables RX to recover data on a symbol by symbol basis (rather than examining pairs of symbols).

Conventional Duobinary System

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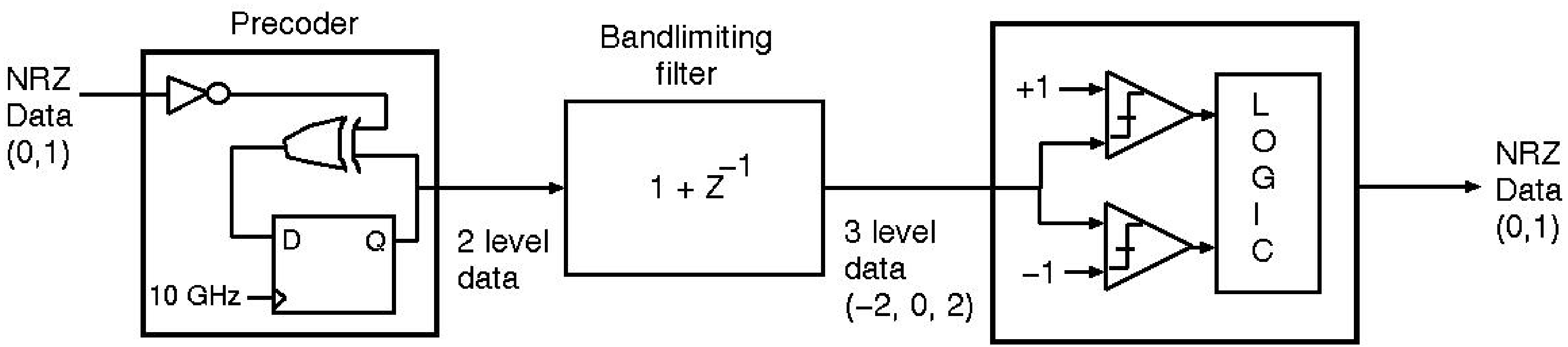

- Precoder can be implemented as shown or in a parallel format before data is serialized to 10 Gb/s

<u>Band-limiting filter typical options:</u>

- Sampled-data filter as shown
- Gaussian continuous-time filter (4th or 5th order) with corner freq ~ 2.5 GHz (25% of data rate)

NRZ vs. Duobinary Response for 10 Gb/s PRBS 2^7-1

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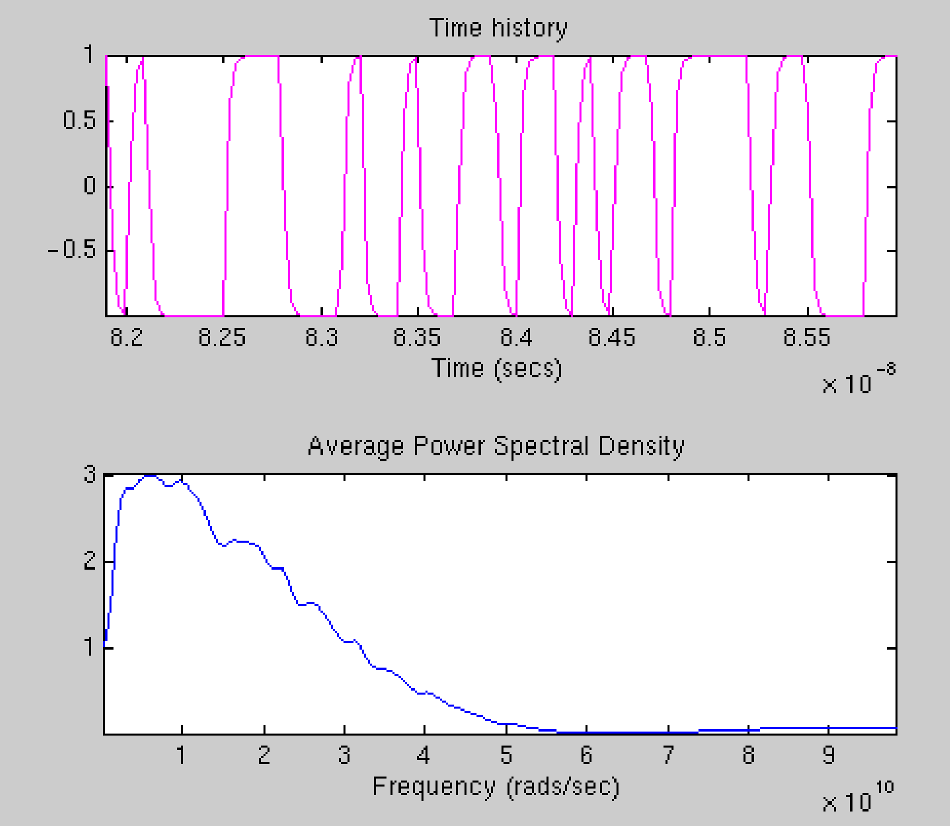
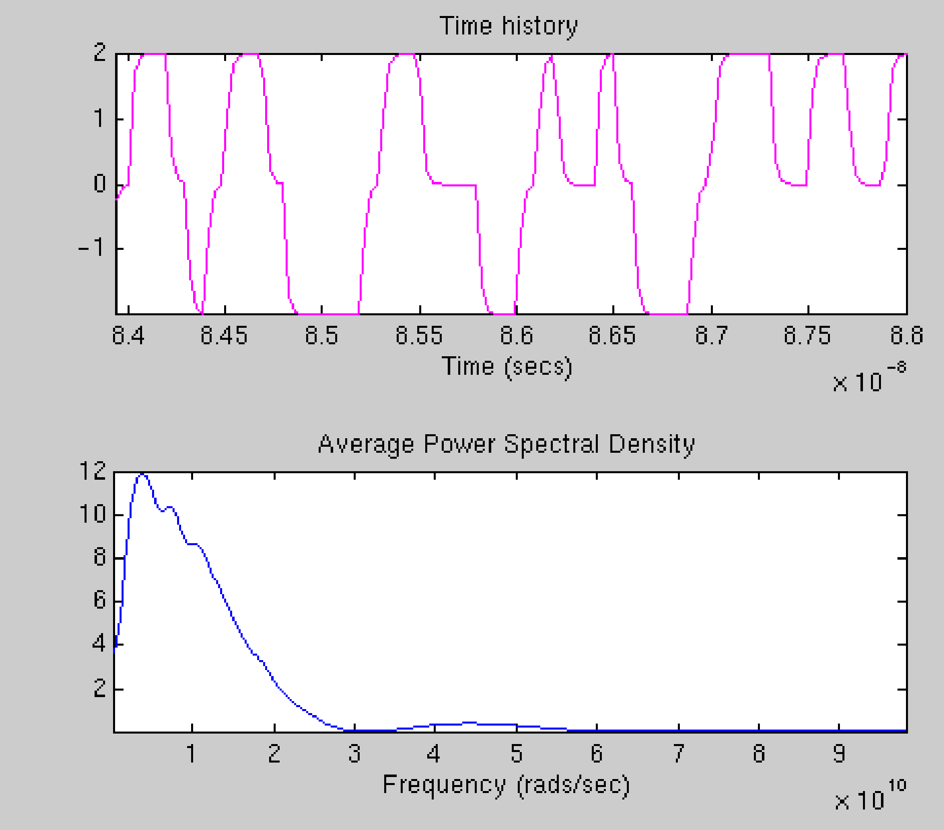
NRZ time domain & spectral content



Duobinary time domain & spectral content



✓ Duobinary spectrum limited to approximately half bandwidth ☺

Implementing the Band-limiting Filter

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- Backplane will perform band-limiting (usually excessive)
- Use receive equalization and/or transmit pre-emphasis to boost higher frequencies
- Benefit of using channel as band-limiting filter for duobinary:
  - Its there
  - RX equalization (or TX pre-emphasis or both) required to yield overall response of $(1 + Z^{-1})$ is modest ➔ can be implemented in CMOS with reasonable complexity / power
  - Low TX or RX boost ➔ minimal amplification of crosstalk ➔ better BER

Examples of Duobinary or Similar Signaling

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- Optical duobinary transmission at 10 Gb/s for metro applications increases range & density of wavelengths

  M. Wichers and W. Rosenkranz, "Optical Duobinary Modulation Schemes Using a Mach-Zehnder Transmitter for Lightwave Systems," IEEE Proceedings of International Conference on Transparent Optical Networks, June 1999, Kielce, Poland.

- Modified-duobinary transmission (PRML) for hard disk drive read channels
  - Data rates ~ 1.8 Gb/s today
  - Band-limiting filter = equalization + head + magnetic media response

    $= (1 + Z^{-1})\,(1 - Z^{-1})$

    (filter attenuates at DC in addition to half the data rate)

  Roy D. Cideciyan, Francios Dolivo, Reto Hermann, Walter Hirt and Wolfgang Scholt "A PRML System for Digital Magnetic Recording" IEEE Journal on Selected Areas in Communications, Vol 10, N0. 1, January 1992

- First generation ISDN modems (early 1980's) used "alternate mark inversion (AMI) coding"

Simulation Model

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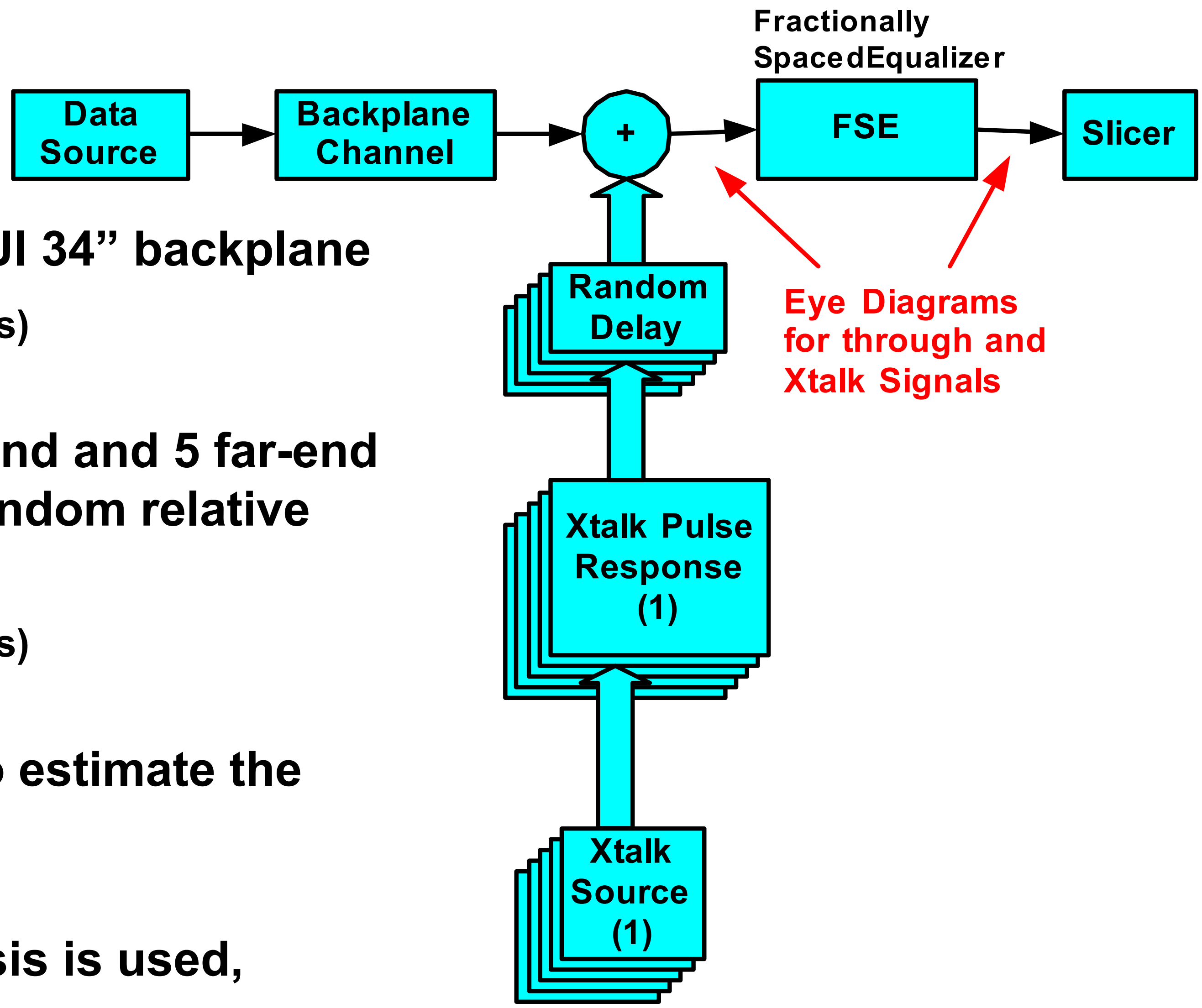

Channel: Tyco XAUI 34” backplane

(measured S parameters)

Crosstalk: 5 near-end and 5 far-end aggressors with random relative delays

(measured S parameters)

FSE: As a model to estimate the required boost

TX: No pre-emphasis is used, PRBS 2^{31} -1

Crosstalk: RX Boost vs. TX Pre-emphasis

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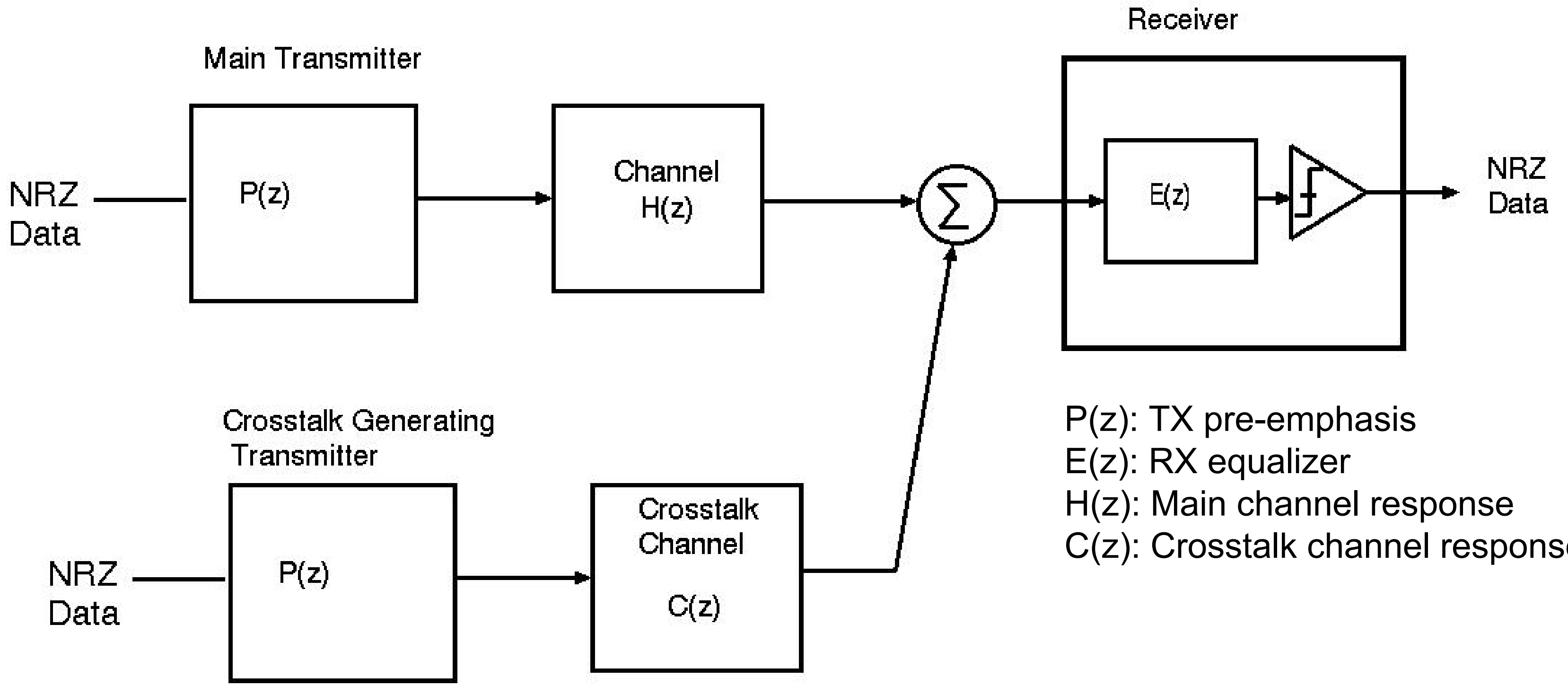

P(z): TX pre-emphasis
E(z): RX equalizer
H(z): Main channel response
C(z): Crosstalk channel response

- Crosstalk at slicer input α P(z) C(z) E(z)

✓ *Distribution of high frequency boost in TX or RX has same effect on crosstalk*

Optimum Fractionally Spaced Equalizer (FSE)

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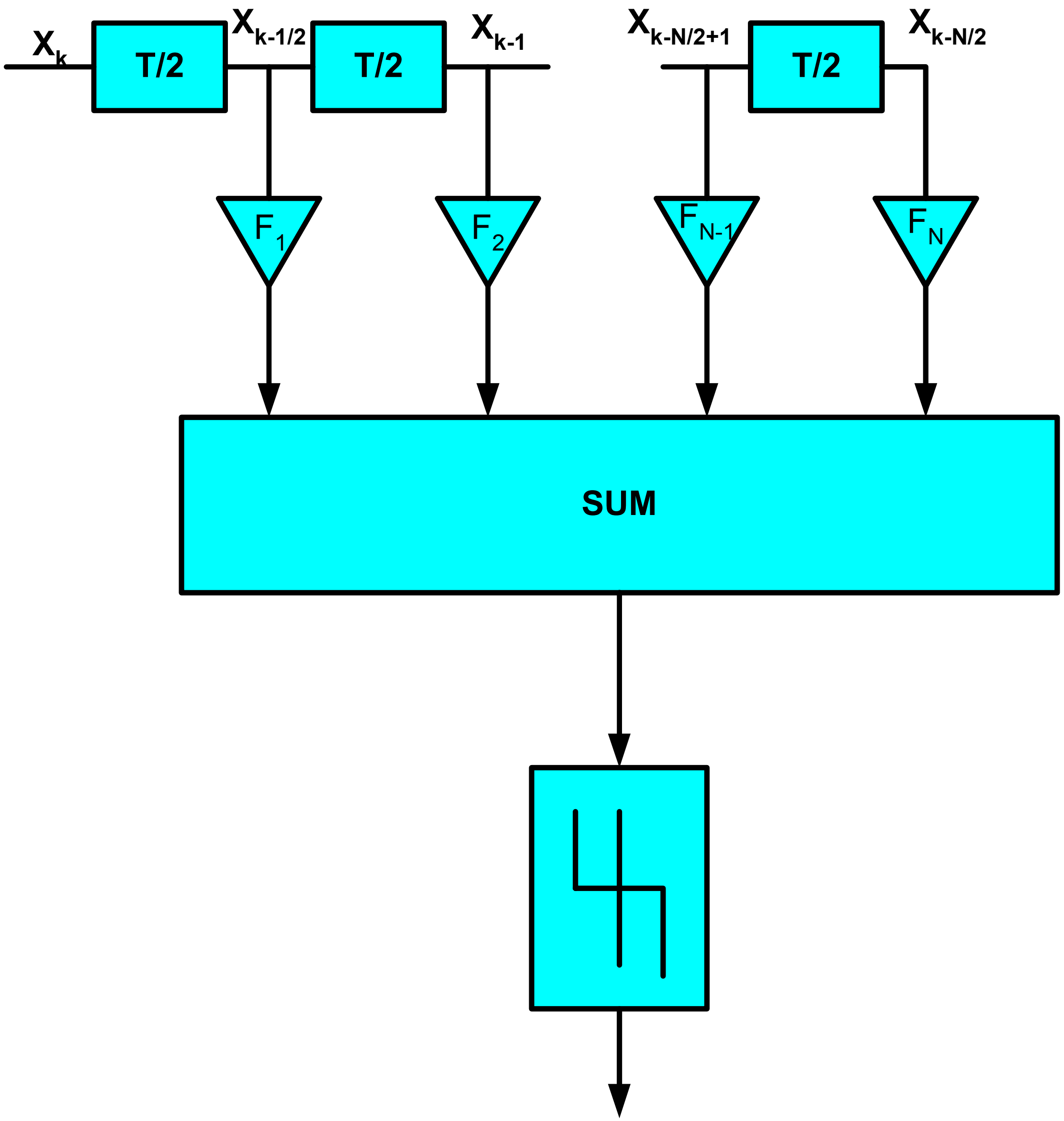
T: Symbol period

Xk: Channel Outputs sampled intervals of T/2

F: Equalizer tap coefficients

H: convolution matrix of channel output vector X sampled at intervals of T



$$F=inv(H'H)H'D,$$
$$H=convmtx(X)\downarrow 2$$

$$D=\begin{cases} ...1... & \text{NRZ, PAM4} \\ ...11... & \text{Duobinary} \end{cases}$$

Crosstalk Spectrums

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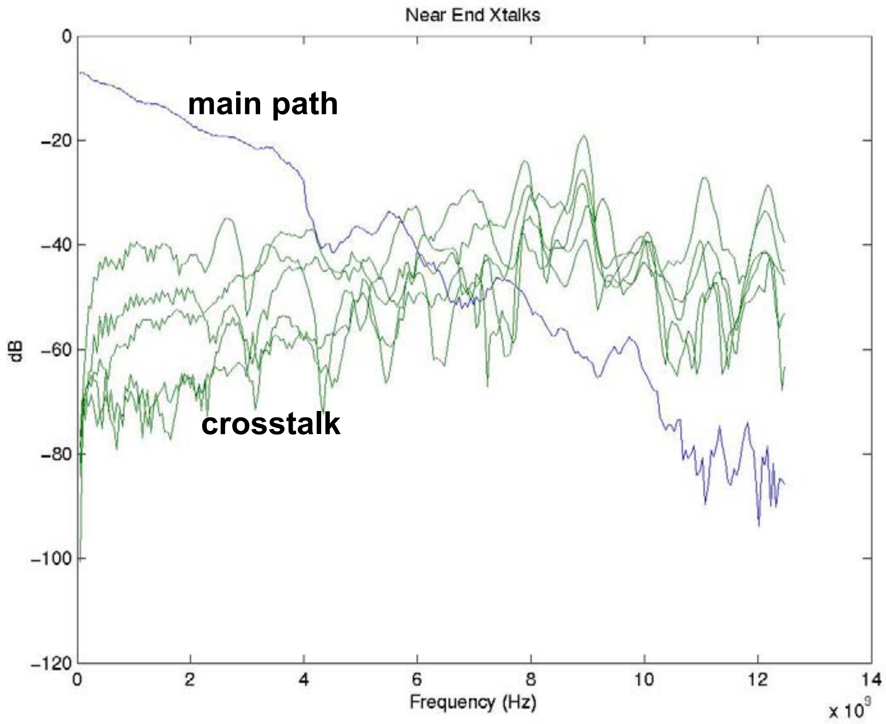
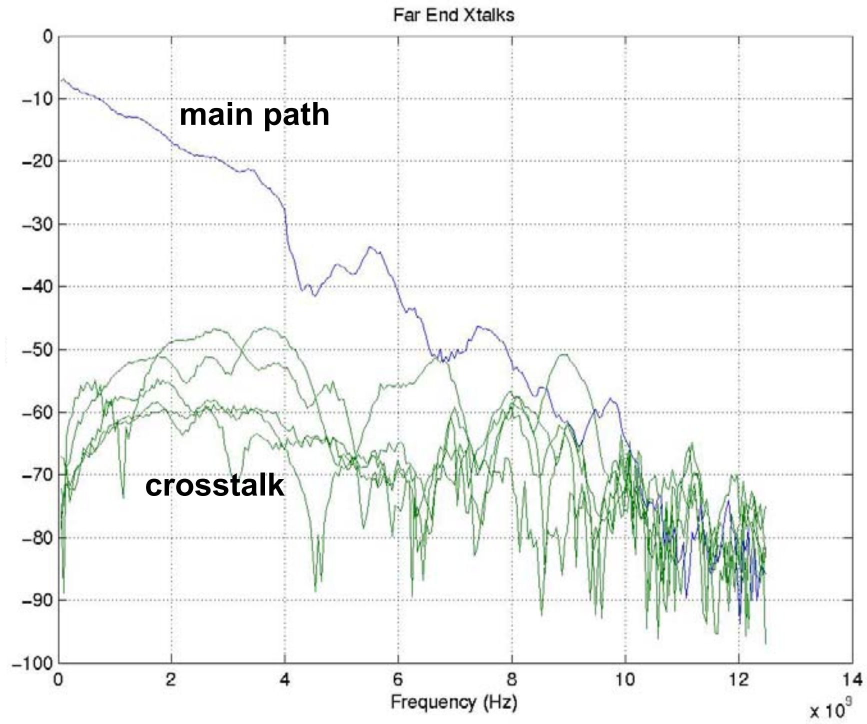
5 near-end Aggressors



5 far-end Aggressors



✓ Near-end crosstalk is much more problematical than far-end crosstalk, especially at high frequencies

All following simulations use 10 aggressors (5 near-end and 5 far-end). Crosstalk results are dominated by two near-end aggressors

NRZ FSE Equalization and Required Boost

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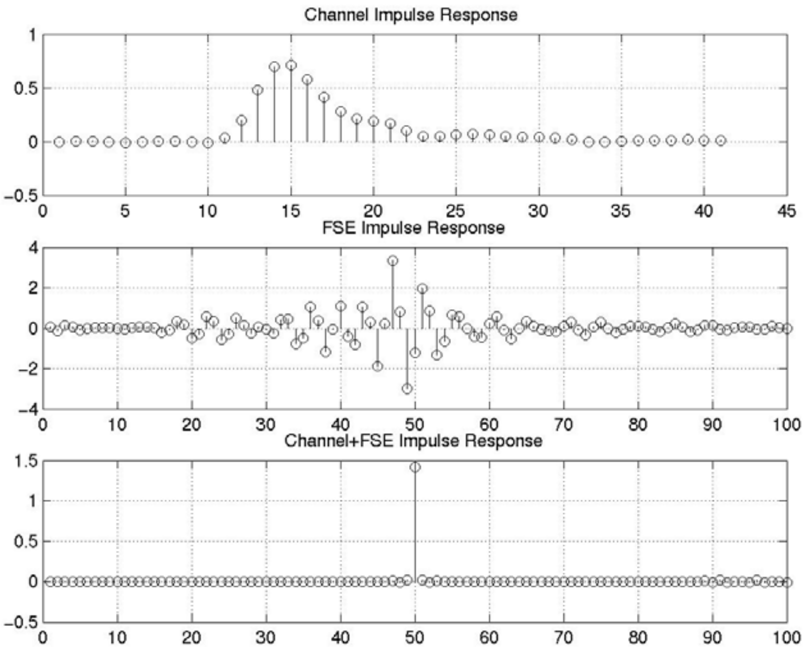

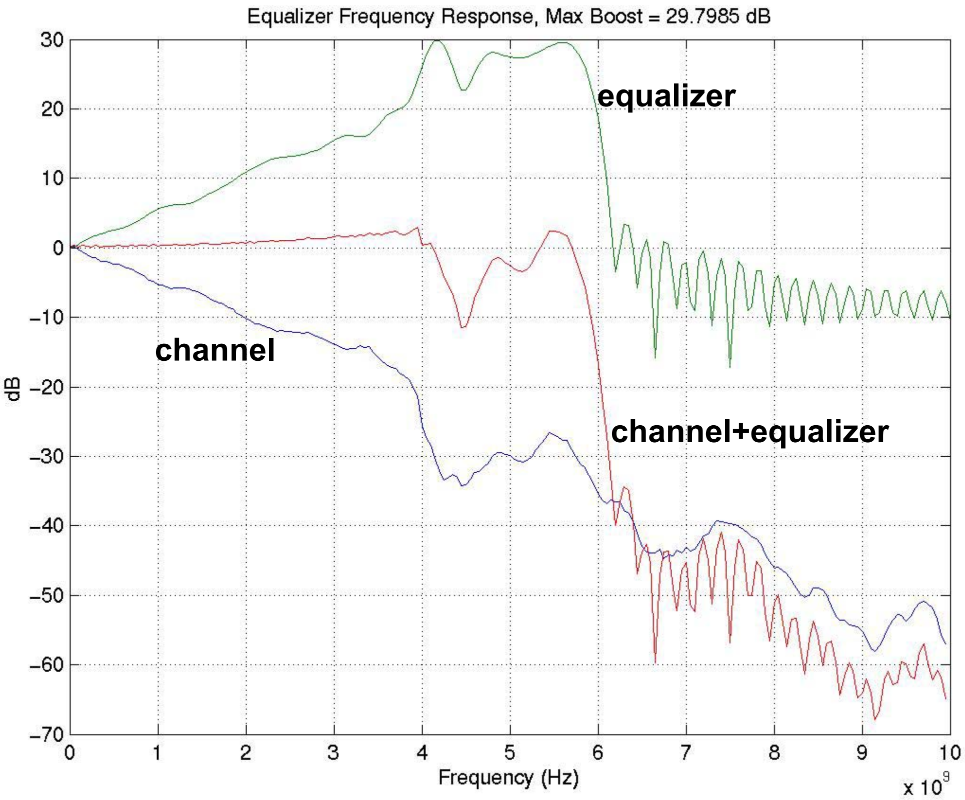

- A boost of about 29.7 dB at 4 to 5 GHz is required.
- In practical design:

  DFE may not be practical due to number of taps and power.

NRZ Eye Diagram Without Crosstalk

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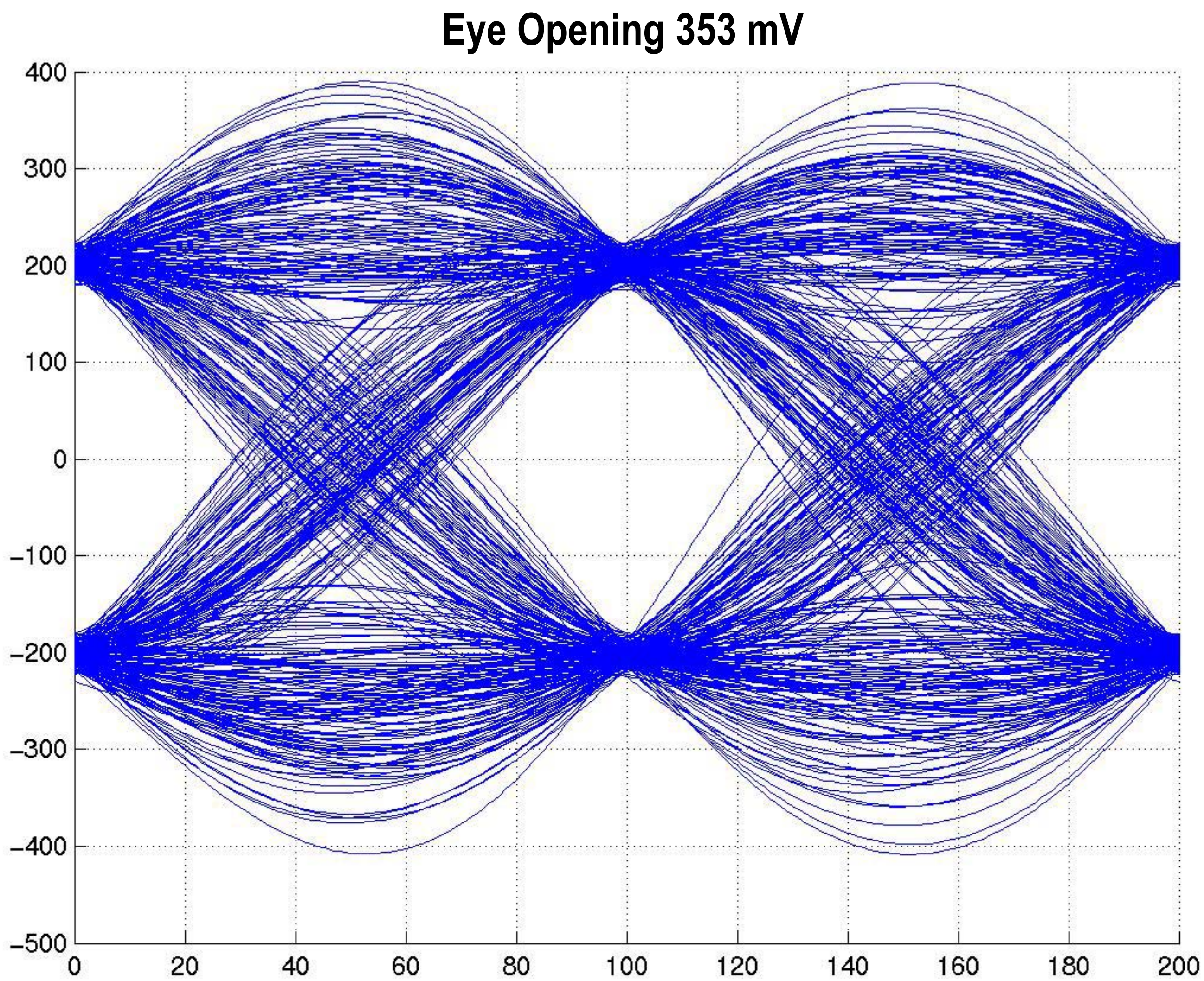

NRZ Eye With Crosstalk (10 Aggressors)

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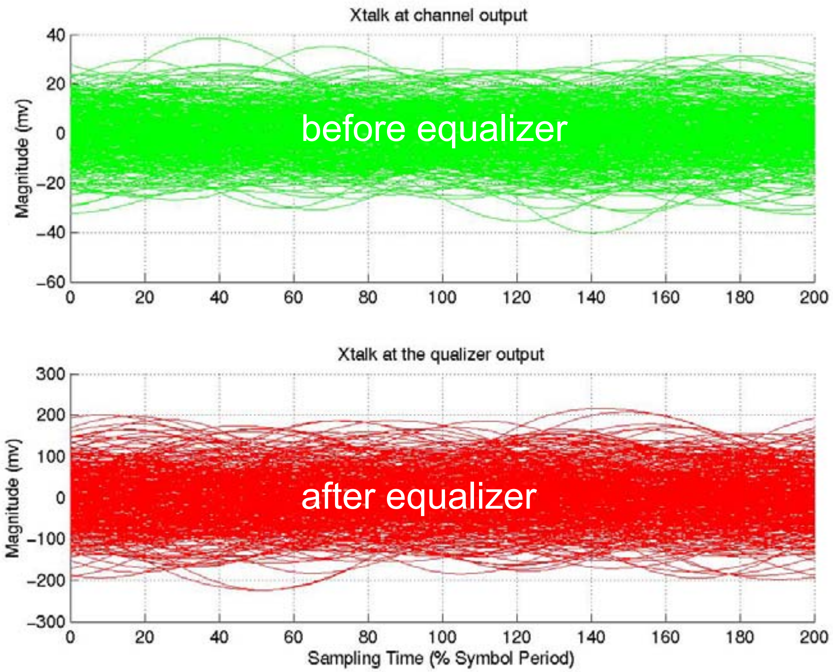
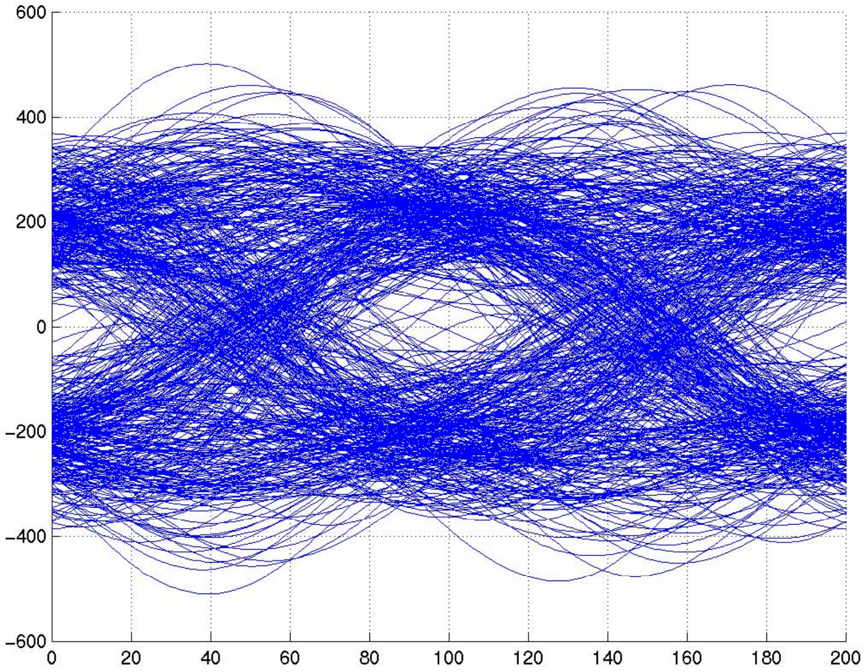
Xtalk diagrams before and after equalizer



Through signal and Xtalk after equalizer



✓ Data eye is closed at slicer due to crosstalk

☹ Data is not recoverable without error margin

PAM4 FSE Equalization and Required Boost

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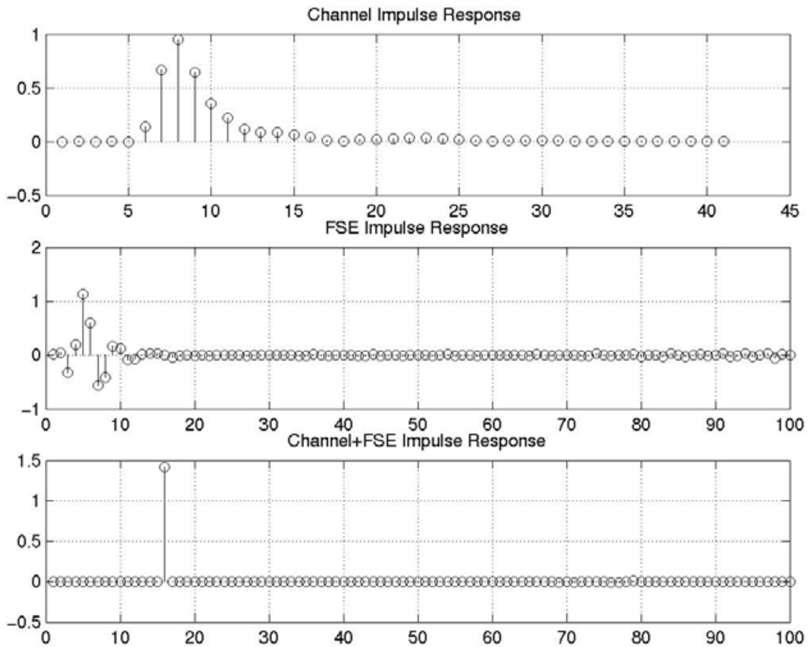

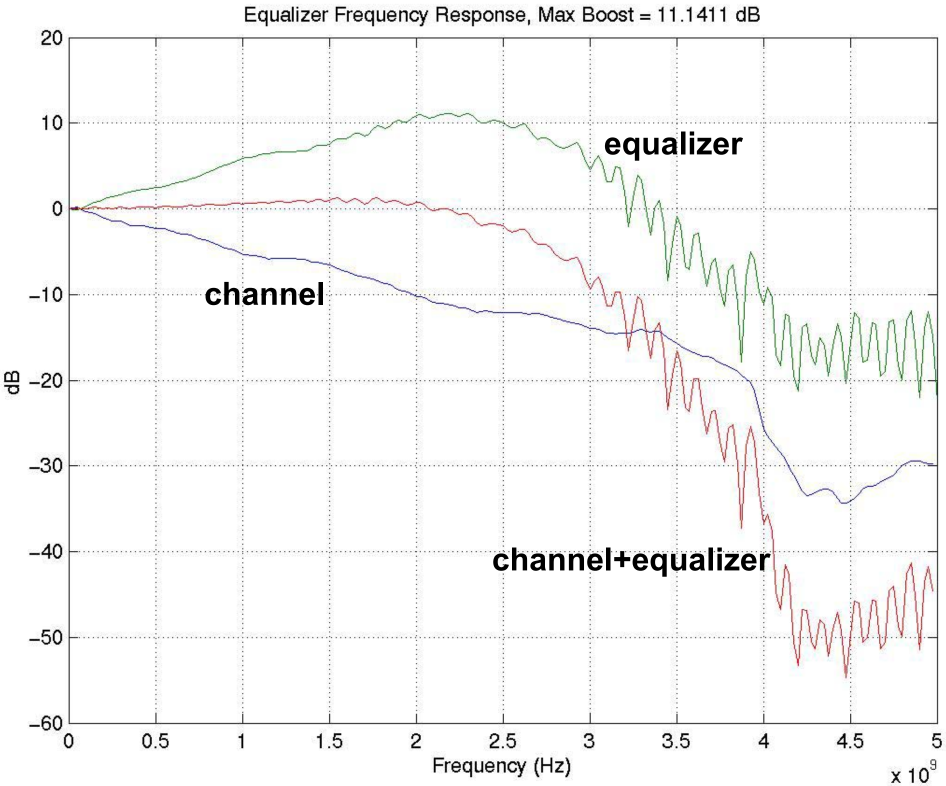

- A boost of about 11.14 dB at 2.25 GHz is required.
- In practical design:

  DFE would NOT be used to relax FFE requirements due to DFE complexity and power.

PAM4 Eye Diagram Without Crosstalk

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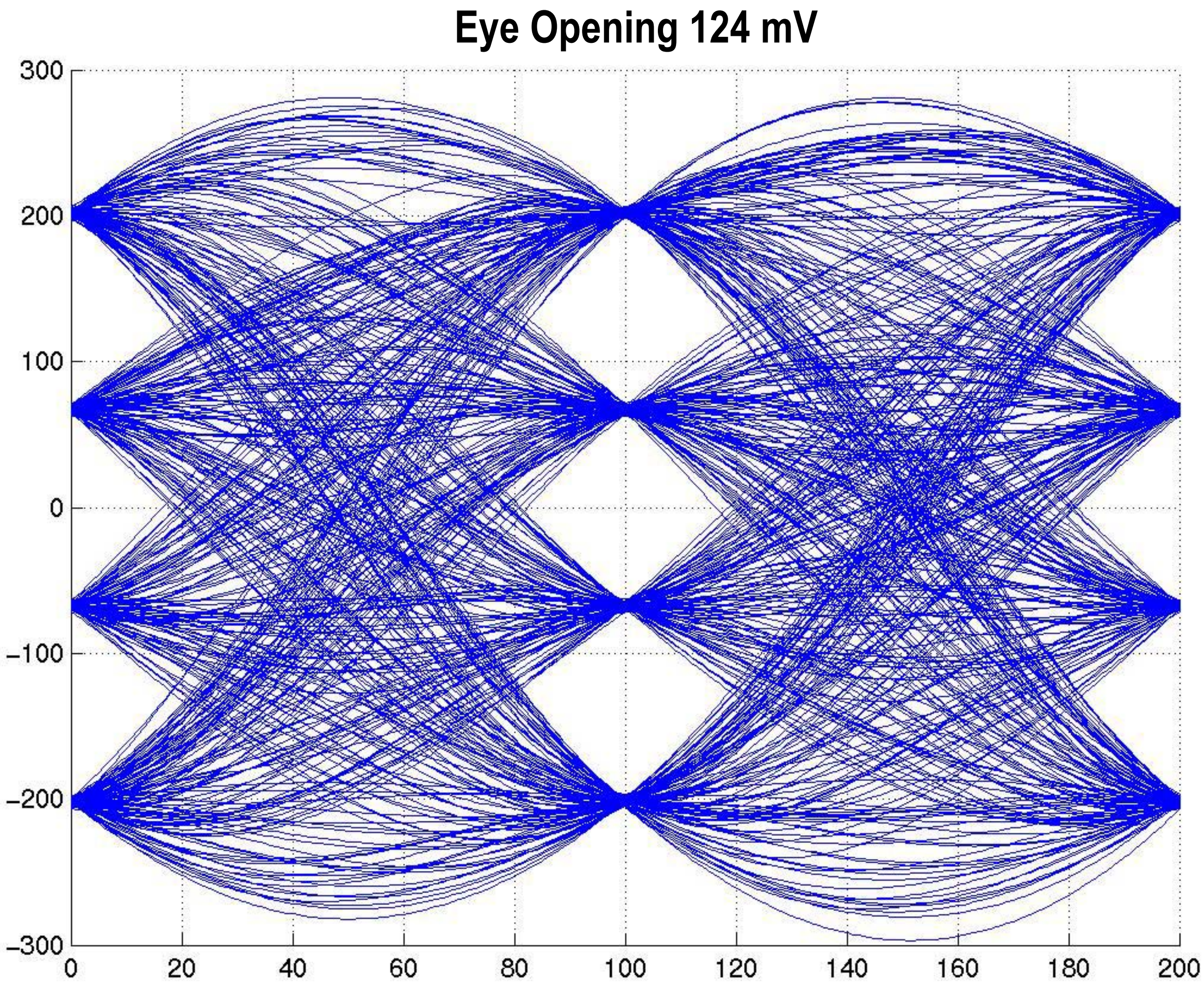

PAM4 Eye Diagram With Crosstalk (10 Aggressors)

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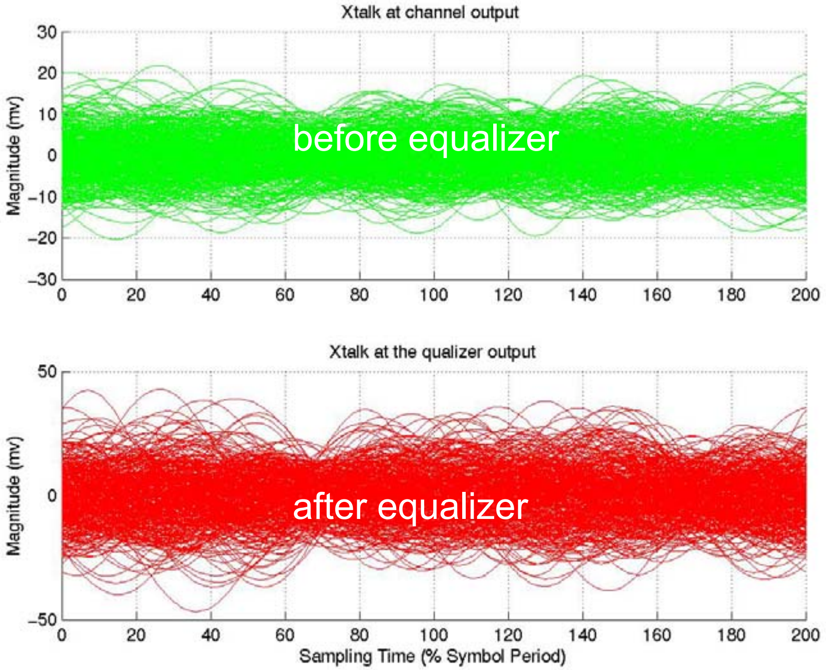
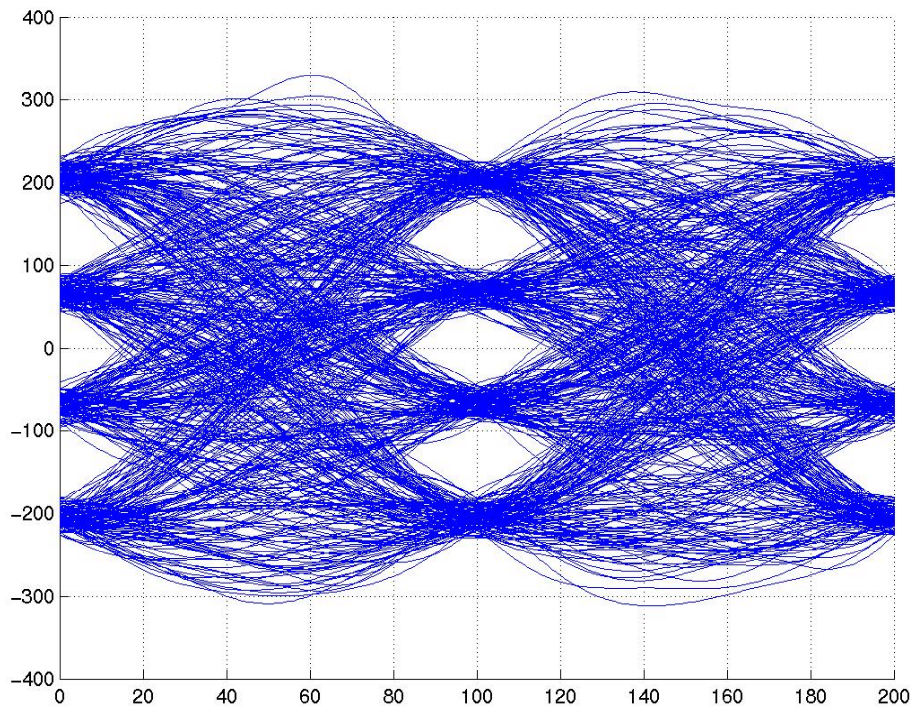
Xtalk diagrams before and after equalizer



Through signal and Xtalk after equalizer



- ✓ Eye opening of ~85 mV and ~52 psec is available
  - 😐 Recovery of data is very practical

Duobinary FSE Equalization & Required Boost

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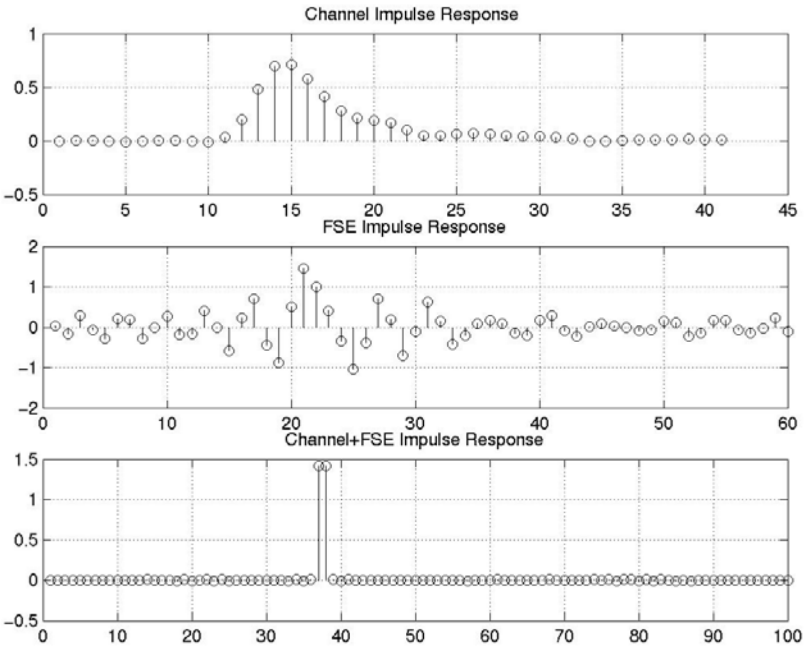

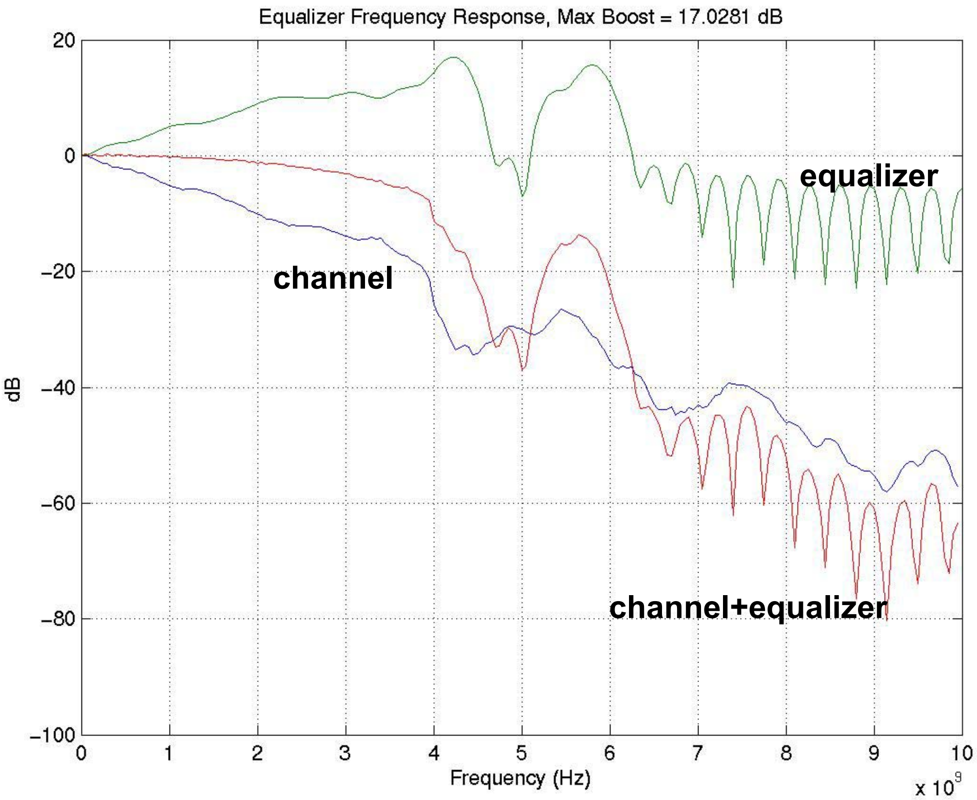

- ➢ **A boost of about 17 dB at 4.25 GHz is required.**
- ➢ **In practical design:**

DFE could be used to relax FFE boost requirements to be under 10 dB.

Duobinary Eye Diagram Without Crosstalk

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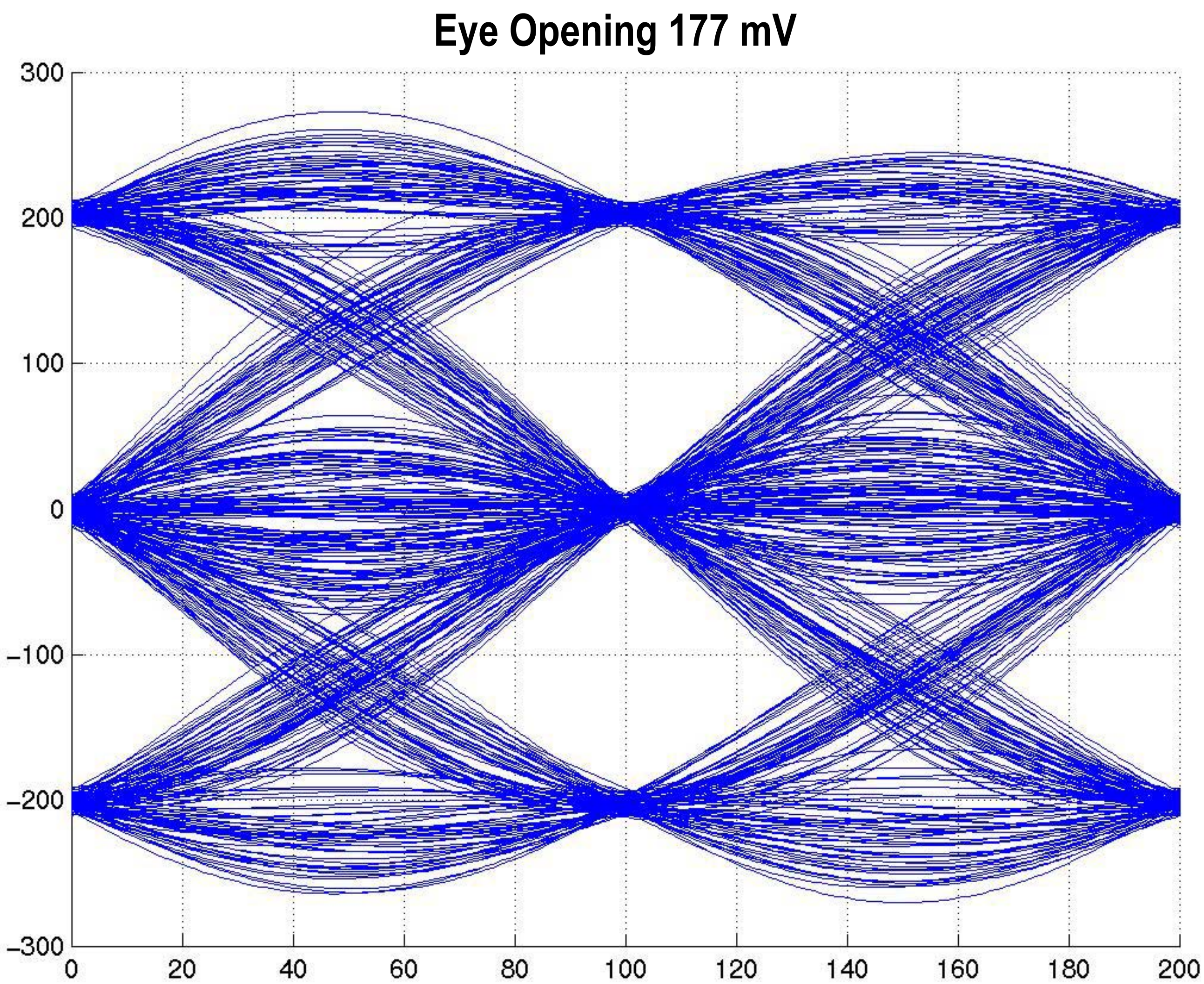

Duobinary Eye Diagram With Crosstalk (10 Aggressors)

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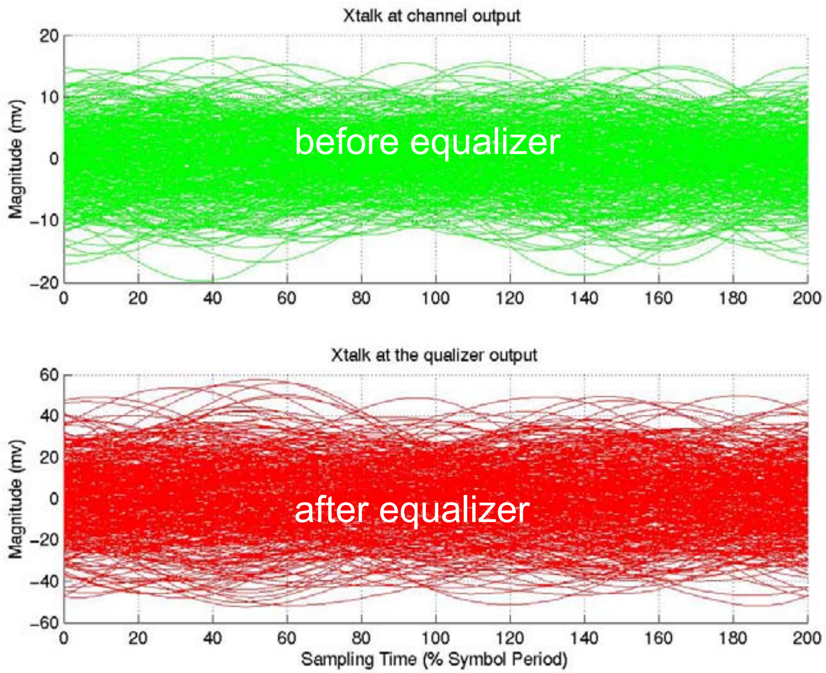
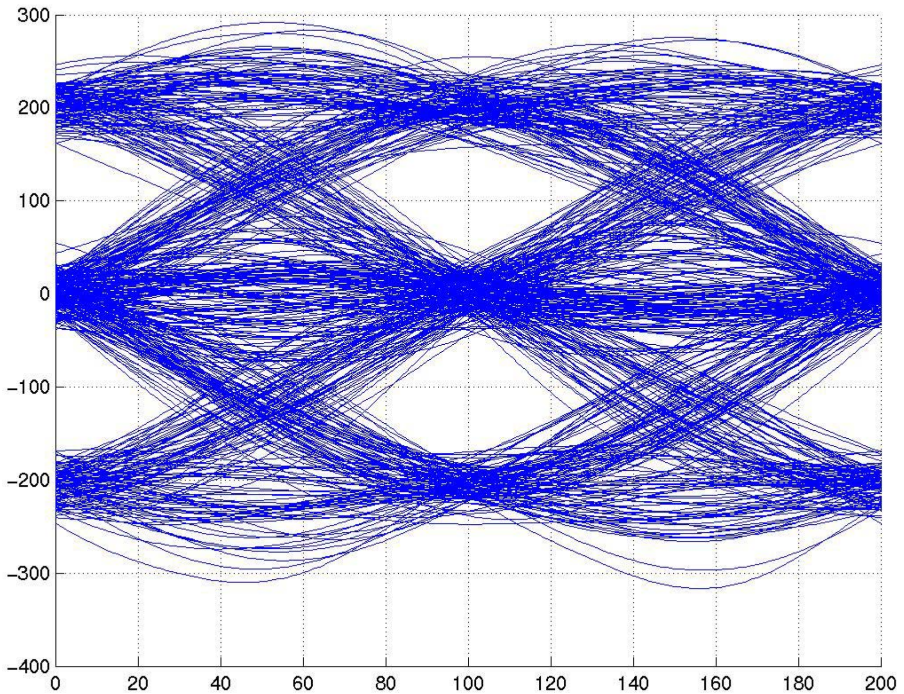
Xtalk diagrams before and after equalizer



Through signal and Xtalk after equalizer



✓ Eye opening of ~91 mV and ~42 psec is available

☺ Best vertical eye compared to NRZ and PAM4

Reduction of RX Boost and Crosstalk

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- Use of TX pre-emphasis to ease RX equalizer design
- Use of DFE to minimize required boost and resulting crosstalk
  - PAM4: DFE is very complex
    - Up to 7 Slicers for LMS adaptations
    - High speed D/A inside the loop
  - NRZ: Due to the high boost required at 5GHZ, crosstalk will worse than duobinary even if DFE is used.
  - Duobinary: No boost is required at 5GHZ which results in lower crosstalk.
- DFE is not practical for PAM4 or NRZ due to the number of taps, D/A converters required (PAM4), power, etc.

Using DFE for Duobinary, w/o crosstalk

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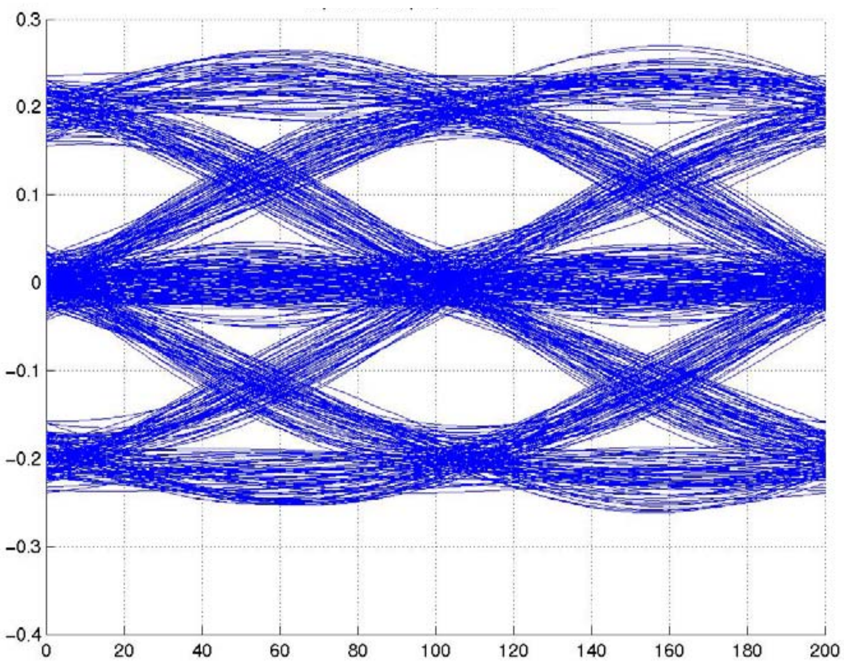
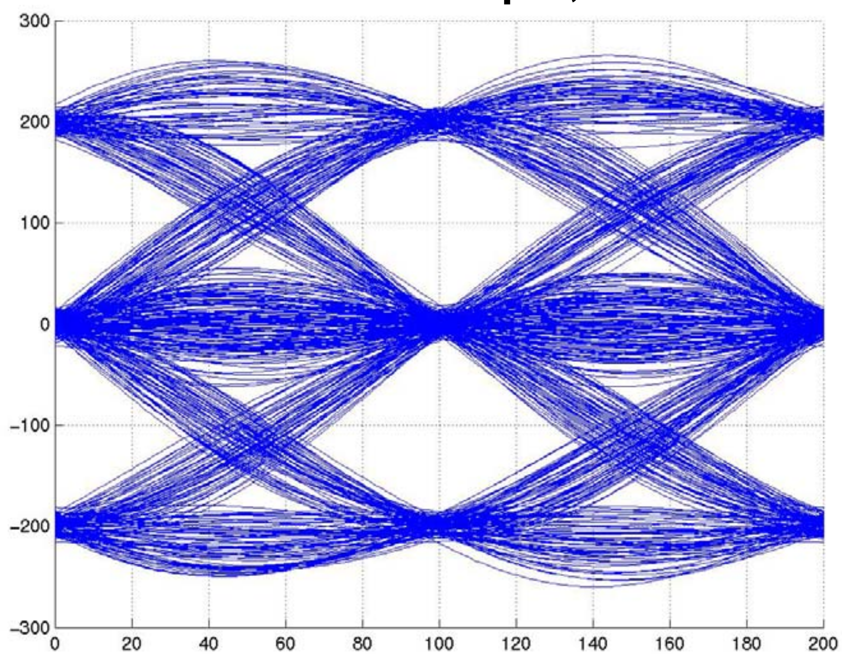
FSE Output only , 115 mV



With DFE Output, 160 mV



✓ **DFE improves eye opening**

Effect of Crosstalk with DFE for Duobinary

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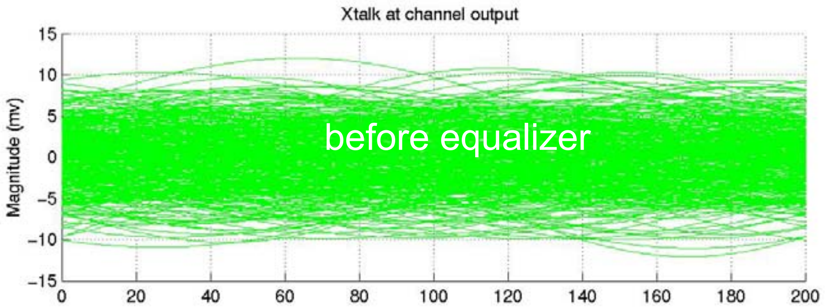
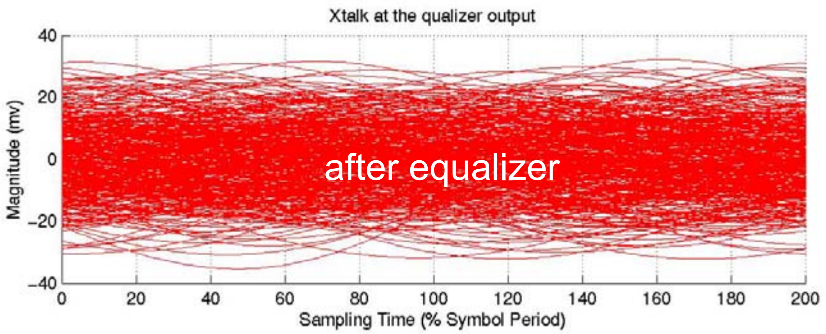
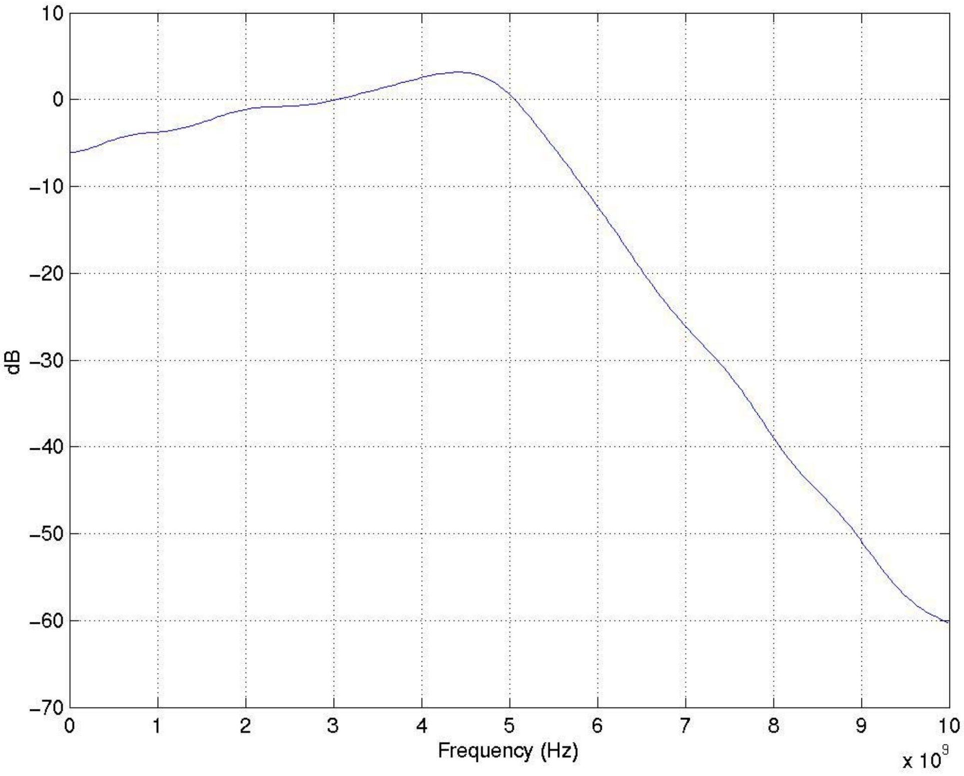
Xtalk diagrams before and after equalizer





Required boost w/ DFE



✓ **With use of DFE, a boost of only 9dB is required for duobinary.**

Signal with Crosstalk at slicer input, w/ DFE

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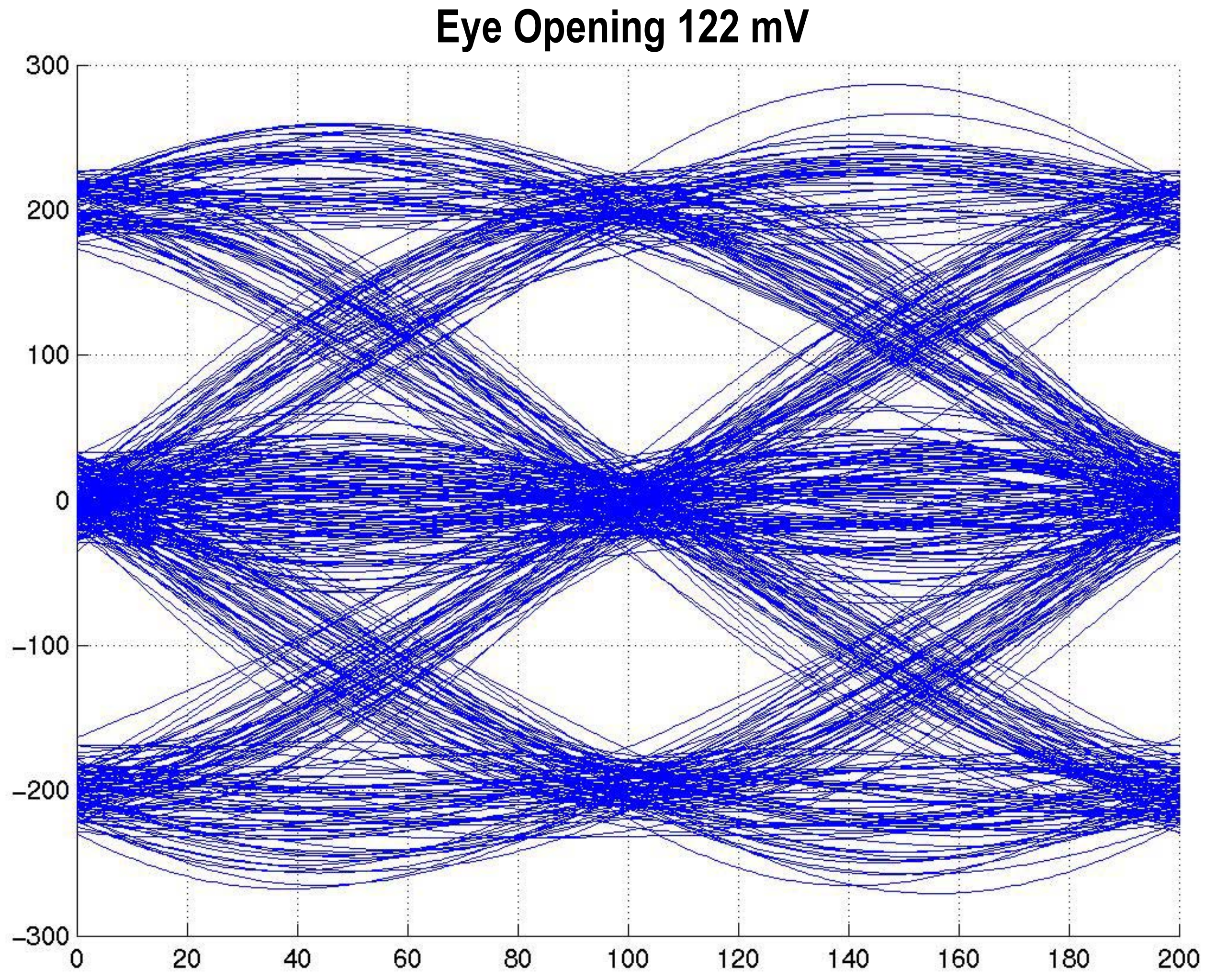

✓ **Use of DFE, vertical eye opening of 122 mV <u>with crosstalk</u> is possible.**

Receiver Power Consumption

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- Duobinary can take advantage of simple low power techniques:
  - Linear receive filter
  - Transmit pre-emphasis
- Duobinary can also use DFE for further optimization
- DFE Implementation
  - NRZ will have the simplest structure (but not necessarily lowest power due to number of taps)
    - Lower number of slicers (up to only 3)
  - PAM4: highest power and complexity
    - High number of slicers (up to 7)
    - High speed 2-bit A/D inside the loop
  - Duobinary: Only a slightly more complex structure w.r.t. NRZ

Crosstalk Results Summary

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	NRZ	PAM4	Duobinary
Required Boost	29.7 dB	11.14 dB	17dB
Vertical Eye Opening w/o Xtalk	352 mV	124 mV	177 mV
Horizontal Eye Opening w/o Xtalk	48 psec	60 psec	53 psec
Vertical Eye Opening w/ Xtalk	0 mV	85 mV	94 mV
Horizontal Eye Opening w/ Xtalk	0 psec	52 psec	42 psec
Vertical Eye Opening w/ Xtalk & DFE*	N/A	N/A	122 mV
Horizontal Eye Opening w/ Xtalk & DFE*	N/A	N/A	45 psec

Note: Crosstalk assumed 10 aggressors (5 near-end and 5 far-end)
* Required boost is ~ 9dB

Summary/Conclusion

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- Duobinary has better crosstalk performance compared to NRZ and PAM4
- PAM and NRZ require more complex design techniques to overcome the effects of crosstalk
- Duobinary allows the use of three equalization techniques
  - Transmit pre-emphasis
  - Linear receive equalization
  - DFE / FFE equalization

✓ Duobinary allows for multiple design options and minimized complexity

Further Analysis on Duobinary

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- Use of IEEE 802.3ap channel model
- Equalizer vs. DFE vs. Pre-emphasis
- Interoperability with NRZ for backwards compatibility
- Power