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Chair for Communications
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Information
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Networks

Adaptive Compensation of Single Channel Distortions with Optical FIR-Filters at 40Gb/s

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Overview

- Adaptive Optical Distortion Compensation
  - Introduction
  - Concept of an Adaptive Optical Equalizer
  - FIR-Filter Structure
  - Simulation Results: Group Velocity Dispersion, Self-Phase Modulation, Polarization Mode Dispersion, Group Delay Ripple
  - Summary

Why Adaptive Distortion Compensation?

- Reconfigurable optical networks need adaptive equalization to follow the dynamic changes of the transmission channel:
  - chromatic dispersion
    - different routes through the network
    - temperature variations
  - nonlinear effects
    - signal distortions dependent on dispersion and signal power
  - PMD
    - birefringence and mode coupling variations

Enabling Technology ≥ 10 Gb/s

Adaptive Distortion Compensation

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- existing concepts
  - electrical equalization by *intersymbol interference minimization* with Finite Impulse Response (FIR)-Filters, Decision Feedback Equalizer (DFE), Viterbi Equalizer

    problem: envelope demodulation in the photo diode (PD)

  - optical compensation by *inverse system modeling* with e.g. DCF, CFBG, cascaded Mach-Zehnder Interferometers (MZI), Ring Resonators (RR), Etalons, VIPA

    but: compensation of only a single fiber impairment

Adaptive Distortion Compensation

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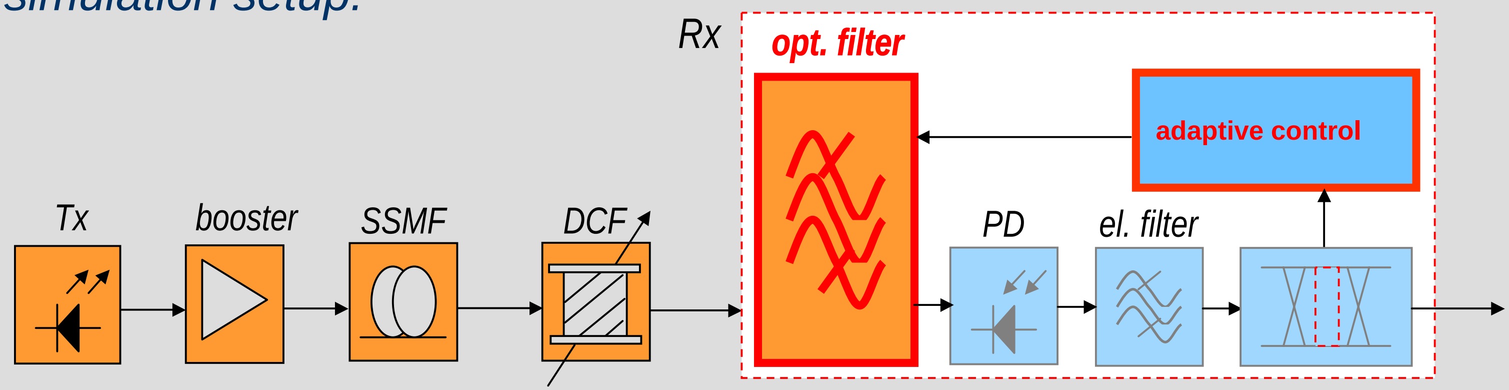
- adaptive equalizer in the optical domain
  - equalization before the PD, phase information available
  - variable complex tap weights (el. filter: only real tap weights)
  - maximization of the electrical eye opening by controling the tap weights of the optical filter with an adaptive algorithm

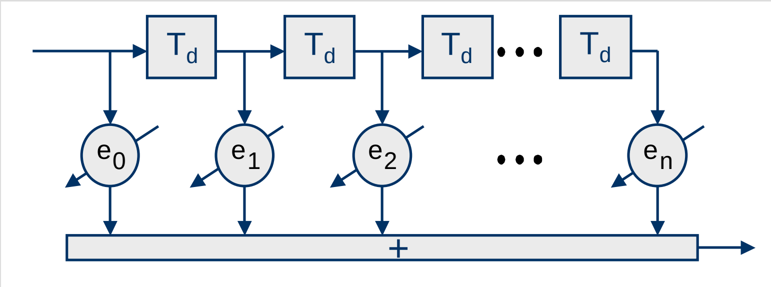
simulation setup:



combined optical equalization of single channel distortions

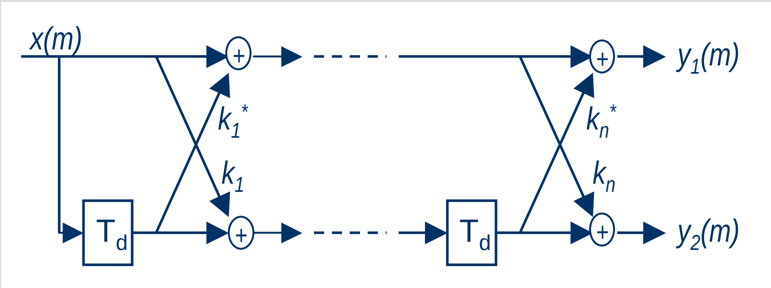
FIR - Filter Structure

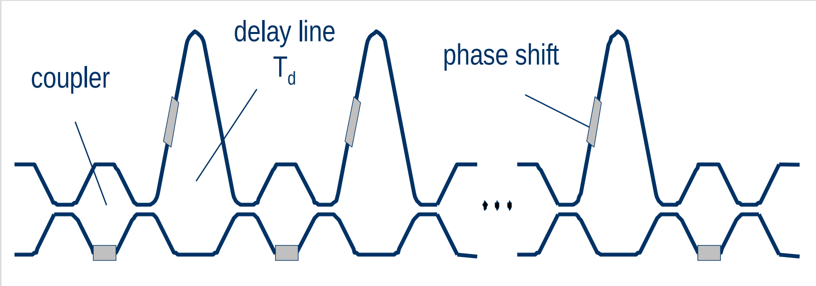
- transversal structure



difficult to realize as optical filter with variable complex tap coefficients

- lattice structure





cascaded Mach-Zehnder Interferometers

FIR - Filter Structure

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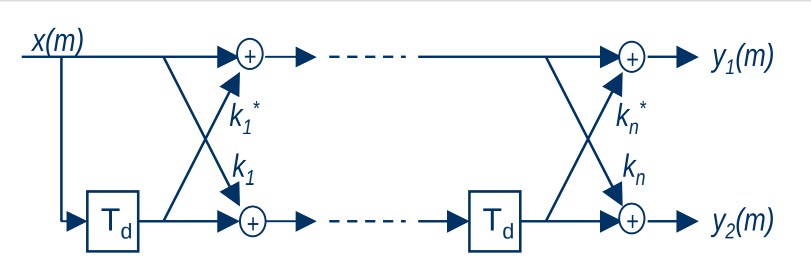
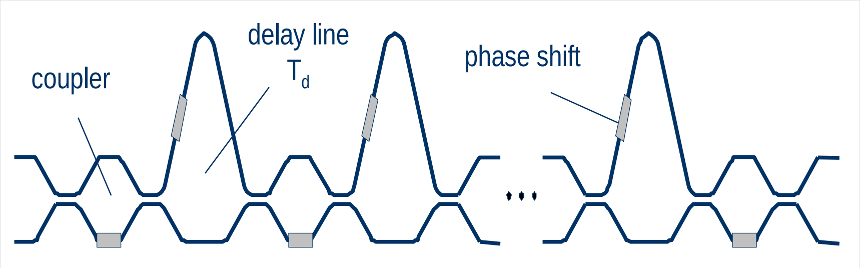
- lattice structure





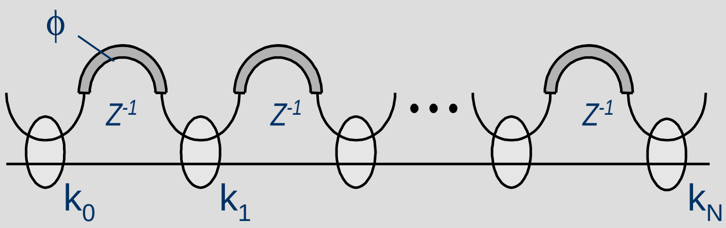
cascaded Mach-Zehnder Interferometers

- complex tap weights by changing the coupling and phase ratio
- the frequency response is periodic: *FSR=1/T_d*

  ⇨ *combined equalization of several channels*

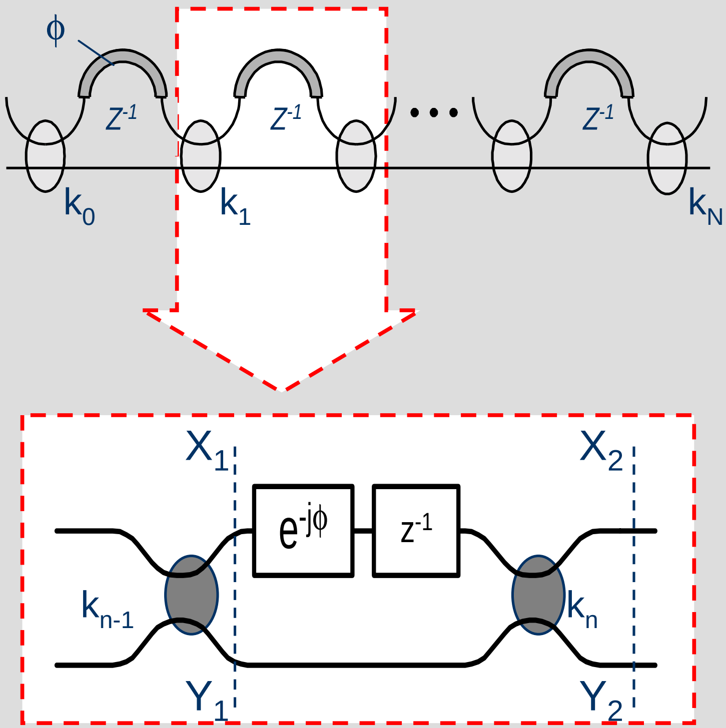
FIR - Filter Structure

- lattice structure



FIR - Filter Structure

- lattice structure



$$\begin{bmatrix} X_n(z) \\ Y_n(z) \end{bmatrix} = \Phi_n(z) \begin{bmatrix} X_{n-1}(z) \\ Y_{n-1}(z) \end{bmatrix}$$

$$\Phi_n(z) = \begin{bmatrix} c_n & -js_n \\ -js_n & c_n \end{bmatrix} \cdot \begin{bmatrix} z^{-1}e^{-j\phi_n} & 0 \\ 0 & 1 \end{bmatrix} = \begin{bmatrix} c_n z^{-1} e^{-j\phi_n} & -js_n \\ -js_n z^{-1} e^{-j\phi_n} & c_n \end{bmatrix}$$

mit $c_n = \sqrt{1-k_n}, \quad s_n = \sqrt{k_n},$

$$\begin{bmatrix} X_n(z) \\ Y_n(z) \end{bmatrix} = \Phi_N \cdots \Phi_1 \Phi_0 \begin{bmatrix} X_{in}(z) \\ Y_{in}(z) \end{bmatrix}$$

40Gb/s Results - GVD

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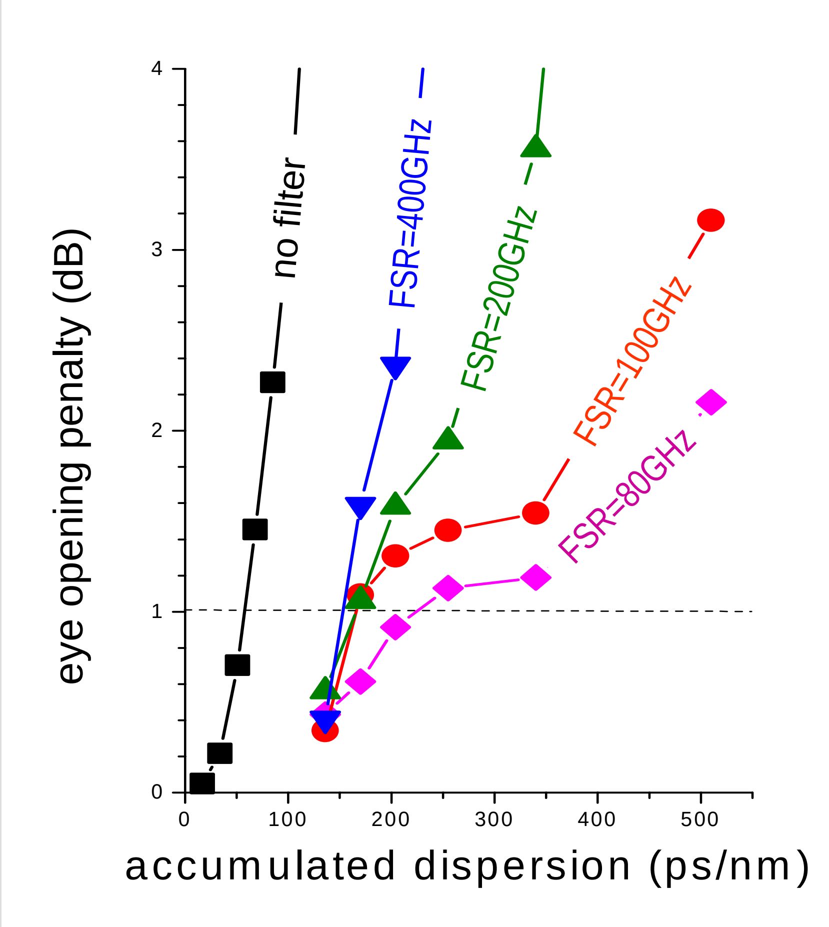
- dispersion tolerance (1dB reference)
  - w/o equalizer: D = ± 60 ps/nm
  - ⇨ *with equalizer: D = ± 200 ps/nm*
- arbitrary accurate equalization with increasing filter order
- equalizing performance = *f(FSR)*
  - increasing distortion ⇨ increasing pulse broadening
  - increasing FSR ⇨ decreasing T_d ⇨ shorter impulse response
  - *increasing pulse broadening & shorter impulse response ⇨ decreasing equalization*



40 Gb/s, linear transmission, filter order: n=10

40Gb/s Results - SPM

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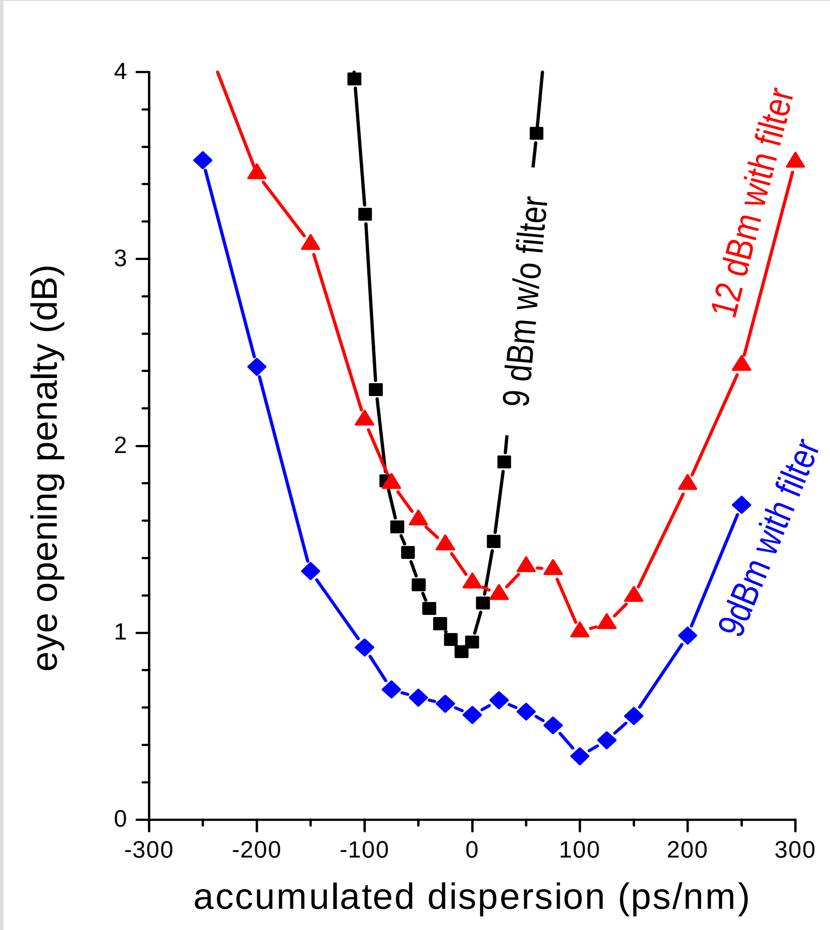
- dispersion tolerance @ 9dBm
  - w/o equalizer: *D=0ps/nm*
  - ⇨ with equalizer: *D = -100 … +200 ps/nm*

- SPM equalization (1dB reference)
  - w/o equalizer: P_{launch} = 9 dBm
  - with equalizer: P_{launch} = 12 dBm
  - ⇨ *SPM equalizing gain: 3 dB*



40 Gb/s, nonlinear transmission, filter order: n=10

PMD Equalization Schemes

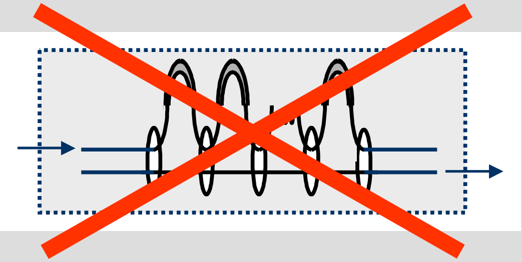
- Adaptive Equalization:

  - equalization with a single filter:

    both orthogonal modes will be equalized with the same transfer function

    ⇨ *slight improvement, eye cosmetics*

1.)

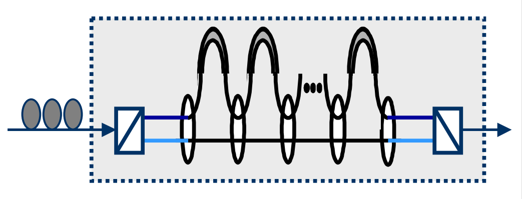


  - equalization with 2 transfer functions:

    by including a polarization beam splitter (PBS) both orthogonal modes see a different transfer function

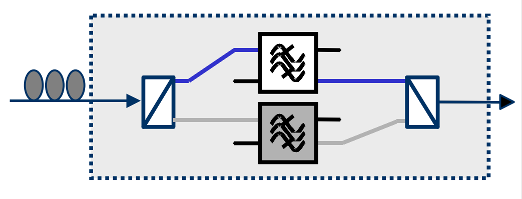
    ⇨ *excellent improvement*
    ⇨ *max $DGD_{komp}=n \cdot T_d$*

2a.)



single filter setup

2b.)



double filter setup

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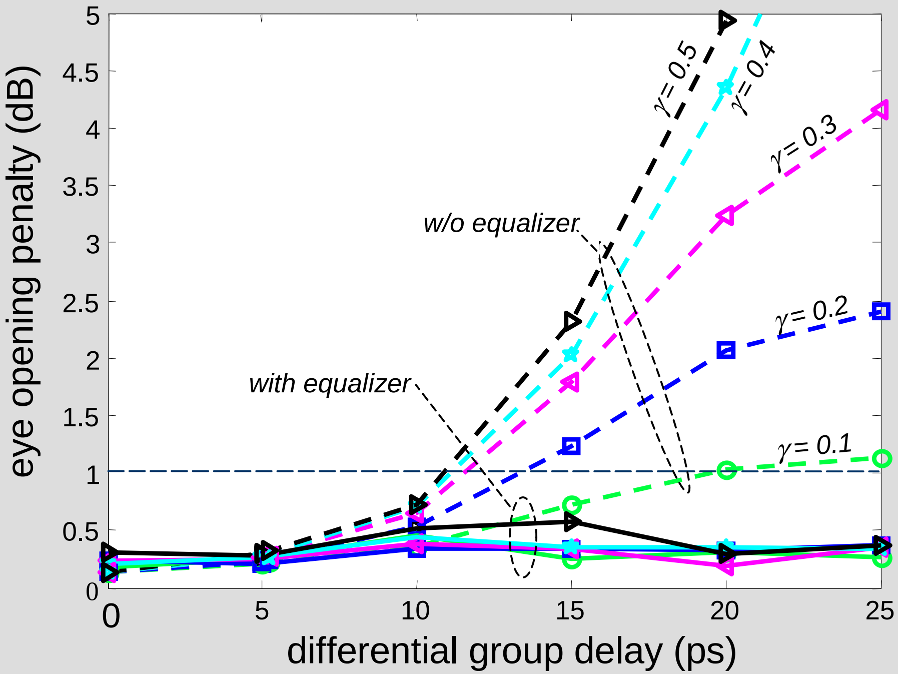
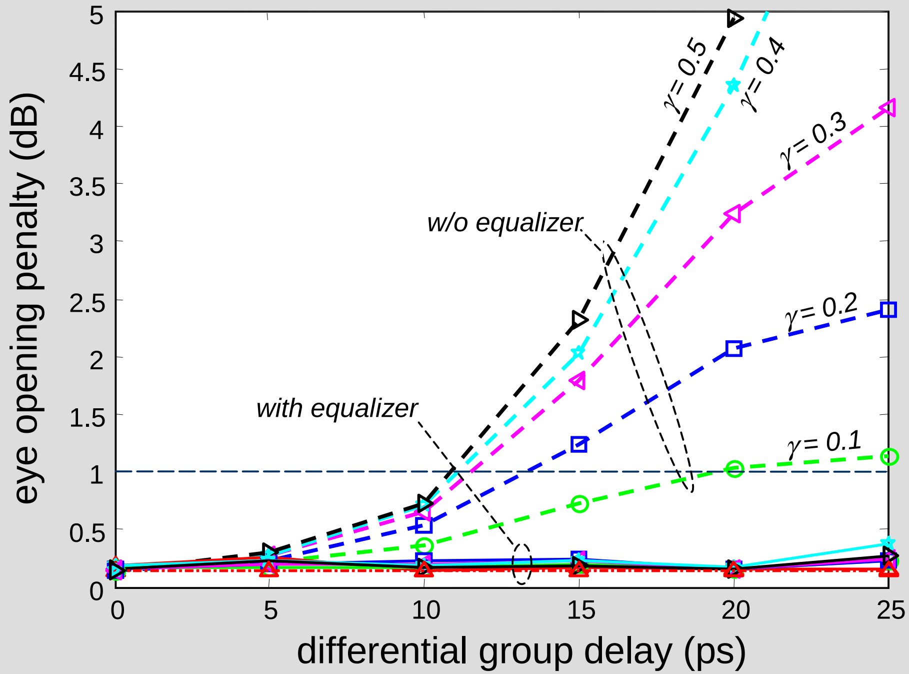
40Gb/s Results - PMD 1st order

single filter setup (filter order n=2)



double filter setup (filter order n=2)



40Gb/s Results - PMD 1st and higher order

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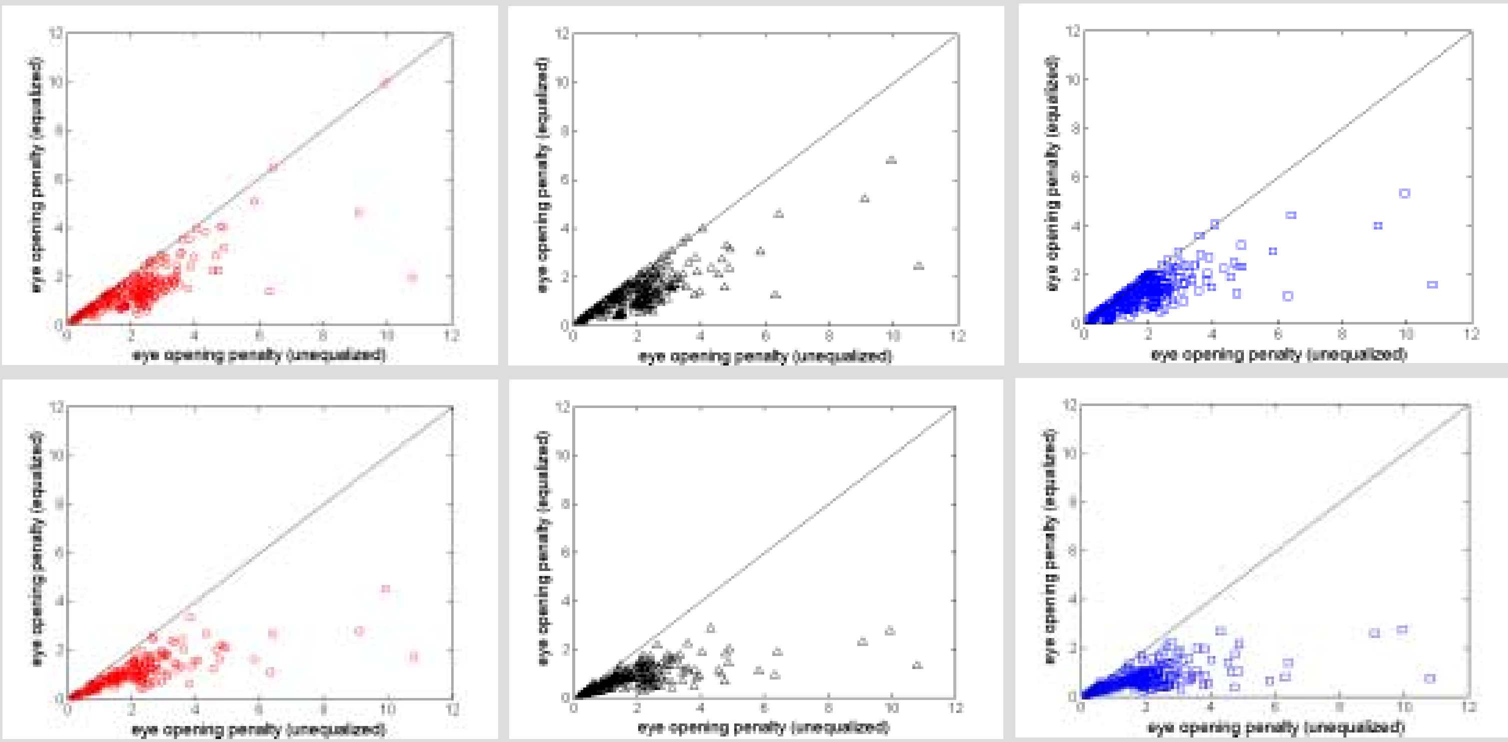
- simulated fiber span: L=100km, D_{PMD}=1ps/√km, PMD_{mean}=10ps

filter order n=2 n=4 n=6

single filter setup

double filter setup



Group Delay Ripple Modeling

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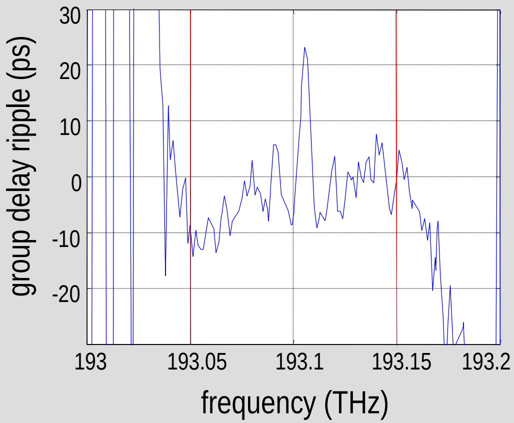
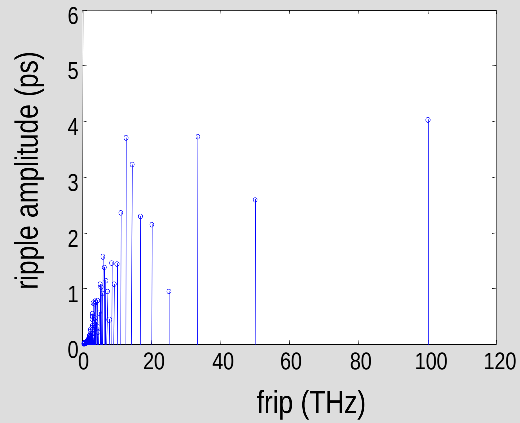
Group Delay Measurement

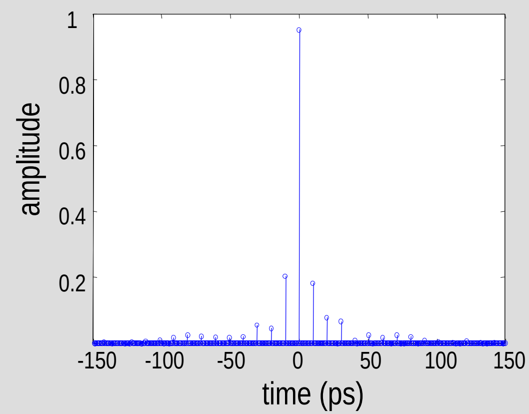


FFT

Ripple Spectrum



Impulse Response



$$t_{g,i}(\omega) = -\Delta t_{g,i} \cos \frac{\omega}{f_{rip,i}}$$

$$h_i(t) = \sum_{k=-\infty}^{\infty} J_k(\Delta t_{g,i} f_{rip,i}) e^{jk\varphi_i} \delta_0(t + k / f_{rip,i})$$

$$h(t) = h_1(t) * h_2(t) * \cdots * h_I(t)$$

GDR Equalization Schemes

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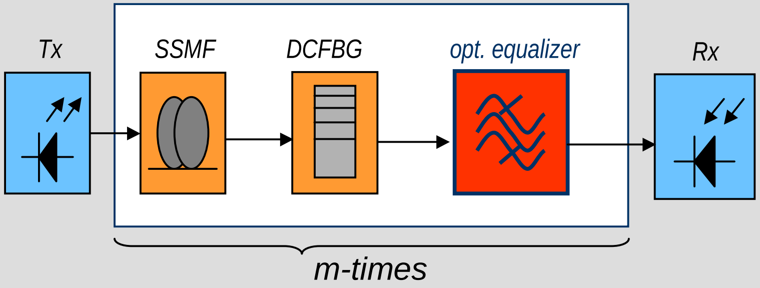
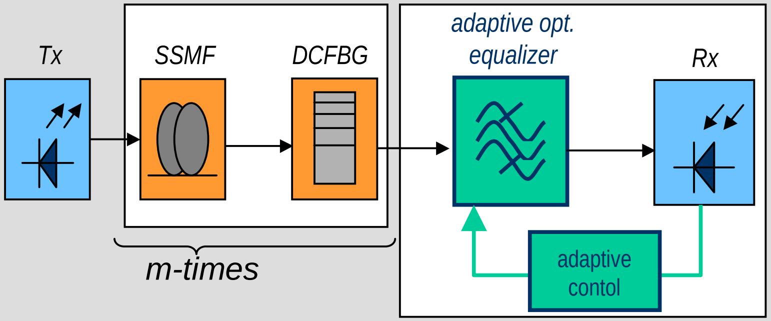
- equalization schemes
  - optical inline compensation by modeling the inverse system

CFBG + Filter = Ripple Free Device



  - post equalization with an adaptive optical filter

ripple mitigated tunable dispersion compensation with fixed DCFBGs



40Gb/s Results - Group Delay Ripple

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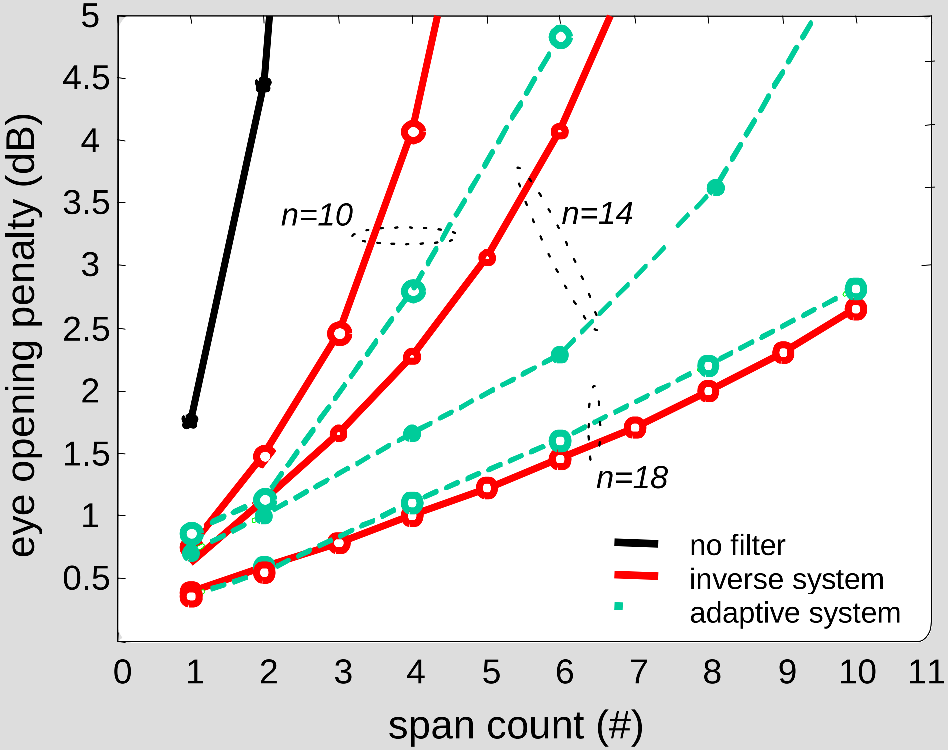
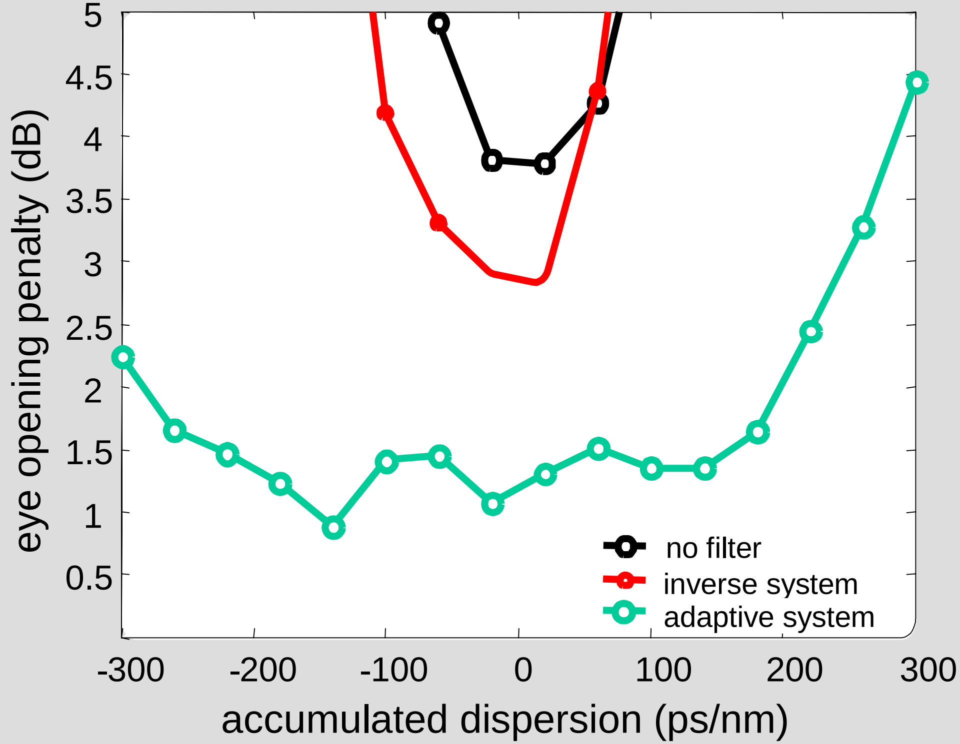
equalization of group delay ripple only



equalization of group delay ripple @ 10dBm, 2spans, n=10



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Summary

- **adaptive equalizer concept:**
  - excellent dispersion tolerance improvement for linear and nonlinear transmission
  - excellent SPM equalization
  - PMD equalization of 1st and higher order
  - group delay ripple compensation

combined optical mitigation of all single channel distortions