Equalization of Multi-Level Formats after Coherent Reception

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Outline

- Introduction
- Simulation setup
- Investigated equalizers for electronic dispersion compensation (EDC)
- Estimation of the equalizer coefficients
- Results for linear and nonlinear channel
  - without EDC
  - Inverse system: T/2 spacing
  - Inverse system: T/4 spacing
  - Zero forcing: MMSE criterion, T/2 spacing
- Conclusions

Introduction

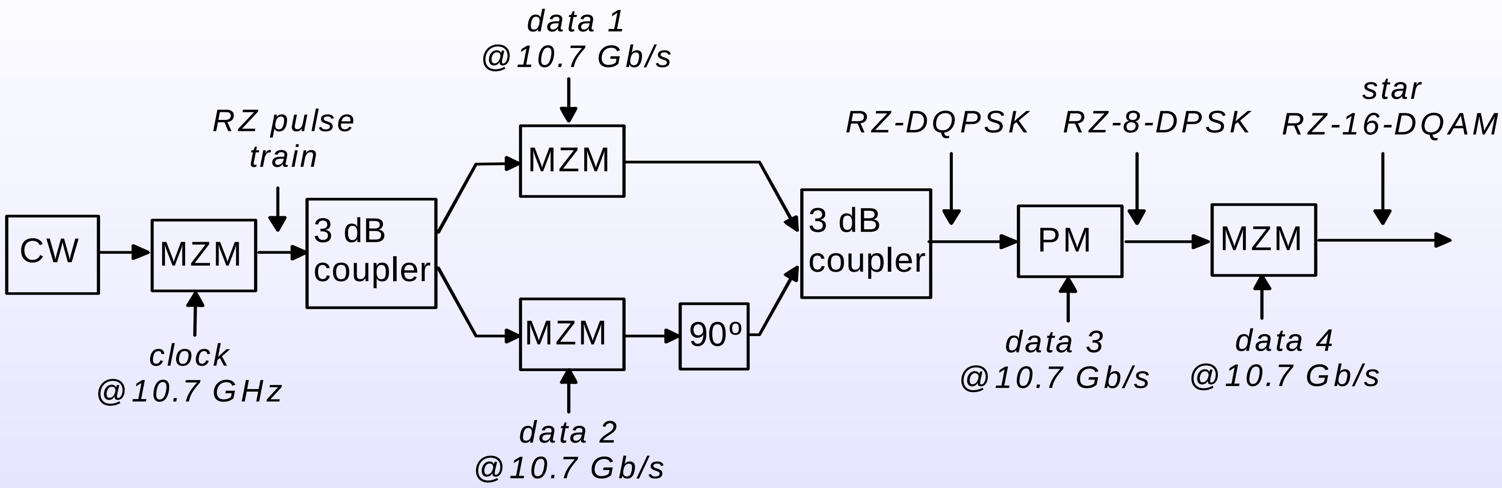
Conventional solution:

- Optical PLL necessary for homodyne coherent receiver
  => complex setup in the optical domain

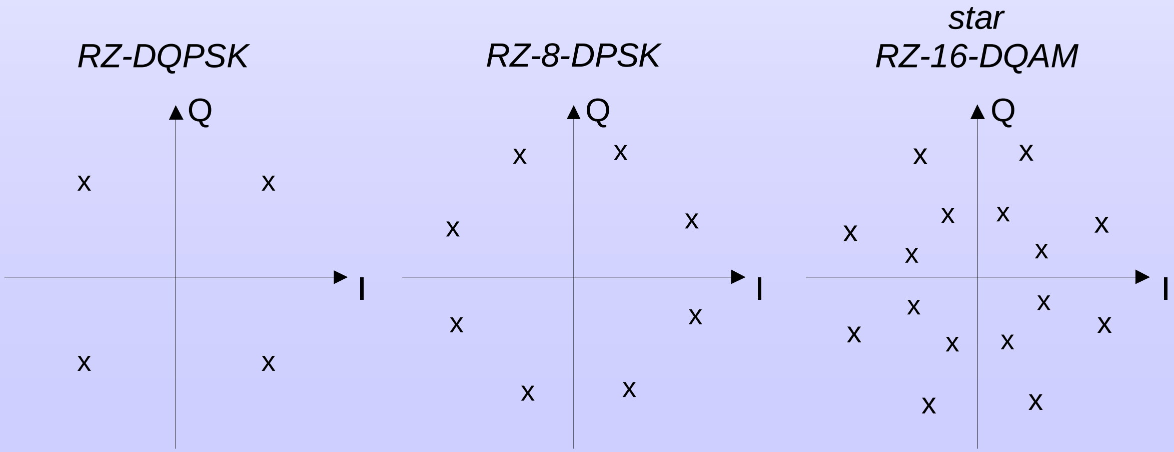
Digital electronic solution:

- Transfer of phase recovery into the digital domain due to availability of high-speed digital signal processing (DSP)
  => reduced complexity in the optical domain
- Equalization of transmission impairments (e.g. dispersion) in the digital domain possible
- Reception of multi-level formats with a coherent receiver
  => reduced complexity in the optical domain
- Same receiver setup for all M-PSK and M-QAM modulation formats, only adaptation of the algorithm necessary

Simulation setup: Transmitter for 10.7 Gsymbols/s



- Signal space constellations:



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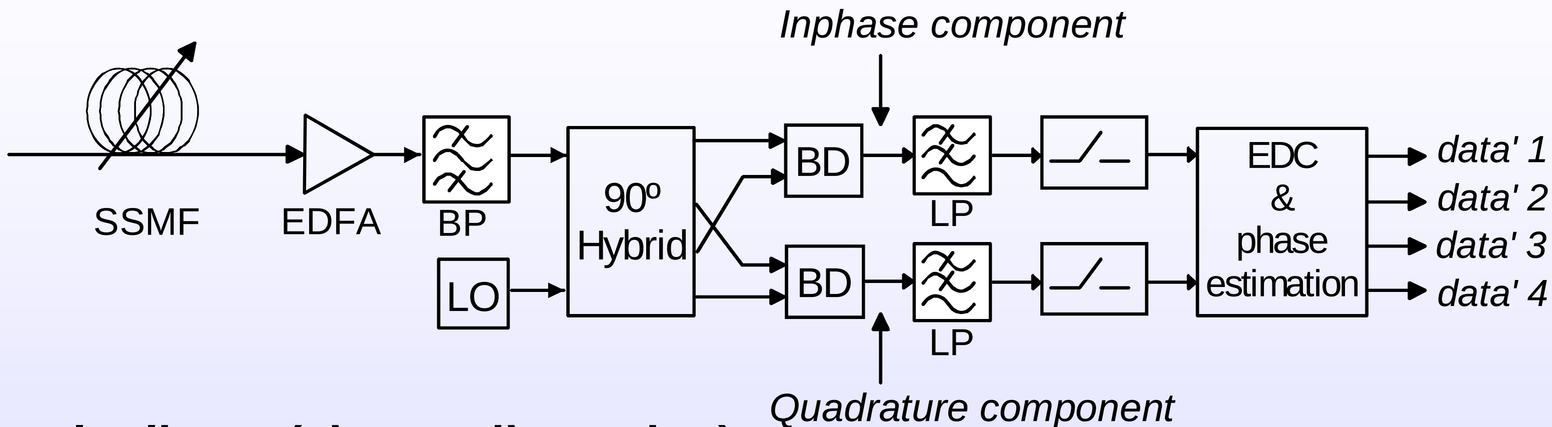
Simulation setup: Channel and receiver for 10.7 Gsymbols/s



Channel: - linear (chrom. dispersion)

- nonlinear (SPM and CD), 5dBm average fiber input power

Receiver: LP: lowpass filter (Butterworth 3rd order, f_{3dB}=11 GHz)

BP: optical bandpass filter (Gaussian, f_{3dB}=44 GHz)

BD: balanced detector

LO: local oscillator

EDC: electronic dispersion compensation

Phase estimation: none, assumption of ideal coherent demodulation to investigate only the performance of the equalizer

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Investigated equalizer for electronic dispersion compensation (EDC)

Investigated equalizer:

- Inverse system with linear FIR filter:
  - Use of the inverse fiber transfer function
  - T/2 spacing:
    - filter length of feed forward equalizer (FFE): 5, 9 and 15 taps
  - T/4 spacing:
    - filter length of feed forward equalizer (FFE): 9, 17 and 29 taps
- Zero forcing with feed forward and decision feedback FIR filters:
  - MMSE (minimum mean square error) criterion. Use of distorted received signal and true data sequence
  - T/2 spacing:
    - filter length of feed forward equalizer (FFE): 5, 9 and 15 taps
    - filter length of decision feedback equalizer (DFE): 0, 1 and 2 taps

Estimation of the coefficients

- Coefficients for the Inverse System:

Frequency response : $H(f) = e^{j2\pi^2 f^2 \beta_2 L} = H_{Fiber}{}^{-1}(f)$

Coefficients: $e_k = h(kT_a) = \int_{-\frac{fa}{2}}^{\frac{fa}{2}} H(f)\, e^{j2\pi f kT_a}\, df$ with f_a – sampling frequency

- Coefficients for the Zero forcing equalizer:

$$e = \left[R_{xx} - \frac{1}{\sigma_d^2} R_{xd} R_{xd}^H \right]^{-1} r_{xd}$$

$$b = \frac{1}{\sigma_d^2} R_{xd}^H e$$

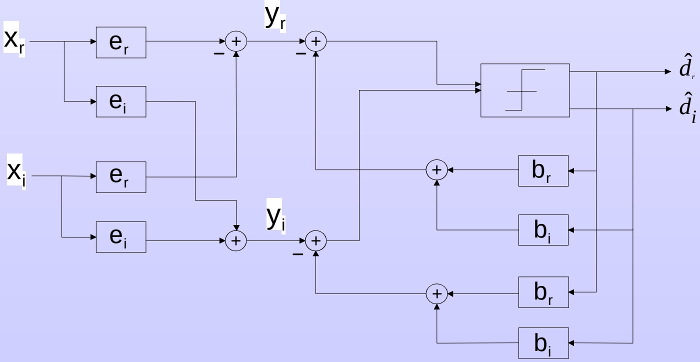
$E\{xx^T\} = R_{xx}$ – auto correlation matrix

$E\{x\,d(n)\} = r_{xd}$ – cross correlation vector

$E\{d^2(n)\} = \sigma_d^2$ – power of data sequence

$E\{xd^T\} = R_{xd}$ – cross correlation matrix

Complex baseband equalizer:



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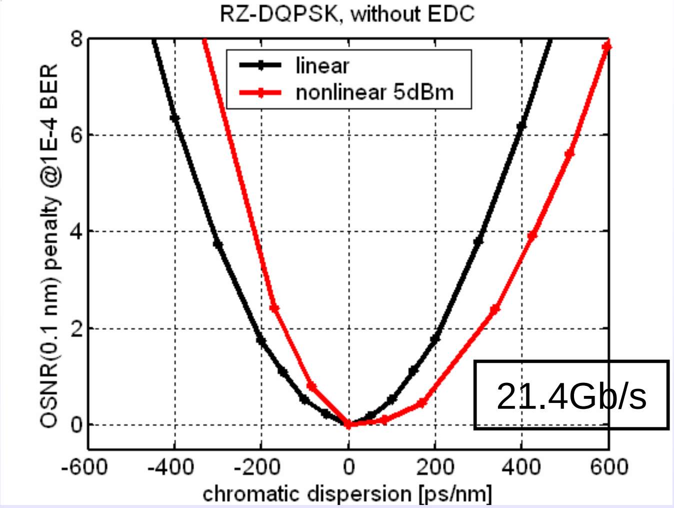
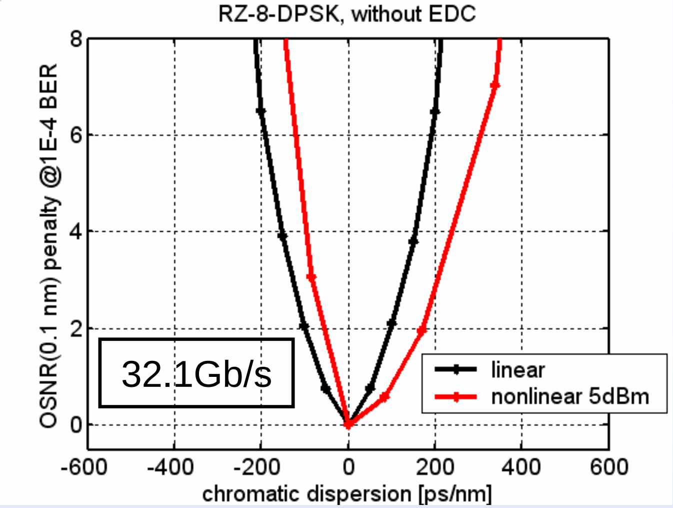
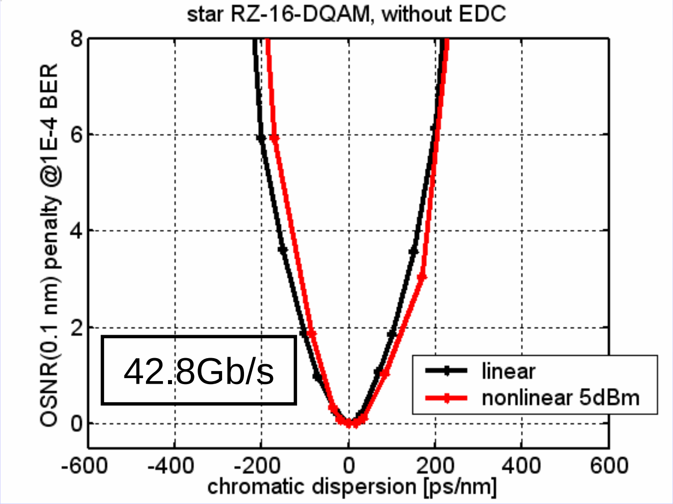
Without EDC, 10.7 GSymbols/s







In nonlinear case interaction of dispersion and SPM:

- Right shift of penalty curves
- Use some positive residual dispersion

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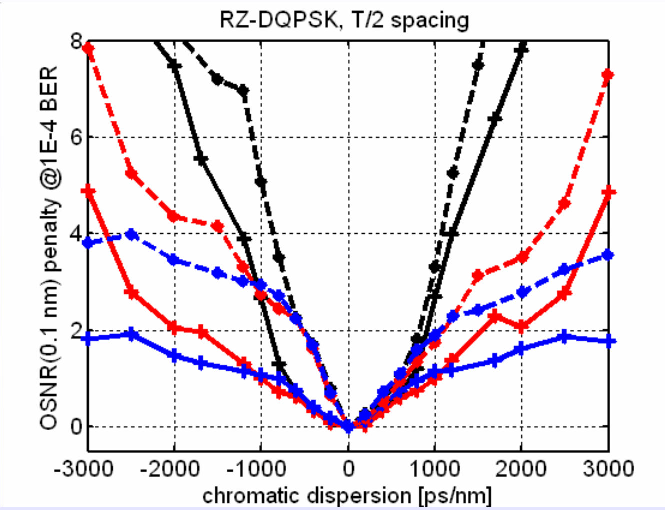
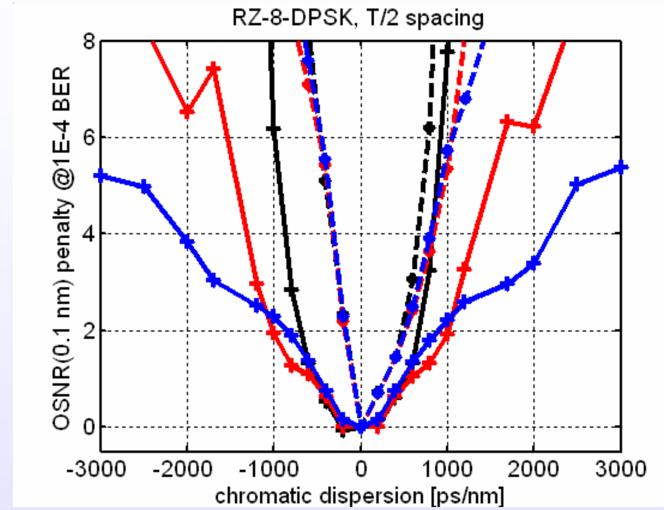
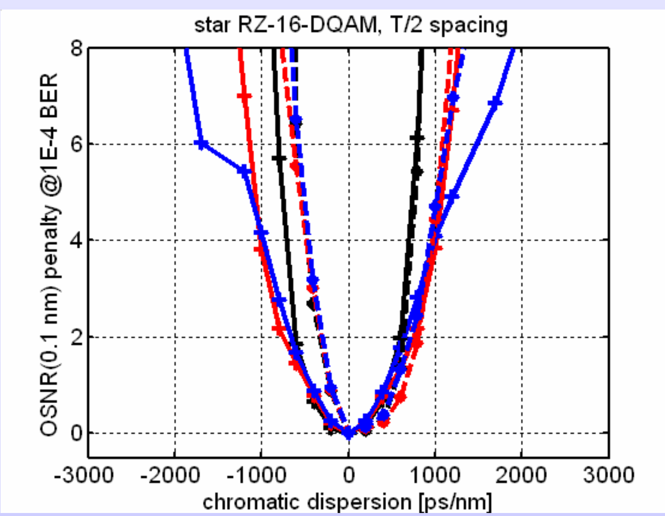
Inverse System: T/2 spacing



FFE[5]-DFE[0]
FFE[9]-DFE[0]
FFE[15]-DFE[0]

linear
nonlinear 5dBm

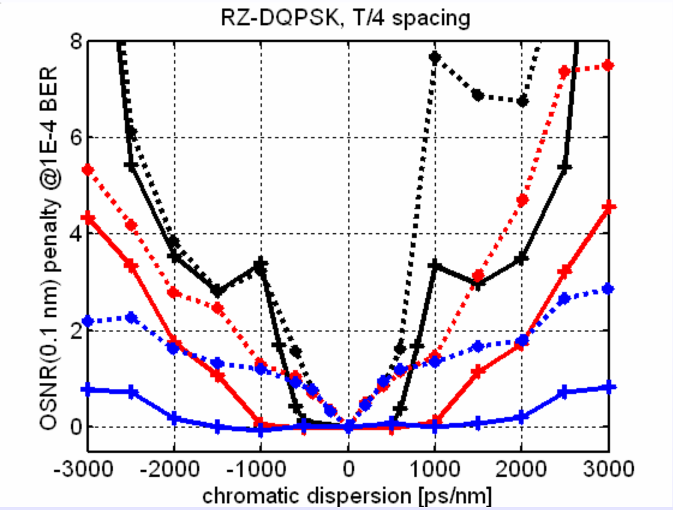


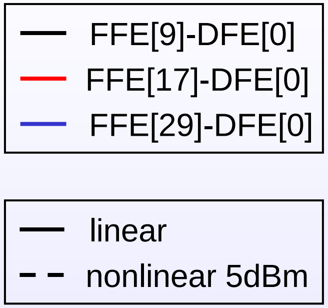


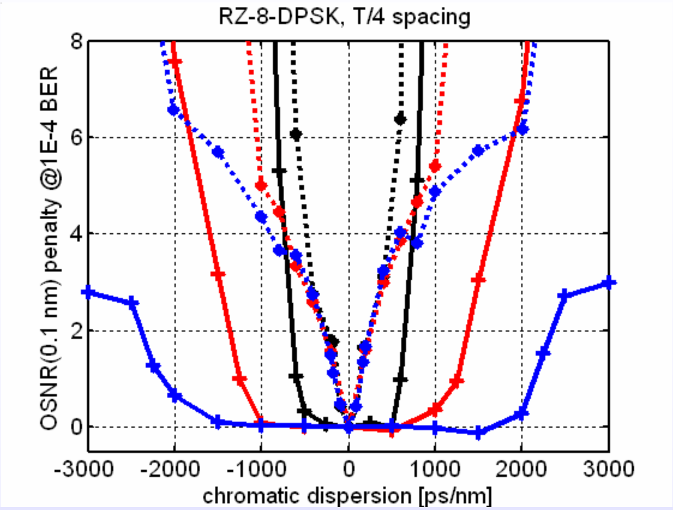
Reduced dispersion tolerance for the nonlinear case:

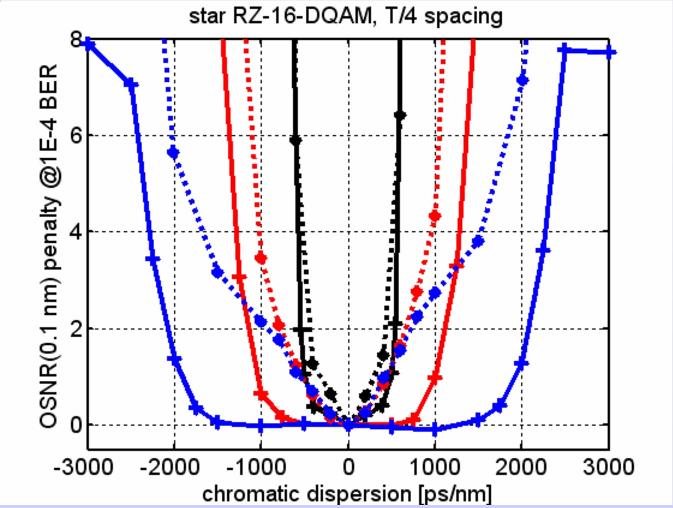
- additional phase shift due to SPM
- equalizer designed for linear case only

Inverse System: T/4 spacing









T/4 equalizer better than T/2 equalizer due to doubled sampling frequency

Better performance of RZ-DQPSK compared to RZ-8-DPSK => larger symbol distance

Better performance of star RZ-16-DQAM compared to RZ-8-DPSK => half of the transmitted symbols have reduced power => less influence of SPM

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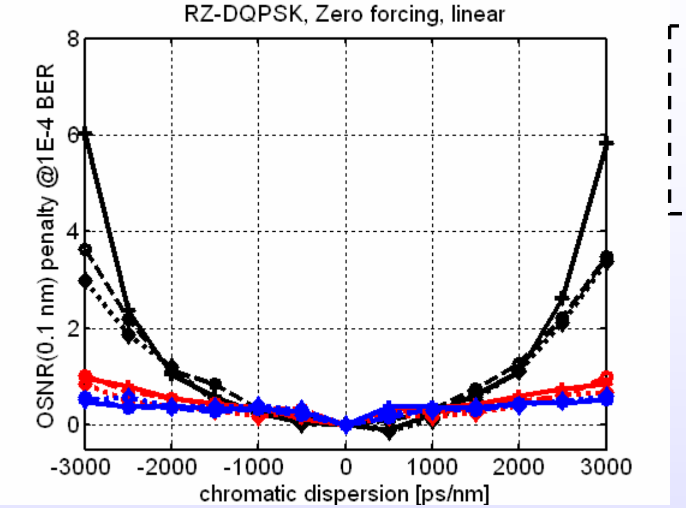
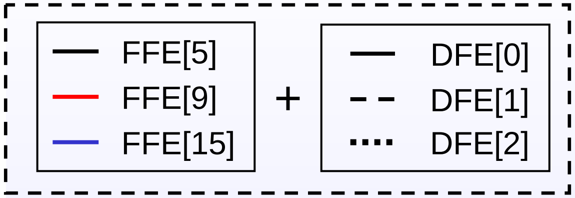
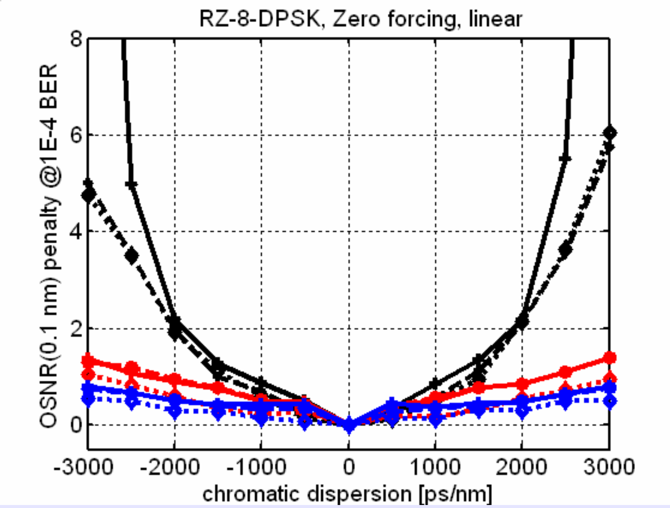
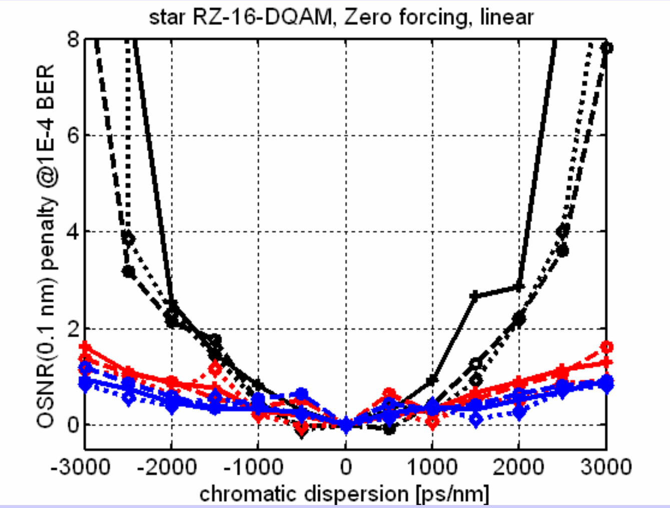
Zero-Forcing: MMSE criterion, T/2 spacing, linear



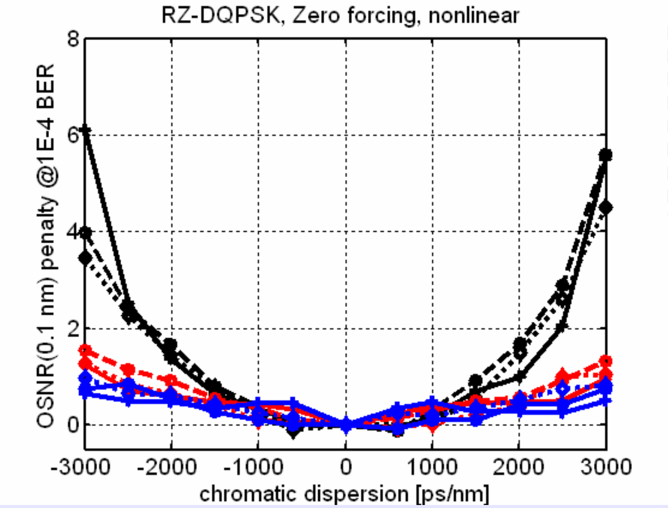


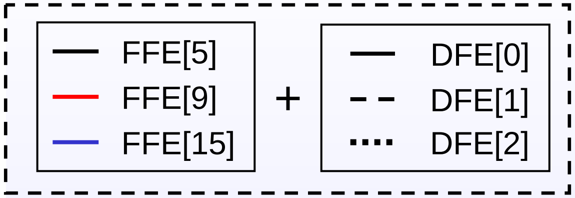


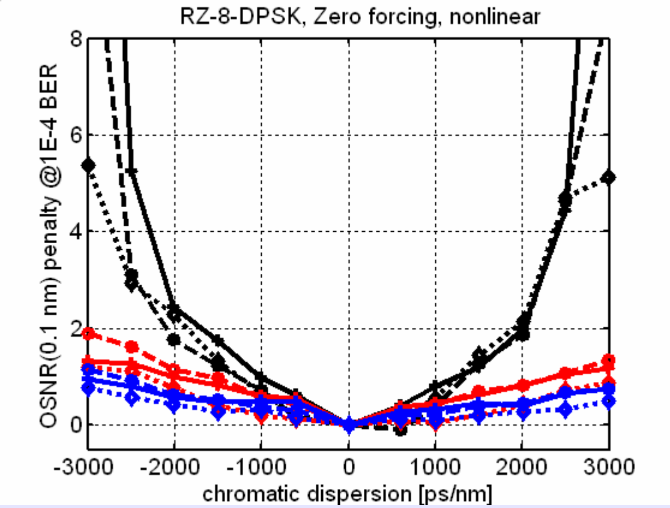


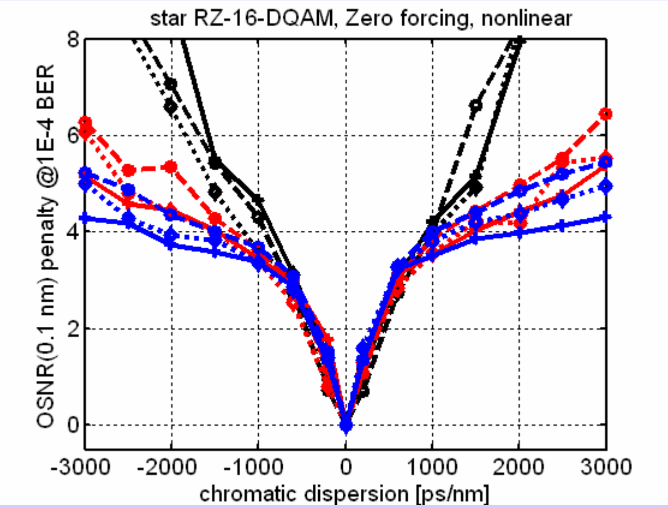
- For all modulation formats nearly same performance of the FFE[9]-DFE[X] and FFE[15]-DFE[X] equalizer
- DFE not required, linear FFE sufficient
- 6000 ps/nm may be equalized

Zero-Forcing: MMSE criterion, T/2 spacing, nonlinear



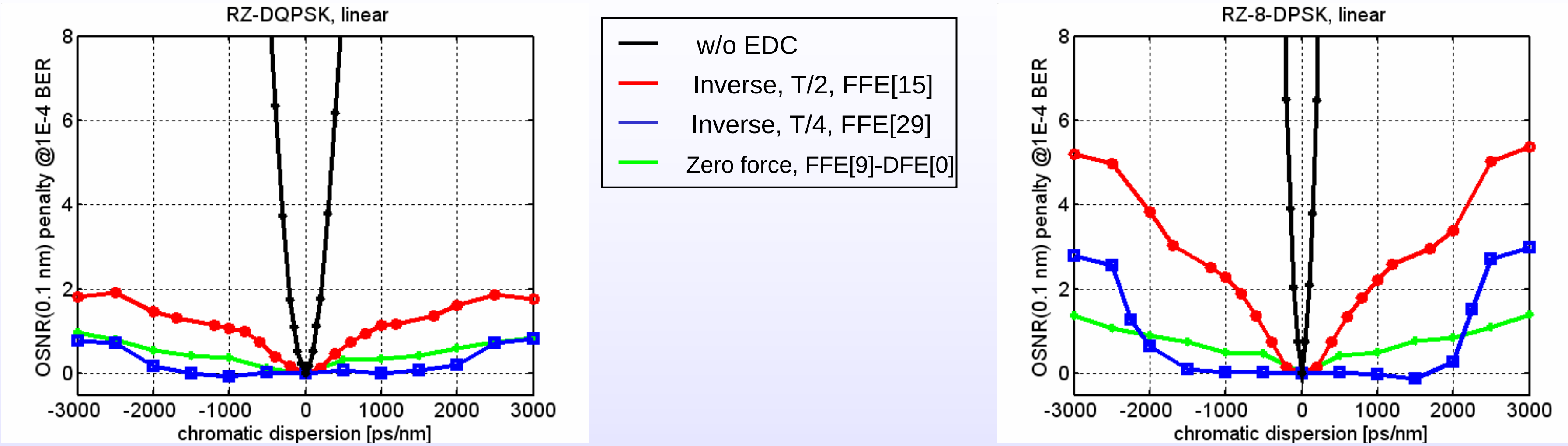


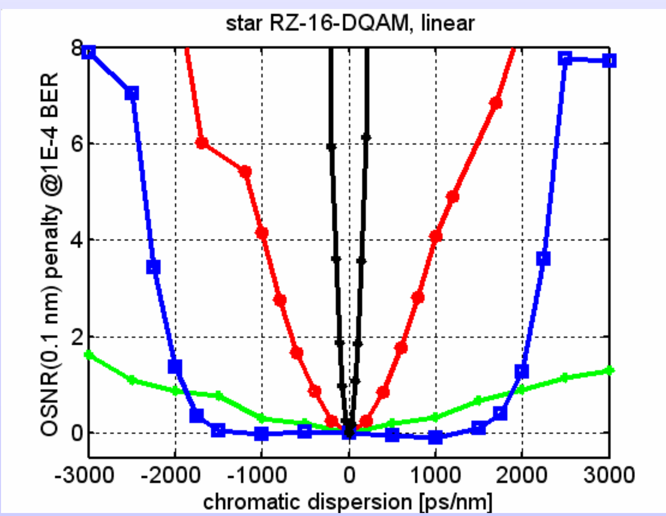




- For RZ-DQPSK and RZ-8-DPSK nearly same performance as for linear case
- Star RZ-16-DQAM: different nonlinear phase shift of the two amplitudes circles => more difficult to equalize

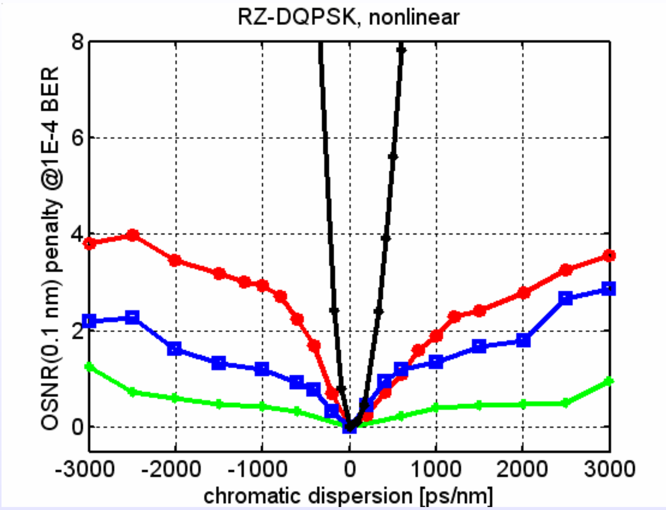
Summary: Comparison of different Equalizer: linear

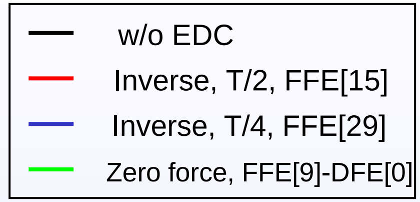


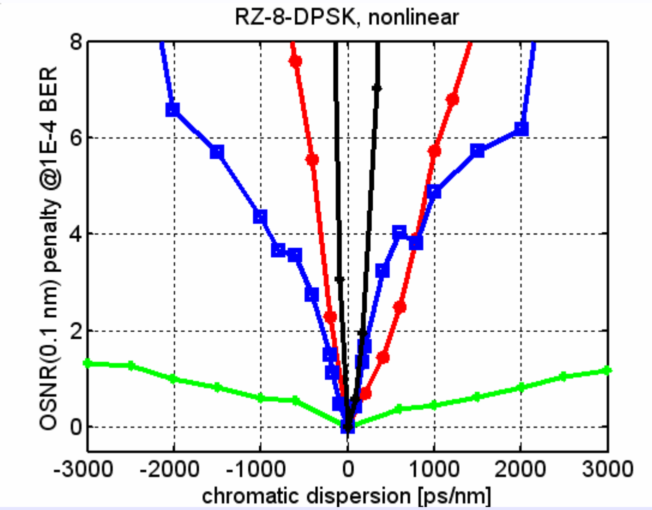


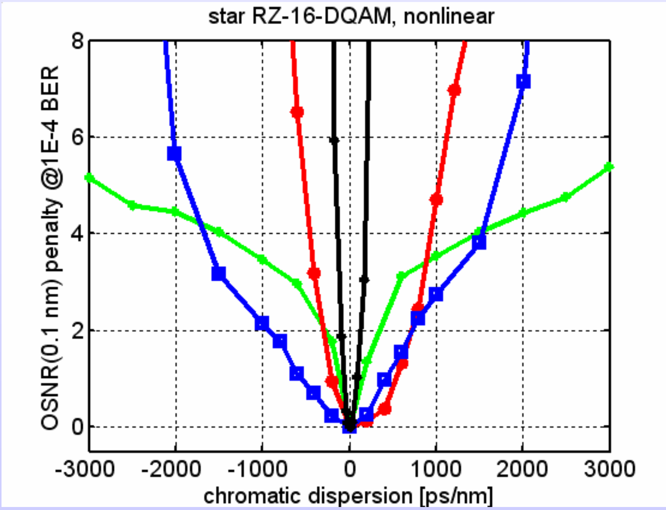
- Better performance of the zero forcing equalizer with 9 taps than the inverse system equalizer with 15 taps and same spacing

Summary: Comparison of different Equalizer: nonlinear









- For RZ-DQPSK and RZ-8-DPSK best performance for the zero forcing equalizer
- Star RZ-16-DQAM difficult to equalize

Conclusions

- Linear channel:
  – Zero forcing equalizer best choice for all modulation formats
  – Dispersion tolerance of 6000 ps/nm at 1dB OSNR penalty

- Nonlinear channel:
  – Reduced dispersion tolerance of inverse system equalizer compared to the linear case due to linear design
  – For RZ-DQPSK and RZ-8-DPSK nearly same performance of the zero forcing equalizer compared to the linear case
    => zero forcing equalizer best choice
  – For star RZ-16-DQAM due to the two ring constellation
    ⇒ different nonlinear phase shift
      ⇒ equalization difficult with zero forcing equalizer

Conclusion

- Worse performance for the inverse system in the nonlinear case due to the not adaptive equalization and the additional nonlinear phase shift
- Best performance for the zero forcing equalizer for higher amounts of dispersion for all modulation formats in the linear case
- For the nonlinear case best performance for the zero forcing equalizer for RZ-DQPSK and RZ-8-DPSK
- For star RZ-16-DQAM only for higher amounts of dispersion best performance for the zero forcing equalizer due to the different nonlinear phase shift of the two circles in the signal space constellation