10Gb/s PMD Using PAM-5 Modulation

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Goals

- **Achieve distance objective of 300m over existing MMF**
- **Operate with single channel optoelectronic (single laser and single photodetector)**
- **Achieve single chip low cost CMOS PHY solution with Hari interface**

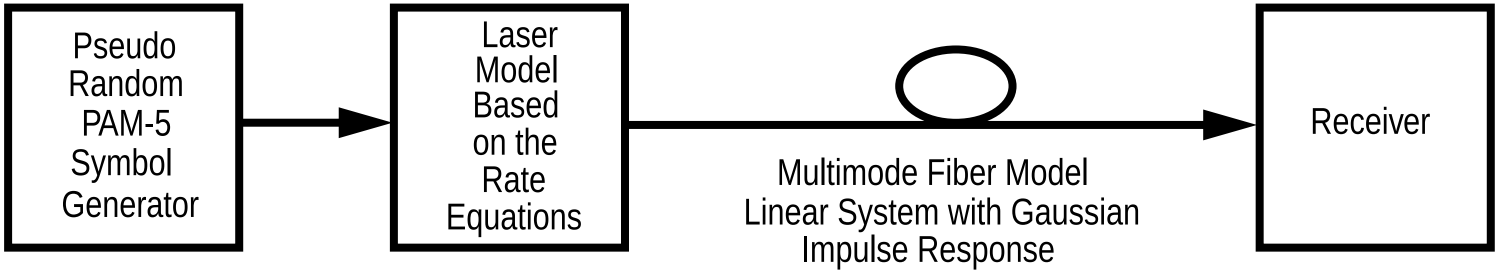
Approach

- **Utilize PAM-5 signaling at 5GBaud**
- **Assume standard 62.5/125μm fiber with bandwidth of 160/500MHz-Km**
- **Use adaptive equalization to compensate for intersymbol interference introduced by bandwidth limited MMF**
  - Assumption is that a 300m MMF is bandwidth limited to 1GHz at 1310nm
  - A nonlinear equalizer can compensate for laser nonlinearity
- **Adaptive equalizer tracks the variations of laser and fiber response over time**

Overview

- Preliminary simulation study of a PAM-5 system
- Laser model
- Fiber model
- Receiver block diagram
- Simulation results
- Future work and conclusions

Channel Model



Laser Model

- The laser is modeled using the rate equations. These are a system of coupled non-linear differential equations. They provide accurate description of nonlinear and transient behavior of the laser

- The specific rate-equation model used in this work is as described in the article *"On Approximate Analytical Solutions of the Rate Equations for Studying Transient Spectra of Injection Lasers"*, by D.Marcuse and T.P.Lee, IEEE J. Quantum Electronics, Sept.1983

- We use the exact equations, not the approximations provided by Marcuse and Lee, and we solve them numerically using a 4^{th} order Runge-Kutta algorithm

- The parameters used are the same as in the reference, except that the bias current is increased to 3 $I_{threshold}$

- We modulate the laser with a pseudo-random sequence of symbols from a PAM-5 alphabet

- We use a 6dB extinction ratio

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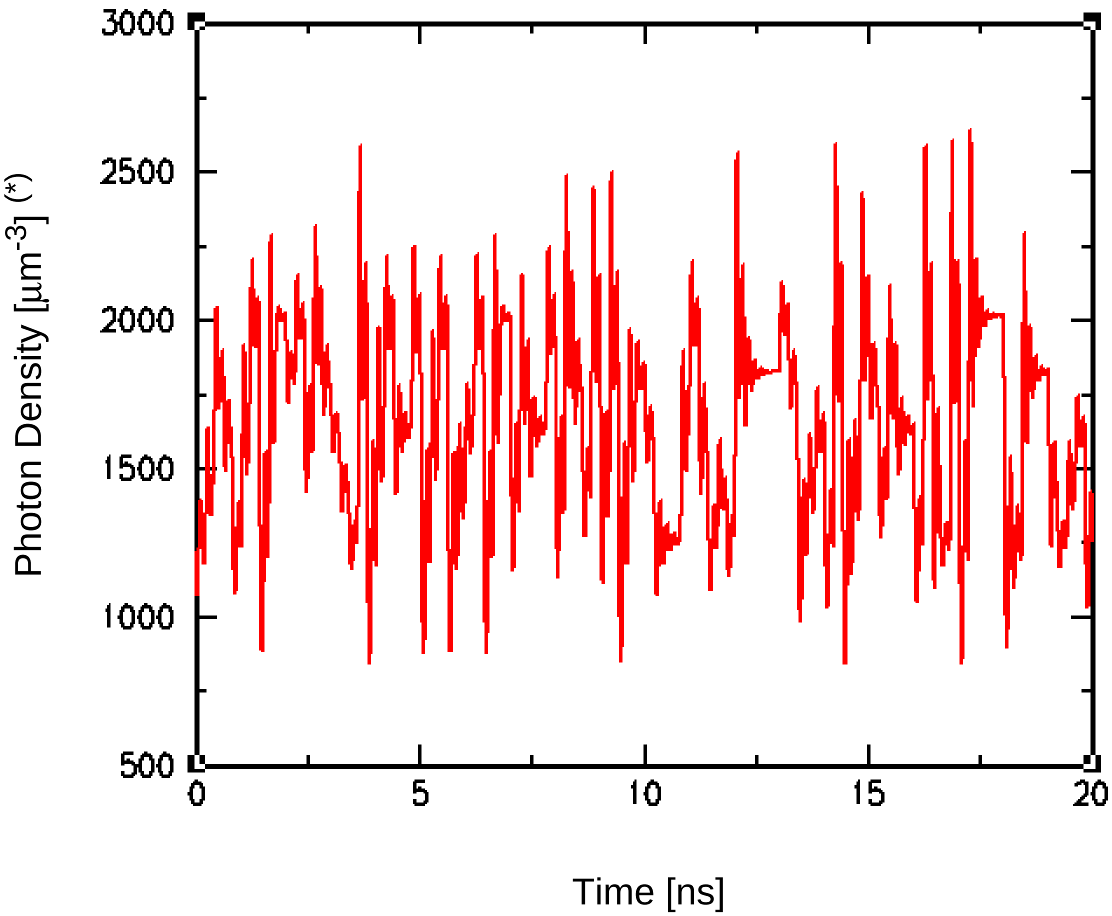
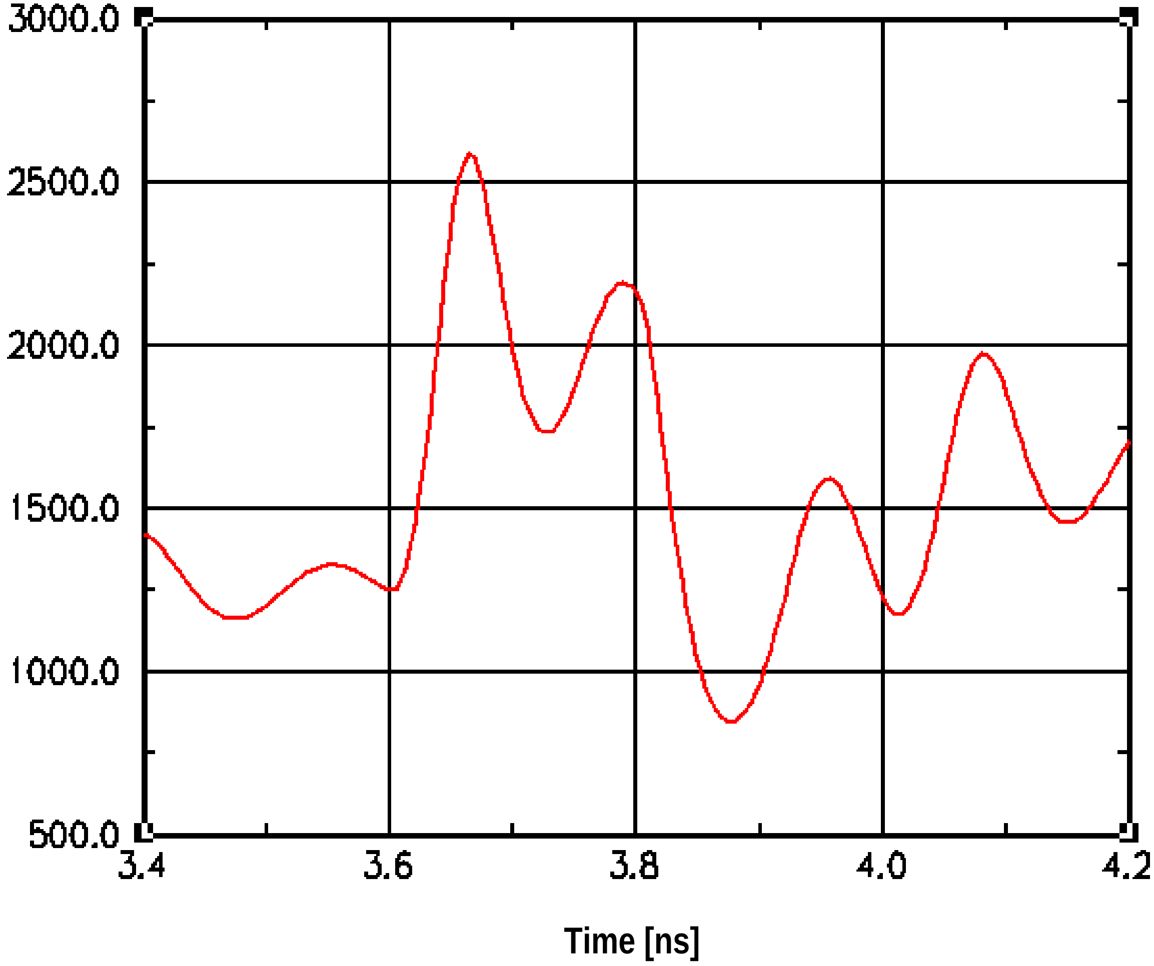
PAM-5 5 GBaud Modulated Laser Ouput



(*) Consistent with a bias current of 60mA

Zoom of Modulated Laser Output



Fiber Model

- **The multimode fiber is modeled as in the article *"Equalization of Multimode Optical Fiber Systems"*, by B.L.Kaspers, Bell System Technical Journal, September 1982**

- **The model consists in a linear dispersive system with a Gaussian impulse response given by**

$$h(t) = \frac{1}{\sqrt{2\pi} \cdot \alpha T} \cdot e^{-[t^2/(2(\alpha T)^2)]}$$

- **The corresponding frequency response is:**

$$H(f) = e^{-[(2\pi\alpha T f)^2/2]}$$

- **The 3dB bandwidth of the fiber is:**

$$f_{3dB} = \frac{0.1325}{\alpha T}$$

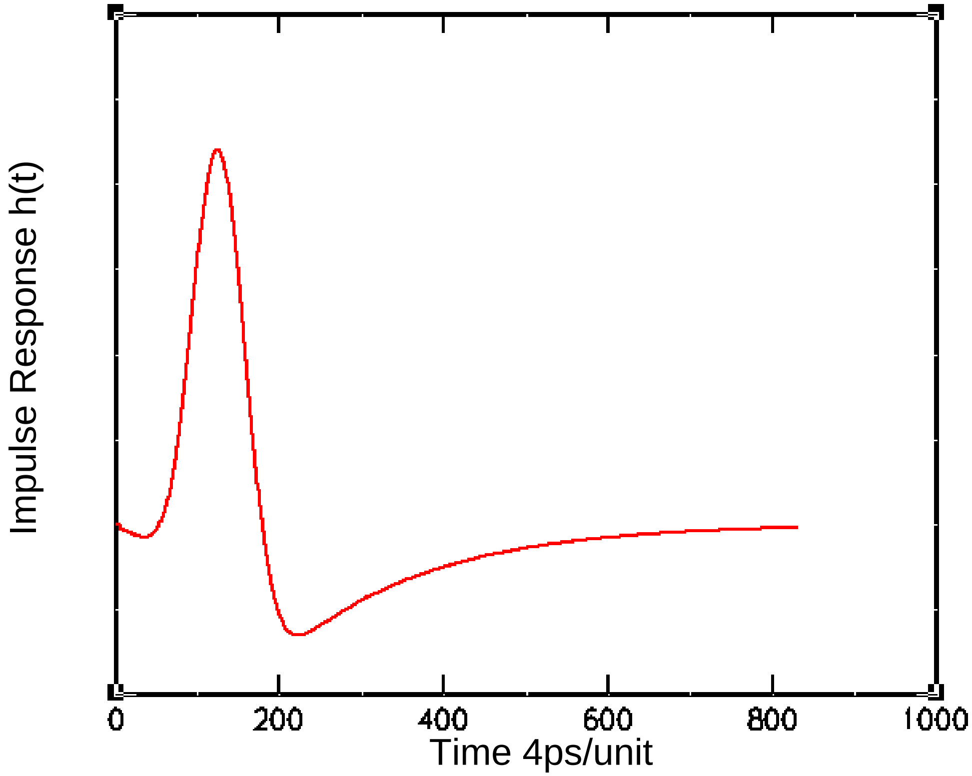
Note: For a given baud period T (=200ps), α controls the bandwidth of the system

- **We assume f_{3dB}=1GHz, which is achieved by making α=0.6625**

More Details About the Channel Model

- **The channel is assumed to be AC coupled. To limit the length of the tail introduced in the impulse response by the AC coupling, we use a first-order high-pass filter with a cutoff frequency of 200MHz**

- **The laser is assumed to have Relative Intensity Noise (RIN) of -130dB/Hz**



Signaling at Faster than Nyquist Rate

- **Multimode fibers have limited bandwidth (~1GHz for the fibers and lengths of interest to HSSG - also depends on the laser)**

- **Faster than Nyquist rate is required to signal at 10Gb/s on these fibers**

- **We have studied signaling at 5GBaud over multimode fibers with 1GHz bandwidth**

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Signaling at Faster than Nyquist Rate

- **The Nyquist theorem establishes that the bandwidth needed to transmit data at a rate f_B=1/T *without intersymbol interference* must be larger than or equal to 1/2T**

- **However many communication systems signal at rates faster than 1/2T, using special techniques to control intersymbol interference**

- **An example are partial response systems**

- **Another example are receivers using *Decision Feedback Equalization (DFE)***

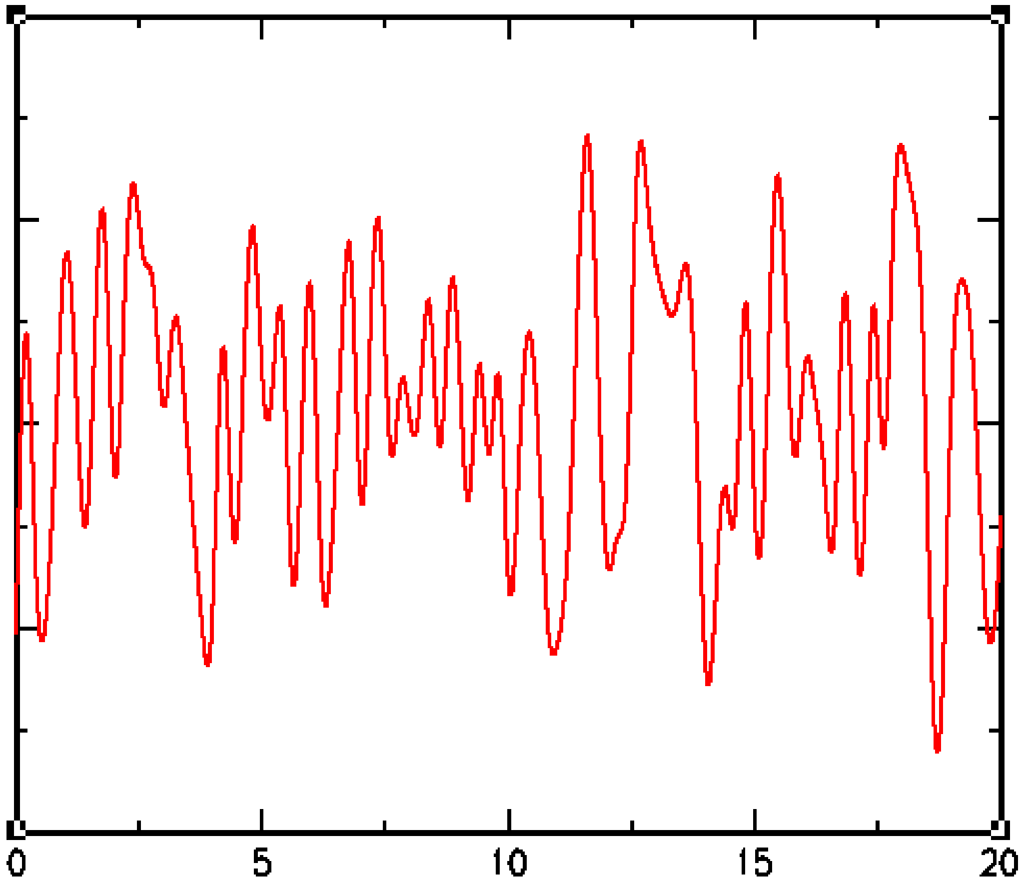
- **DFE has been used for several decades in narrowband communications systems such as voiceband modems**

- **More recently, it has been used in *100Base-TX* and *1000Base-T* Ethernet Transceivers**

Signaling at Faster than Nyquist Rate

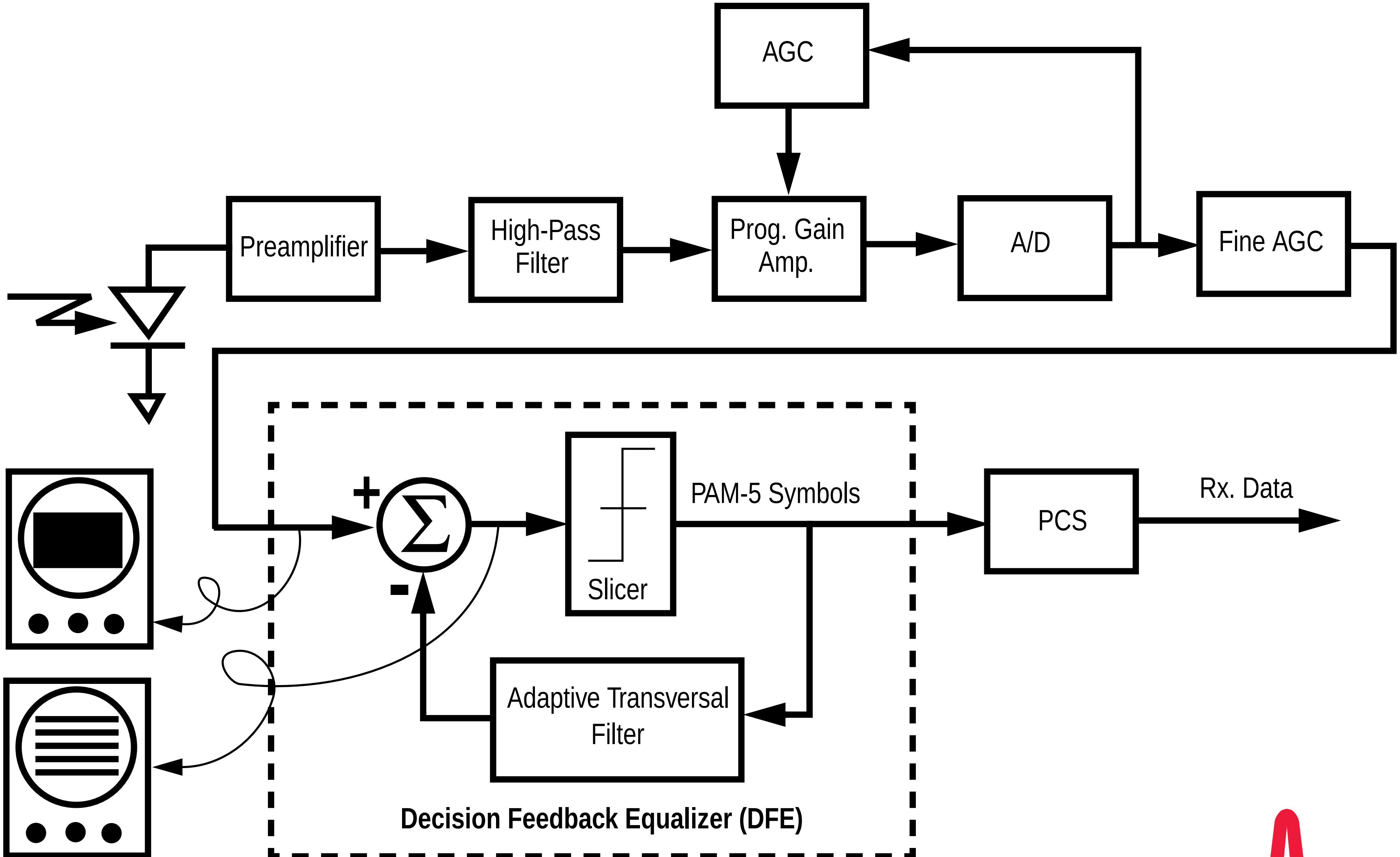
- **Decision Feedback Equalization is almost ideally suited to the problem of equalizing multimode fibers, as pointed out by Kasper**
- **Kasper also points out that in fiber optic channels it is possible to signal at rates *considerably higher* than Nyquist when using DFE based receivers**
- **In our simulations we signal at 2.5 times the Nyquist rate (data rate 10Gb/s, baud rate f_B=5GHz, bandwidth BW=1GHz)**
- **Our bandwidth assumption is consistent with 500m of 160/500MHz-Km fiber at 1310nm, or 160m of the same fiber at 850nm**

PAM-5 5 GBaud Signal at the Output of the Receiver



Time [ns]

Receiver Model



NOTE: This is a conceptual system-level diagram. More on implementation later

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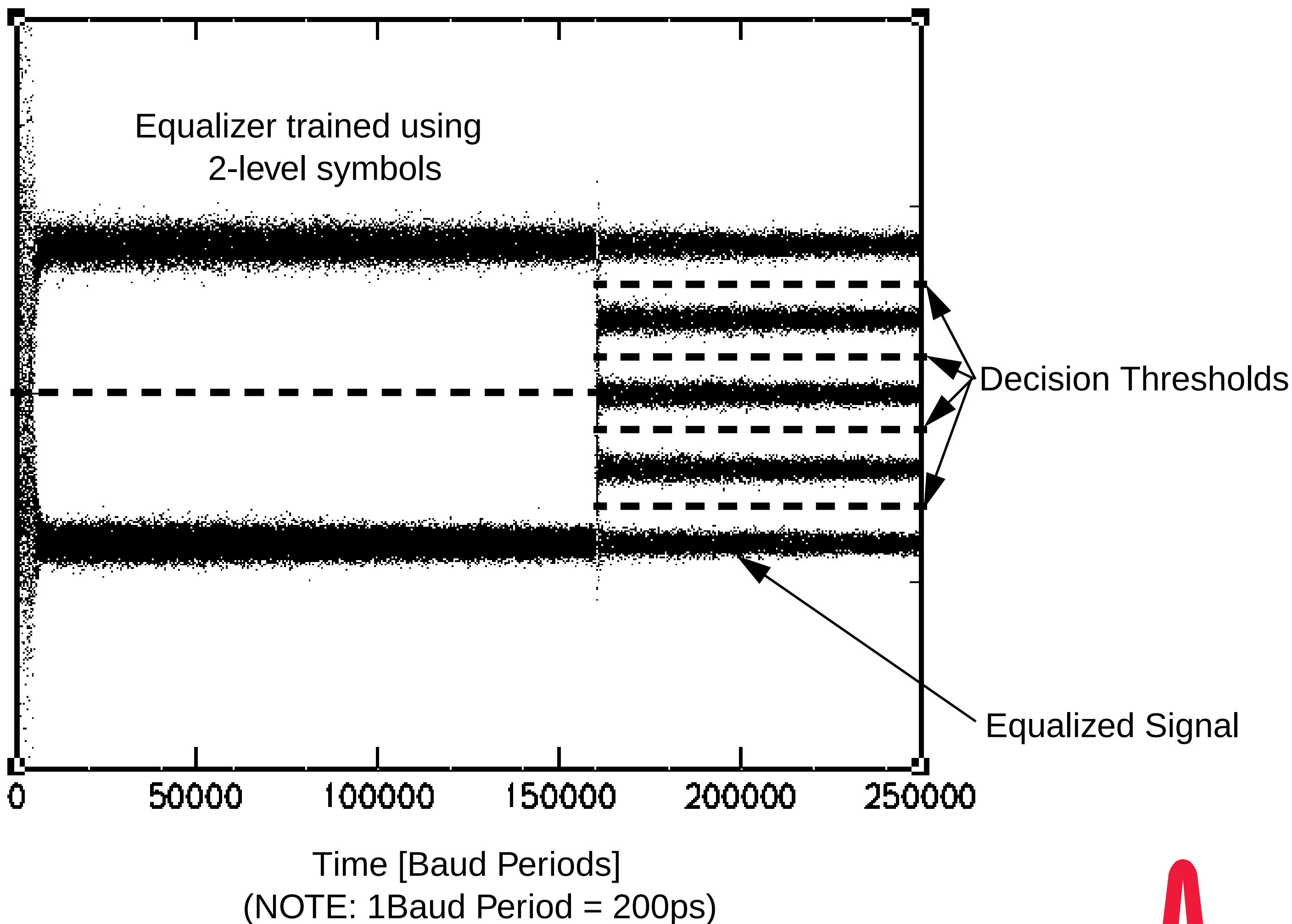
Eye Pattern



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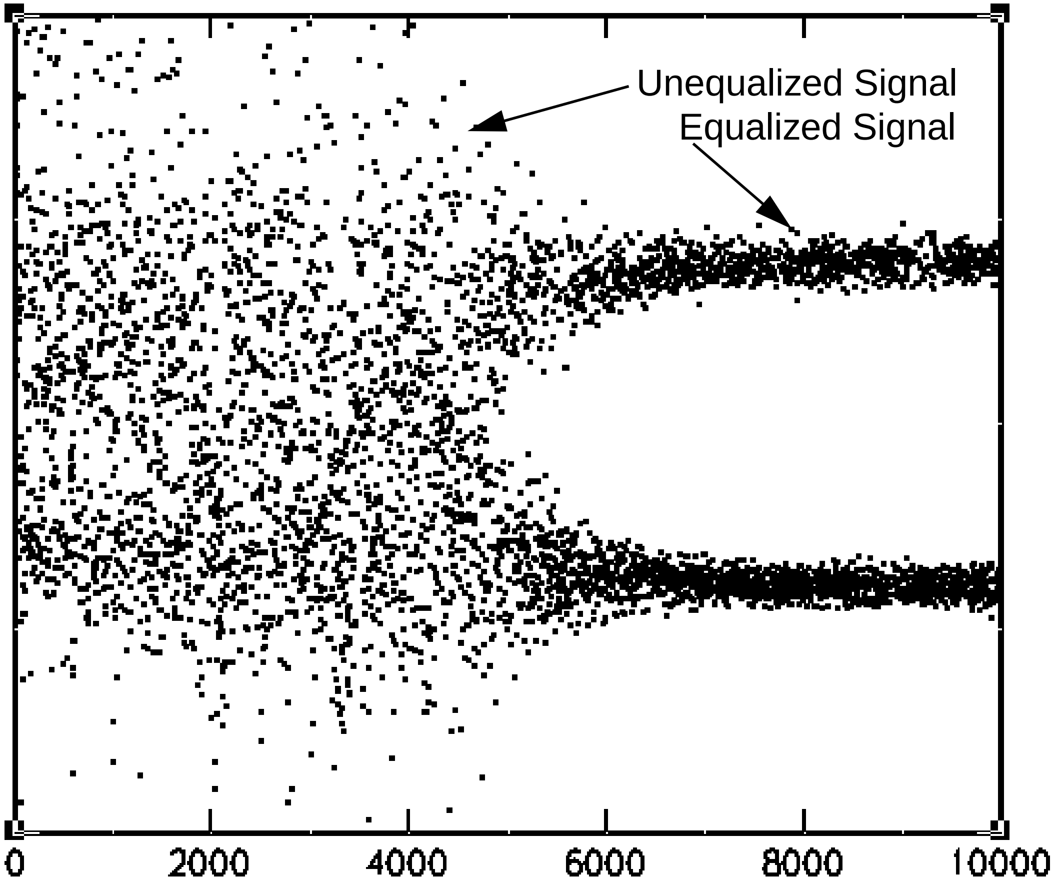
Zoom of Eye Pattern
(showing the initial convergence of the equalizer)



Time [Baud Periods]

Future Work

- **Improve laser model**
  - Model used represents edge emitters
  - Will add VCSEL model
- **Incorporate a modulation code, most likely a trellis code**
  - Could provide coding gain of ~6dB
- **Parallelization of the A/D conversion and DSP functions**
- **Measurements and experimental verification**

Conclusions

- **We have simulated a PAM-5 system operating over multimode fibers, using a rate equation model for the laser and a Gaussian dispersion model for the fiber**
- **The receiver is based on a DFE, and enables signaling at a rate 5 times larger than the 3dB bandwidth of the channel, which in this study is assumed equal to 1GHz**
- **Although this study is preliminary and more detailed modeling supple-mented with measurements is required, we are convinced that PAM-5 at 5GBaud symbol rate is a viable and attractive proposition**
- **We intend to provide more detailed results at the March Plenary**