Equalization and Forward Error Correction
in
Optical Communications

Werner Rosenkranz, Cunmin Xia, Patrick Faraj

University of Kiel, Germany

Email: wr@tf.uni-kiel.de, Tel: +49 431-8806300

Outline

1. Remarks on Equalizers, Modulation Formats, FEC
2. Electronic Equalizers & Modulation Formats
3. FEC & Modulation Formats
4. Conclusions

The Demand in Optical Networks

- **Increase Capacity & Robustness**
- **Reduce Cost**

- Optical communications: Development stages:
  - ➢ Single mode fibre : low loss @1550nm, low dispersion @1310nm
  - ➢ Optical amplifiers @1550nm: regenerate in optical domain
  - ➢ High-speed data rates: 2.5Gb/s → 10Gb/s → 40Gb/s [→160Gb/s]
  - ➢ DWDM (Dense Wave Division Multiplex): more fibre bands (more channels)
    - Dense channel spacing, spectral efficiency
  - ➢ Advanced **signal processing**:
    - Robust, efficient → cost saving!

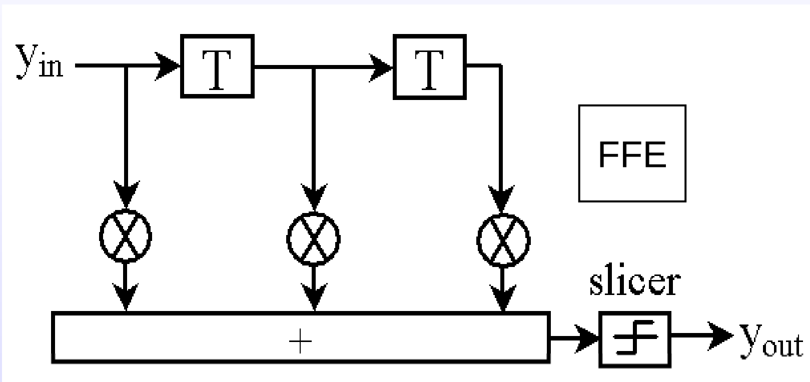
- **modulation, equalization, channel coding, …**

1. Electronic Equalizers (EDC) & Modulation Formats

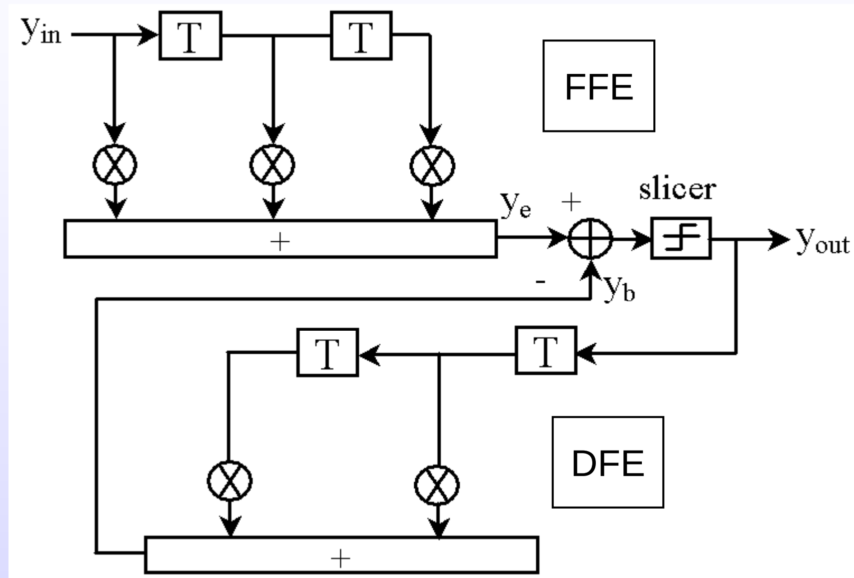
- Introduction of different EDC setups
- EDC on CD and PMD mitigation for advanced modulation formats
  - Optical duobinary modulation (ODB)
  - Differential-phase-shift-keyed (DPSK)
  - Optical single side band modulation (OSSB)
- EDC on strong optical filtering
- Conclusions on EDC

EDC setups (1)

FFE



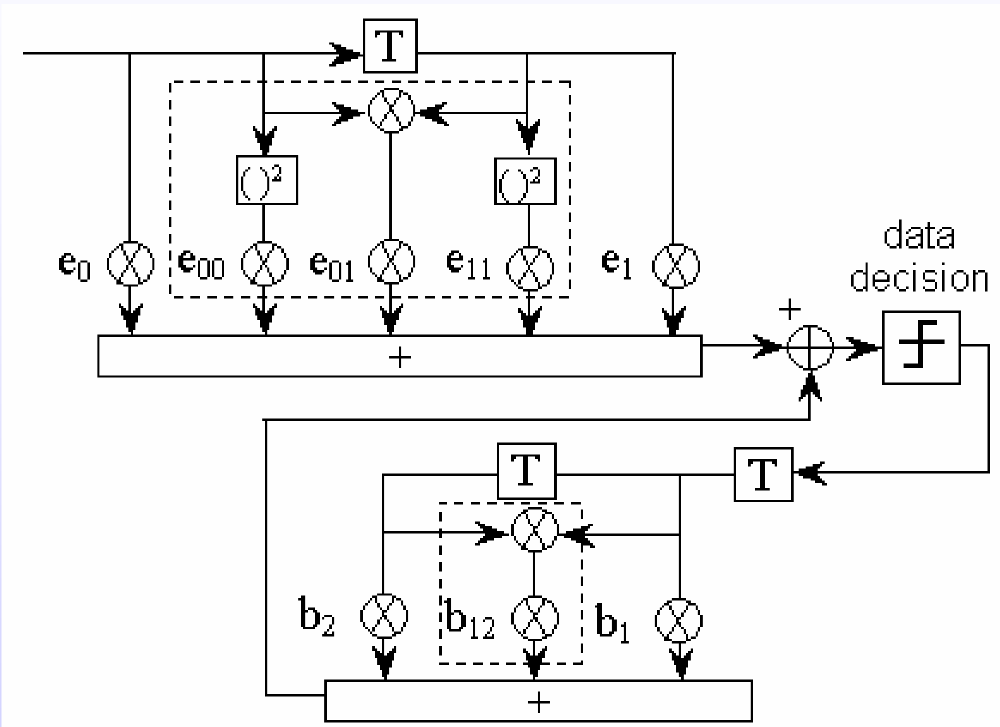
FFE-DFE



- Delay tap spacing: T (synchronous) or T/2 (fractionally spaced)
- Zero forcing equalizers → "Zero" ISI
- Equalization coefficients are adaptively optimized, based on MMSE rule.

EDC setups (2)

<u>Nonlinear-FFE-DFE</u>



Nonlinear order of FFE

Nonlinear order of DFE

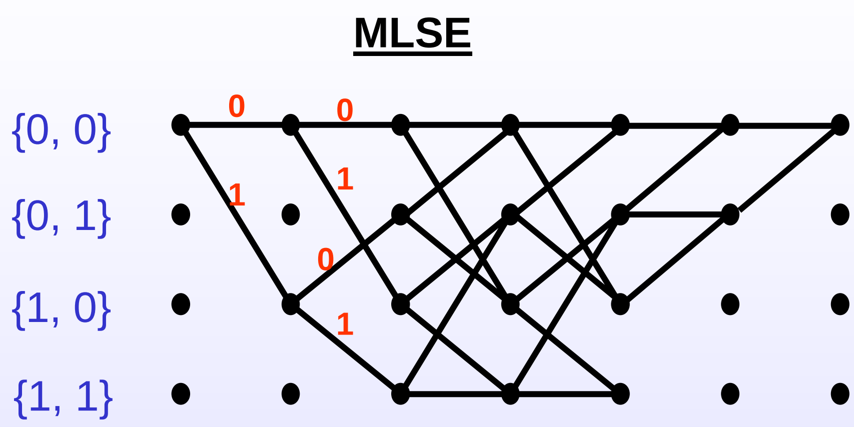
NL[2,2]-FFE[1]-DFE[2]

Order of FFE

Order of DFE

- Extended from FFE-DFE including nonlinear ISI mitigation.
- Based on Volterra theory.

EDC setups (3)



- Optimum receiver based on Viterbi algortihm
- Channel estimation (based on Lookup table method where PDF is estimated) first with training symbols.
- High speed A/D Converter required
- Memory: 2 or 3 (ISI from 2 or 3 previous bits)

Classification of Electronic Equalizers

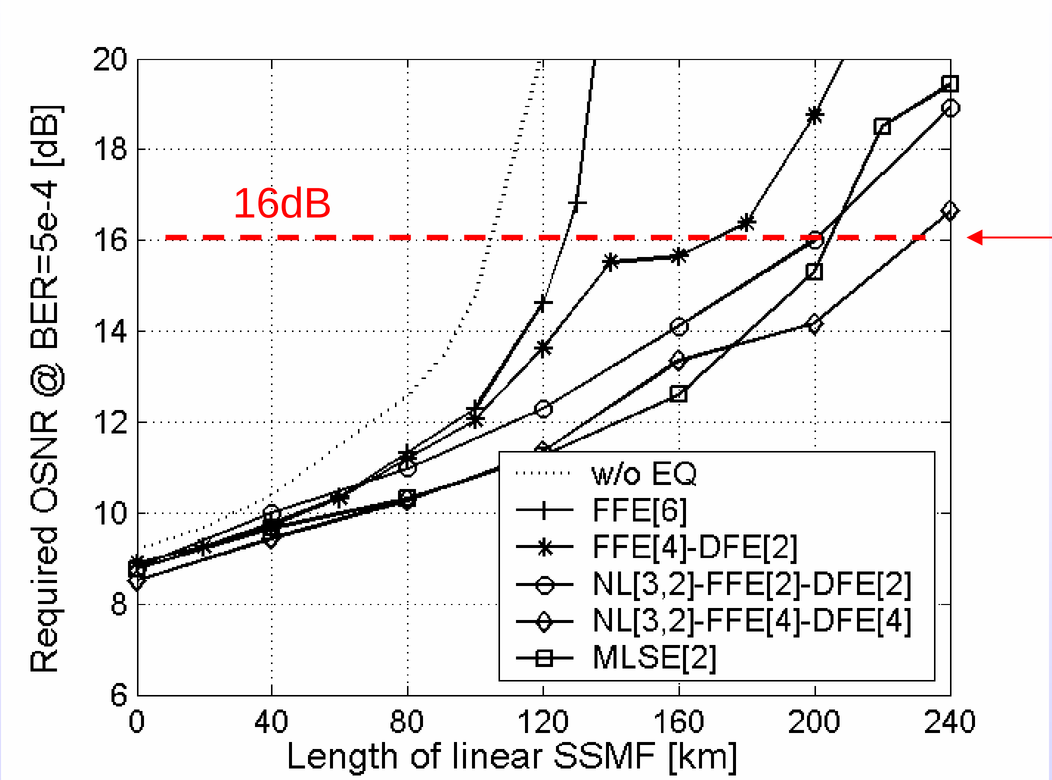
- FFE
- FFE-DFE

} Basically linear devices, Designed for linear distortions

- NL-FFE-DFE
- MLSE

} Designed for nonlinear systems

EDC on CD mitigation for OOK



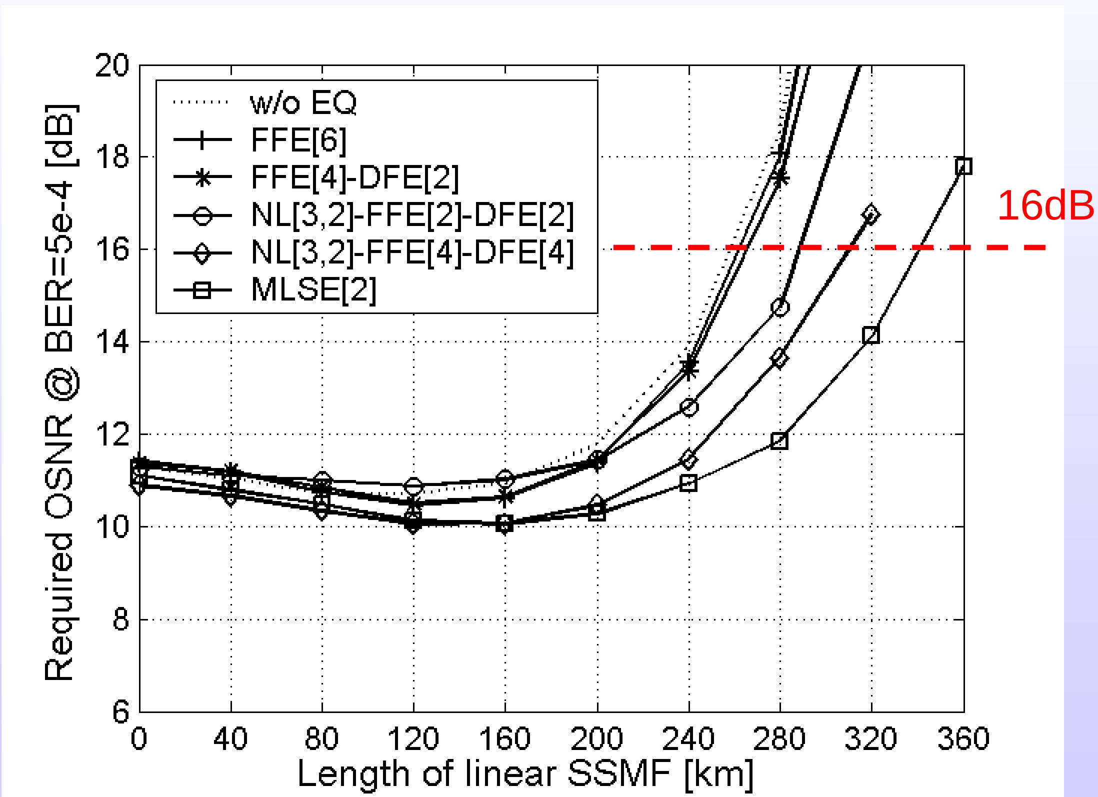
For comparison, we assume that OSNR=16dB is available

2 samples/bit, 10Gb/s

- Linear FFE[6] results in only small equalization gain (100km → 125km)!
- Nonlinear NL[3,2]-FFE[4]-DFE[4] achieve much better performance and similar performance to MLSE[2]

EDC on CD mitigation for Optical Duobinary (ODB)

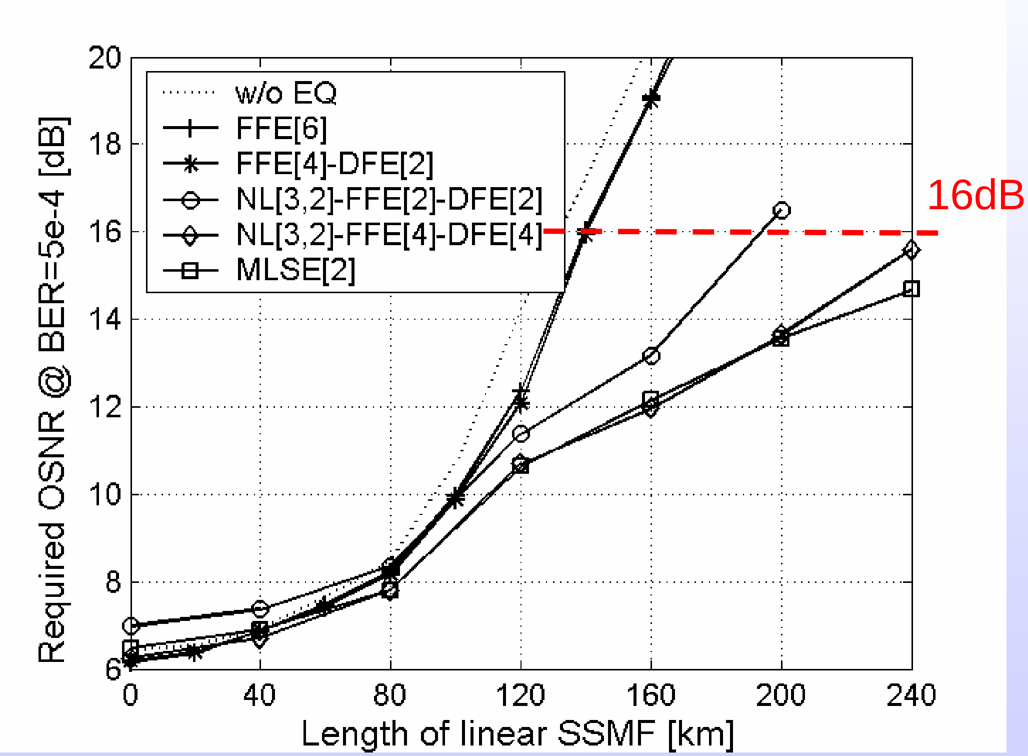
2 samples/bit, 10Gb/s



- ODB: larger dispersion tolerance, B2B penalty
- FFE and FFE-DFE nearly no performance improvement
- NL-FFE-DFE can achieve sub-optimum performance
- MLSE[2] required for better performance

EDC on CD mitigation for NRZ-DPSK

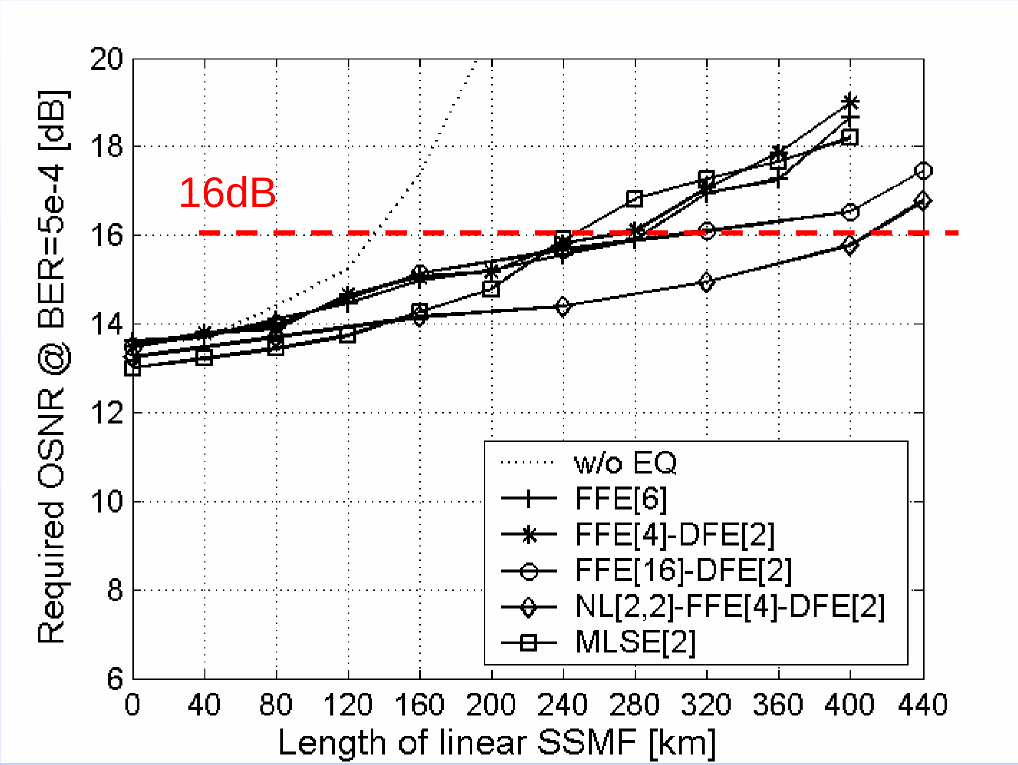
2 samples/bit, 10Gb/s



- FFE/FFE-DFE can only achieve very small performance improvement, similar to ODB!
- NL-FFE-DFE approaches MLSE

EDC on CD mitigation for Optical Single Sideband (OSSB)

2 samples/bit, 10Gb/s



- Excellent equalizer gain for all EDC
- FFE[6] can achieve the similar performance to MLSE[2], i.e. FFE alone can achieve very good compensation
- Nonlinear equalizers not required!

Why different EDC Performance for different Modulation Formats?

- Problem with electronic post-detection equalizers:

  Photo diode detects magnitude squared of complex envelope: $|z(t)|^2$

  →"envelope detection"

  Nonlinear transmission, Phase information is lost.

- But: Most Equalizers (especially FFE and FFE-DFE) are designed

  for linear transmission!

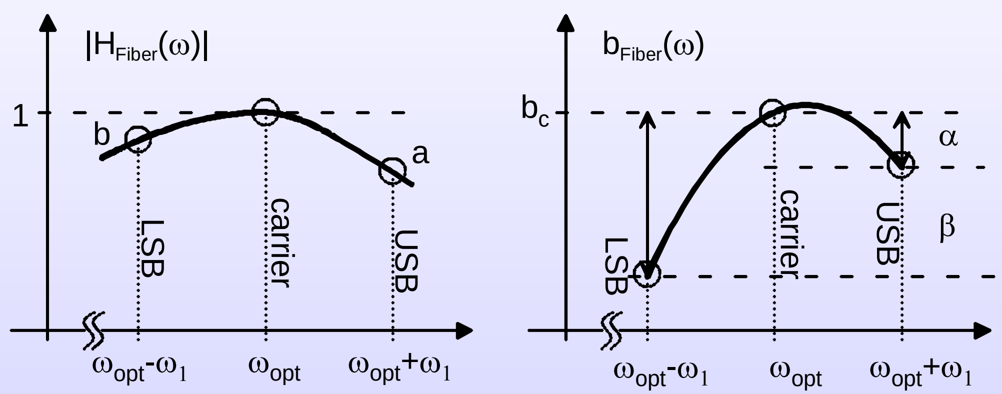
  They mitigate the linear components in the received signal only!

- Let us check for the linear components of OOK, DPSK,ODB,OSSB after "envelope detection" (direct detection)

Single Spectral Component & Dispersive Fibre

- We investigate, how a single frequency component at ω_1 of the electrical field is converted in the electrical domain, assuming a dispersive fiber and different modulation formats

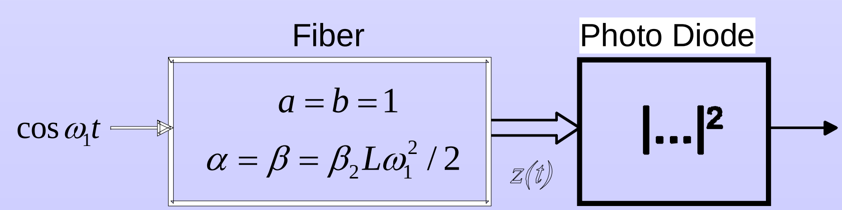
Frequency response of fiber channel



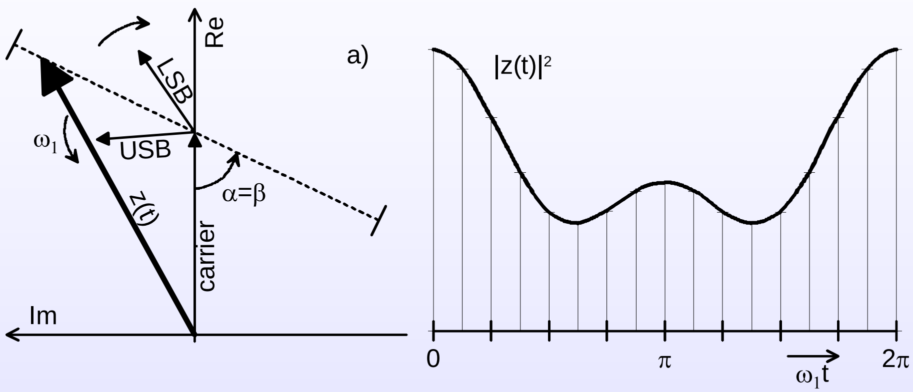
- Complex envelope of electrical field in LP domain

$$z(t) = 1 + a \cdot \frac{m}{2} \exp[j(\omega_1 t - \alpha)] + b \cdot \frac{m}{2} \exp[j(-\omega_1 t - \beta)]$$

carrier — upper SB — lower SB



OOK Direct Detection



Phasor diagram:

1. Carrier
2. Upper side band
3. Lower side band

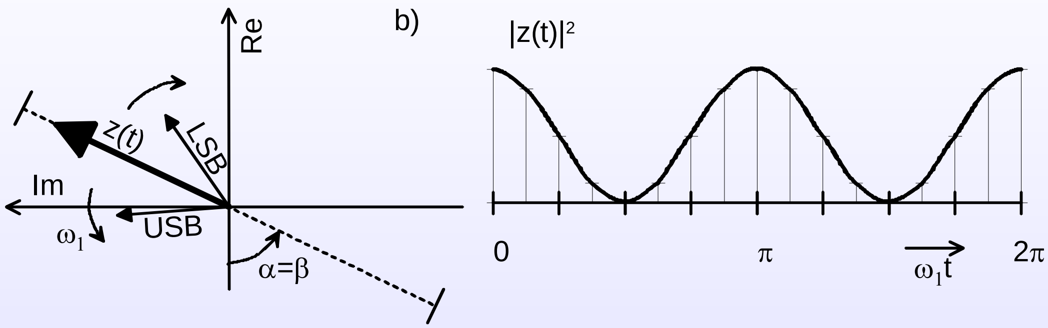
Waveform:

Linear component + Nonlinear distortions!

$$|z_{OOK}(t)|^2 = 1 + \frac{m^2}{2} + 2m\cos\alpha\cdot\cos\omega_1 t + \frac{m^2}{2}\cos 2\omega_1 t$$

DC linear distortions

DPSK, ODB Direct Detection (Carrier Suppressed)



Phasor diagram:

1. Upper side band
2. Lower side band

No carrier!

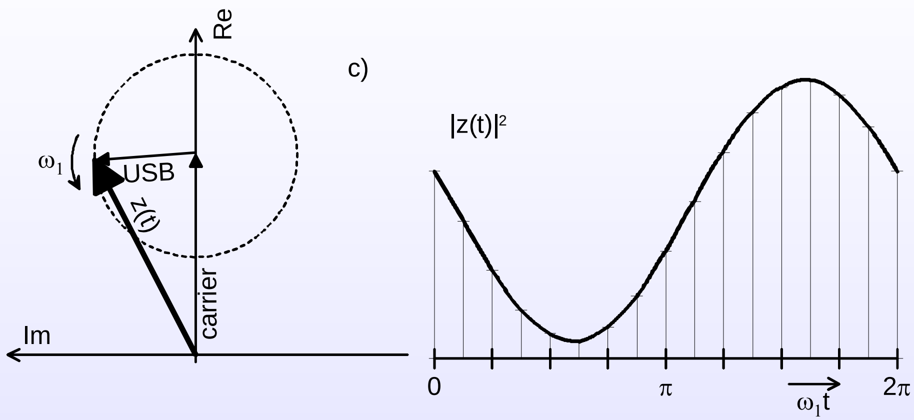
Waveform:

Only nonlinear distortions!

$$|z_{DPSK,ODB}(t)|^2 = \frac{m^2}{2}(1 \quad + \quad \cos 2\omega_1 t)$$

DC nl. distortions

OSSB Direct Detection



Phasor diagram:

1. Carrier
2. Upper side band

No lower side band

Waveform:

Linear distortions!

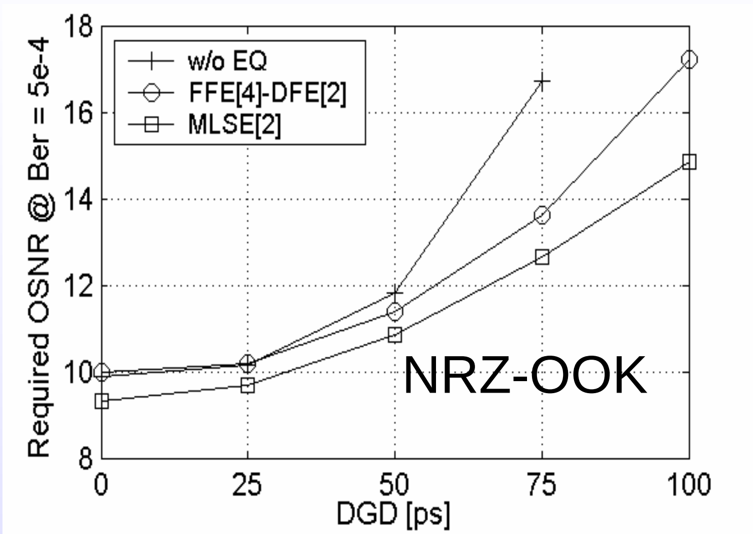
$$|z_{OSSB}(t)|^2 = 1 + \frac{m^2}{4} + m \cdot \cos(\omega_1 t - \alpha)$$

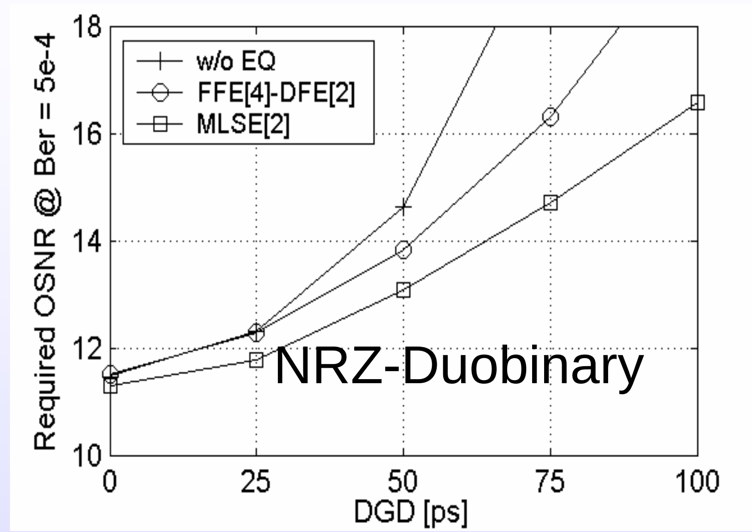
DC linear

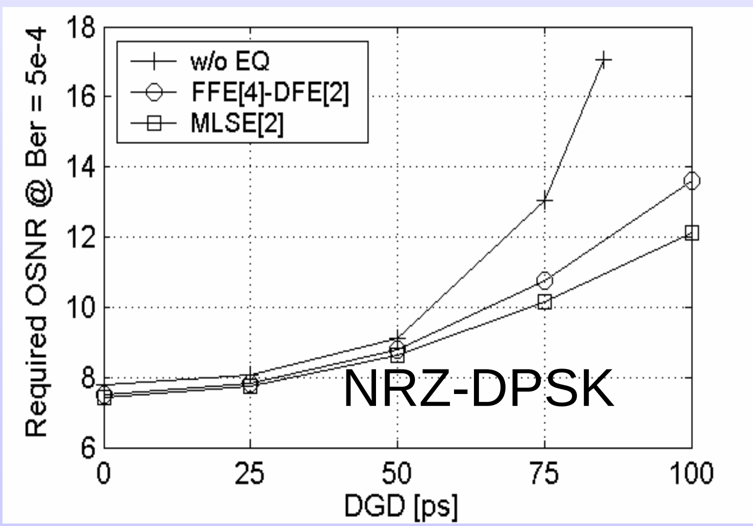
Modulation Format & EDC Performance on CD

- OOK
  - Linear component with pure amplitude frequency dependency
  - cosα amplitude frequency response
  - Nonlinear term present
  - Intermediate performance!→ nonlinear equalizer preferred!
- ODB, DPSK
  - No linear component
  - Heavily nonlinear
  - Worst performance!→ nonlinear equalizer required!
- OSSB
  - Only linear component with pure phase frequency dependency
  - Phase frequency response
  - Best performance → linear equalizer sufficient!

EDC on PMD mitigation for different modulation formats





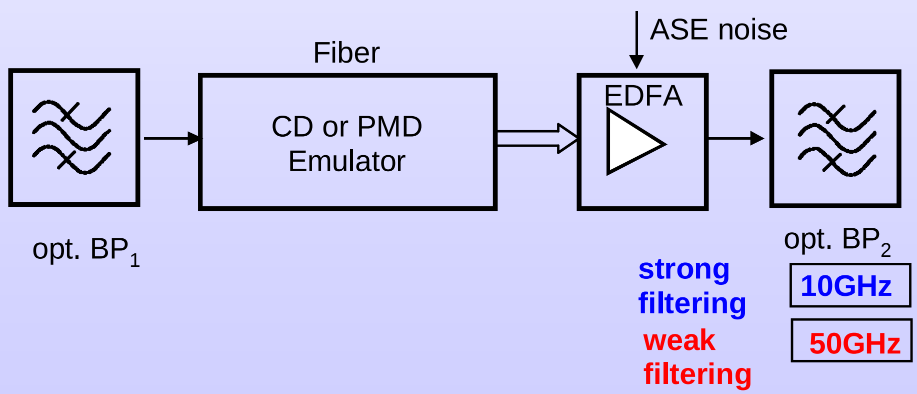


- 1st- order PMD results in <u>linear distortions</u> in the electrical domain!
- Good performance of EDC on PMD mitigation for all modulation formats

EDC for strong optical filtering

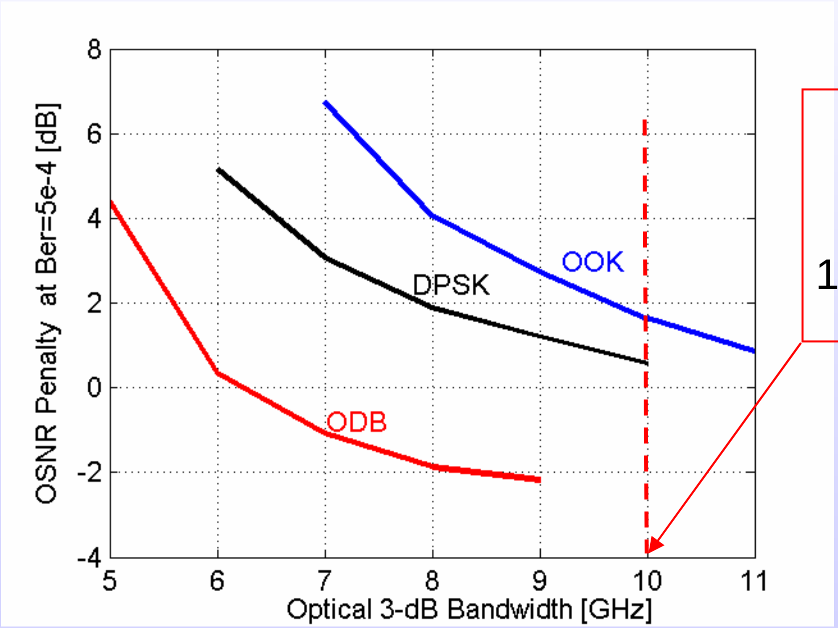
- Spectral Efficiency: reduce bandwidth by strong optical filtering (WDM-DEMUX)
- Strong (narrow-band) filtering may truncate the signal spectrum → ISI
- Mitigate this kind of ISI by Equalization

Optical Channel, 10Gb/s



Tolerance to Strong Optical Filtering

OSNR penalty introduced by strong optical filtering, data rate: 10Gb/s



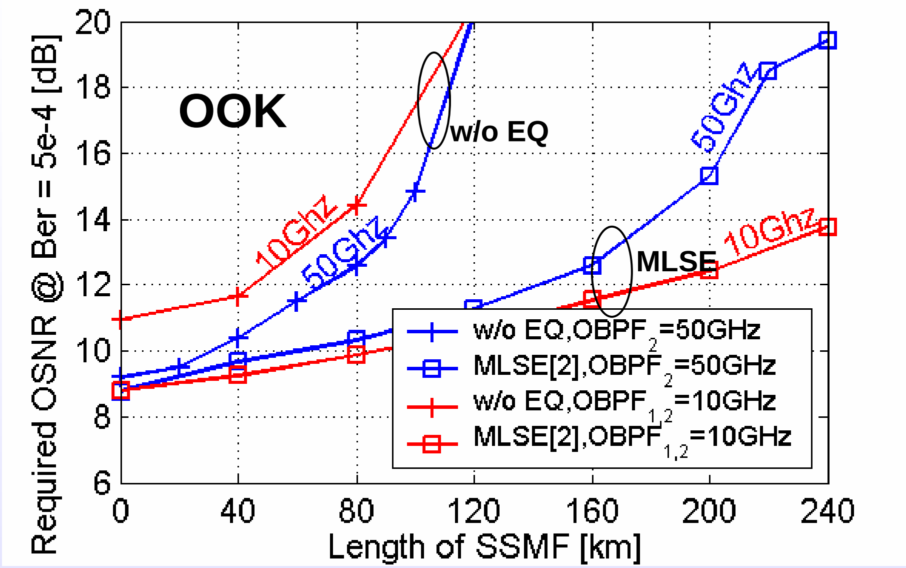
Simulation:

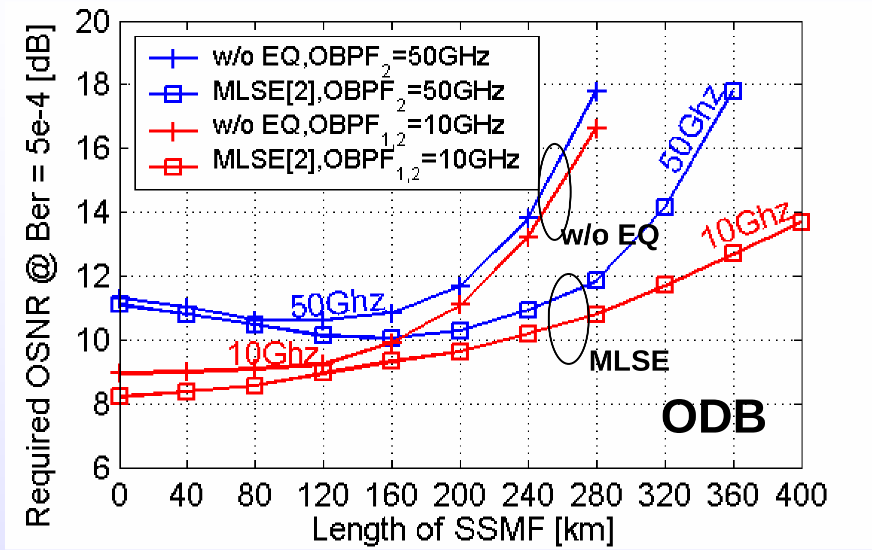
Narrow-band

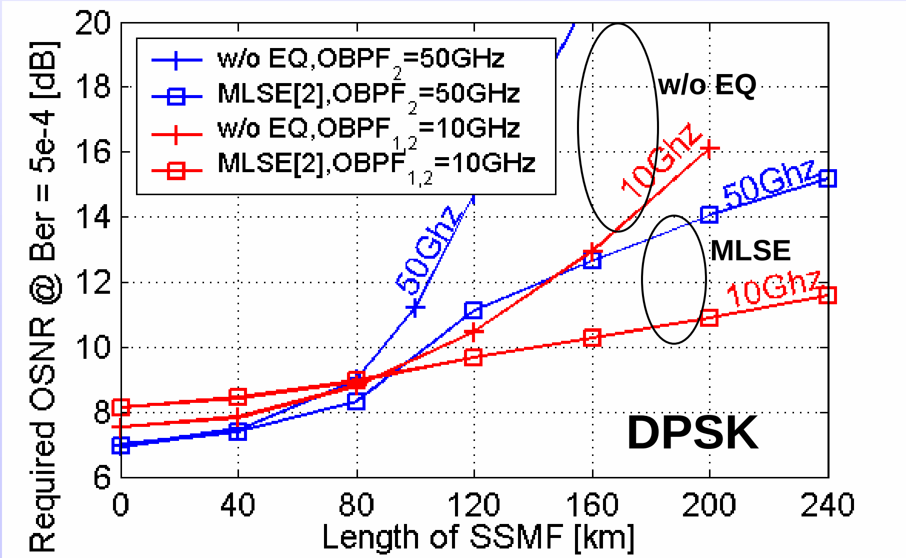
10GHz optical filter

Compare results with wide band (50GHz) filter

EDC(MLSE): CD+Strong Optical Filtering

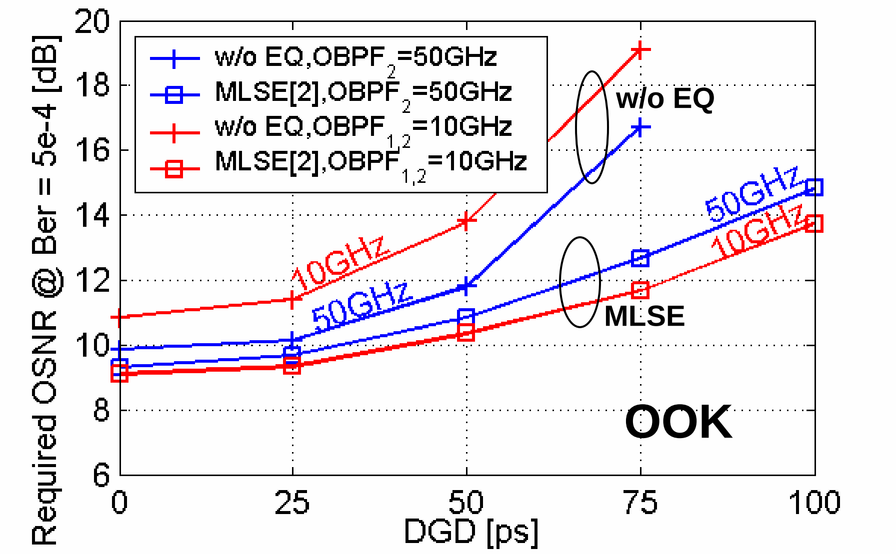


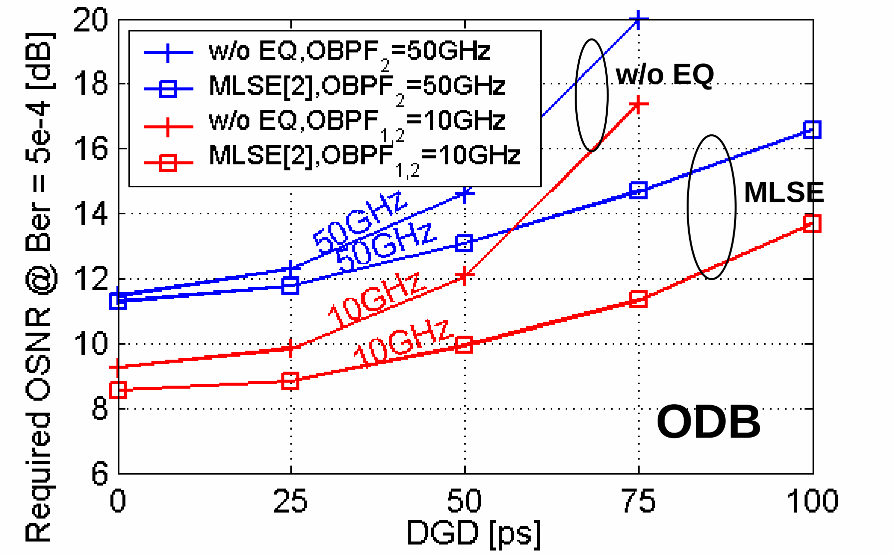


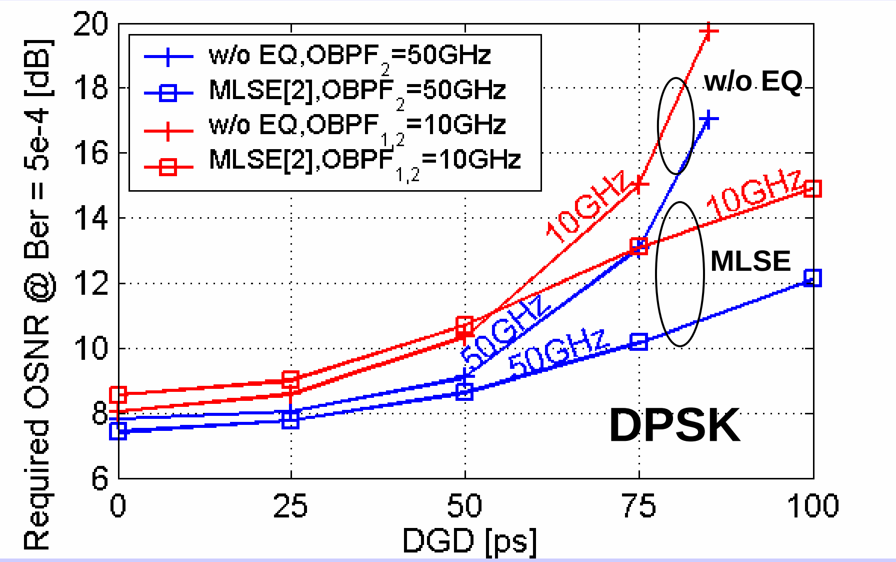


- MLSE can mitigate the distortion from both CD and strong optical filtering effectively for OOK and ODB
- DPSK robust against strong optical filtering

EDC(MLSE): PMD+Strong Optical Filtering







- MLSE can mitigate the distortion from both PMD and strong optical filtering effectively for OOK, DPSK and ODB

Conclusions: EDC

- EDC performance on CD reduced for ODB and DPSK.
- Linear equalizer alone can achieve good performance for OSSB.
- Nonlinear FFE-DFE shows nearly as good performance as MLSE.
- Good performance of EDC on PMD mitigation for all modulation formats.
- MLSE can mitigate efficiently the distortions due to strong optical filtering.

2. Forward Error Correction & Modulation Formats

- Forward Error Correction
  - FEC Block Codes
  - Convolutional Codes
  - Concatenated Block Codes
- Modulation Formats with FEC
- FEC Coding and the Influence of Dispersion
- Summary and Comments

Forward Error Correction (1)

1st Generation of Forward Error Correction Codes:

ITU-T G.975 Standard: *"Forward error correction for submarine systems"* (1996)

RS(255,239) with 6.7% overhead (OH) and ~6dB Net Coding Gain (NCG) @ 10^{-13}

2nd Generation of Forward Error Correction Codes:

Proprietary Codes: Alcatel, Vitesse, Ciena,…

Concatenated Block Codes with 12→25% OH and up to 8 dB NCG @ 10^{-13}

3rd Generation of Forward Error Correction Codes:

Turbo Product Codes: Iterative decoding, Soft-Decision
> 10% OH, and around 11 dB NCG @ 10^{-13}

Advanced FEC: Proprietary and new ITU-T G.975.1 (2004)
Around 7% OH and > 9 dB NCG @ 10^{-13}

Forward Error Correction (2)

Standard Reed-Solomon (RS) block codes

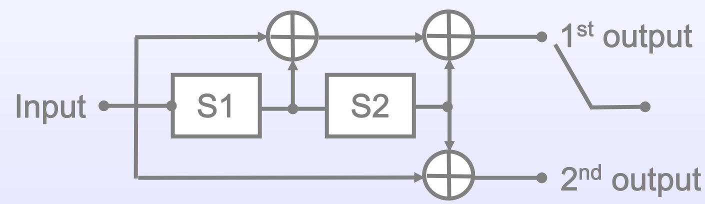
Code length	*n=255 bytes*
Message length	*k=239 bytes*
Error correcting capability	*t=(n-k)/2=8 bytes*
Code Rate	*R=n/k=0.937*

6.7% Overhead

Non-Recursive (2,1,2)-Convolutional Code

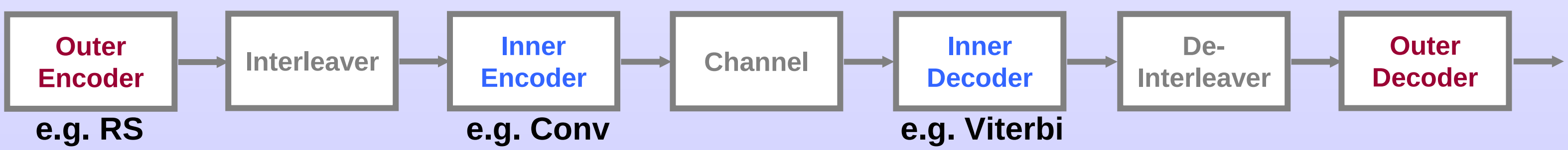
Output bits	*n=2*
Input bits	*k=1*
Memory	*m=2*
Code Rate	*R=0.5*

100% Overhead



Serial Concatenation of block and convolutional codes

- Outer RS block encoder and inner convolutional encoder



- Viterbi Decoders tend to produce short burst errors through error propagation
- RS codes are able to correct burst errors
- Interleaving can further increase burst-error correction capability

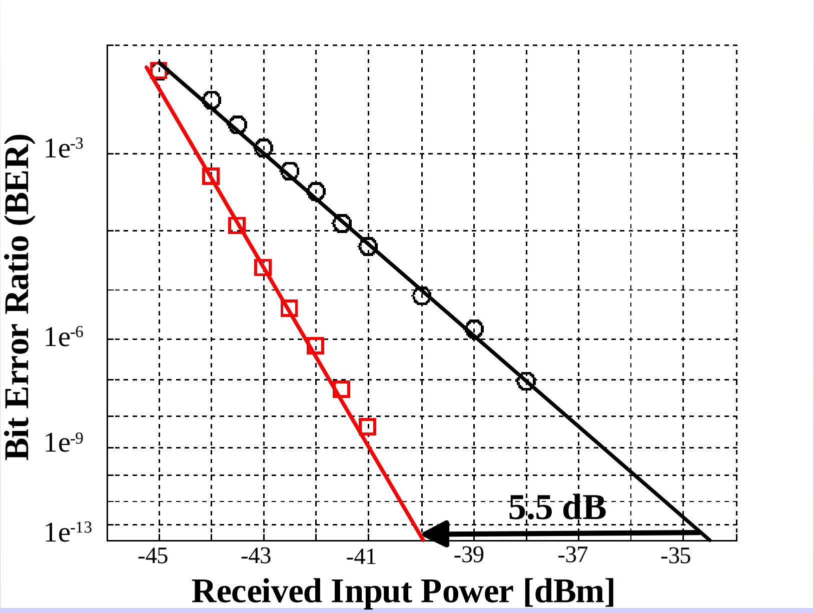
Concatenated Codes

BER Curves measured by Monte-Carlo simulation:

BER for BCH(255,239)+BCH(255,239)

13.8 % Overhead

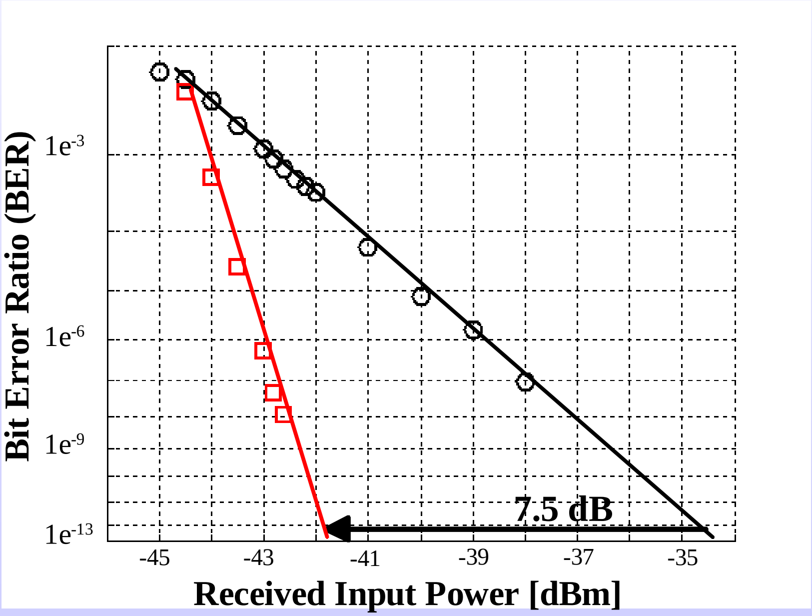
o 10 Gb/s Uncoded
□ 10 Gb/s Corrected



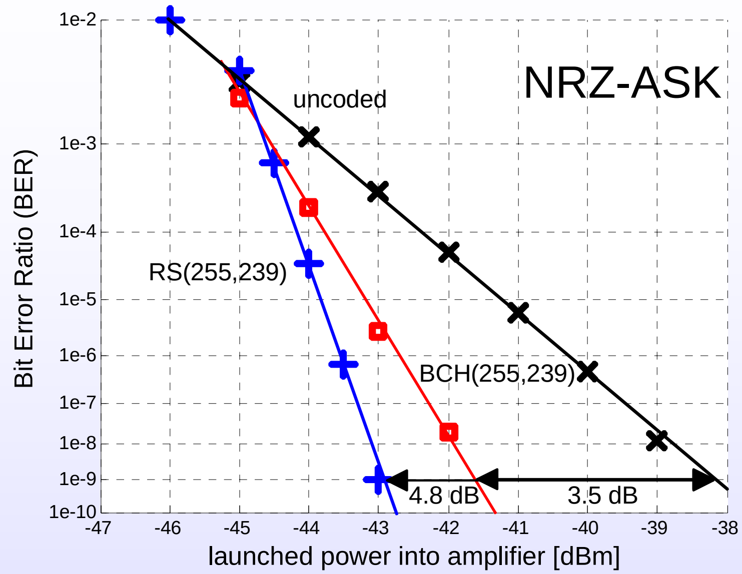
BER for RS(255,239)+RS(255,239)

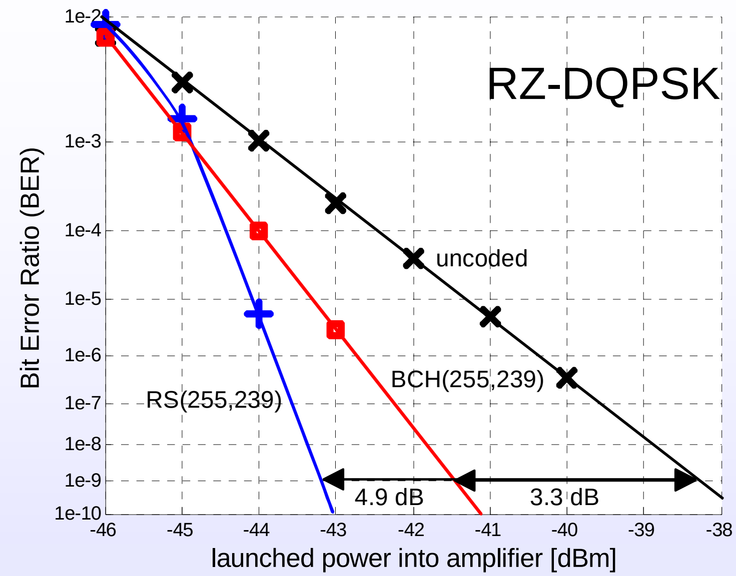
13.8 % Overhead

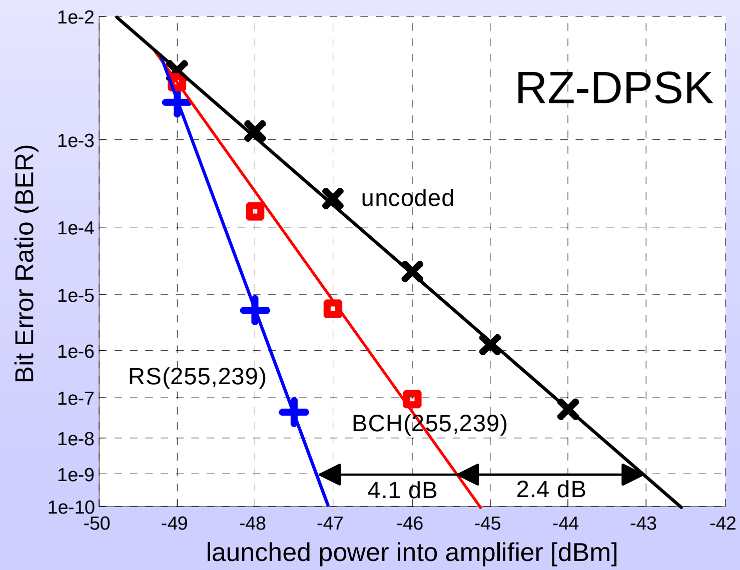
o 10 Gb/s Uncoded
□ 10 Gb/s Corrected

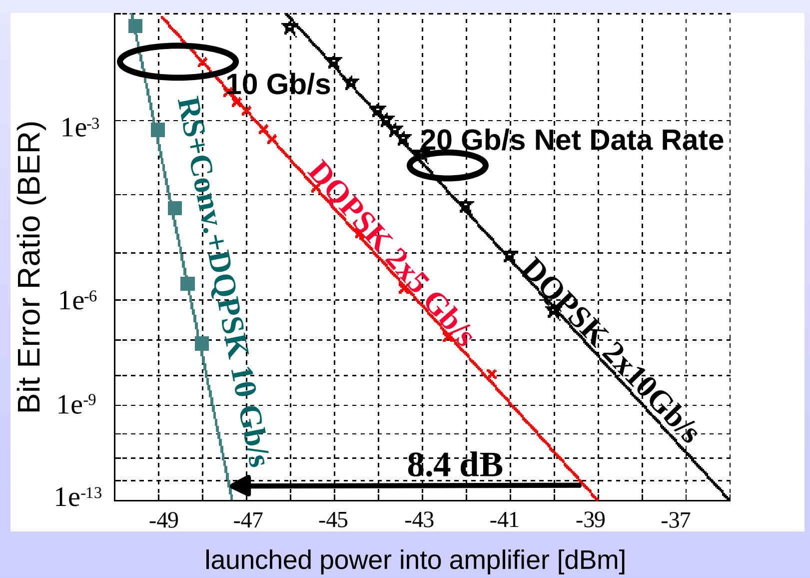


Modulation Formats with FEC

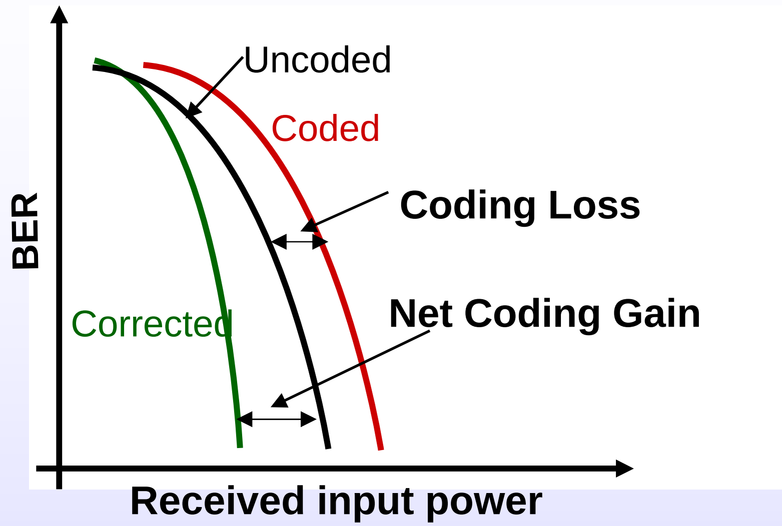








FEC Coding and the influence of Dispersion



Quadratic Phase Response

$$H(j\omega) = \exp\left(-j\left(\frac{\beta_2}{2}\omega^2\right)\cdot L\right)$$

Quadratic Influence of Frequency

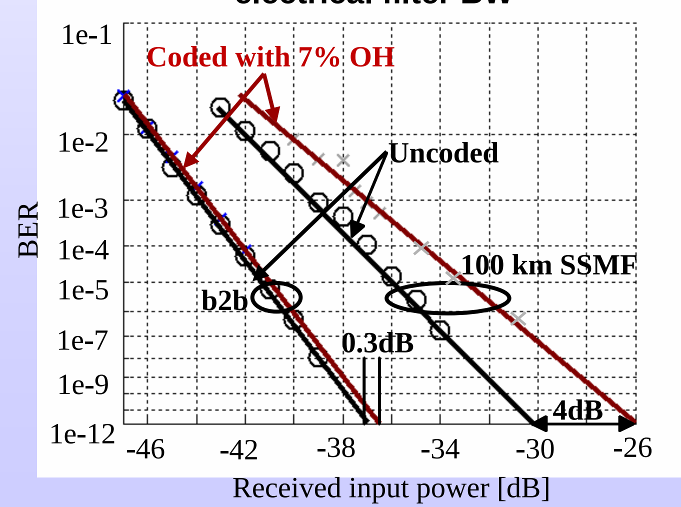
Dispersion ⟷ Overhead

How large can the Overhead be for a given Dispersion Value?

Higher Overhead

- ☺ Good Correction Capability
- ☺ Higher Net Coding Gain
- ☹ Increasing the Data Rate
- ☹ Stronger influence of Chromatic Dispersion
- ☹ Higher Coding Loss

Monte Carlo Simulation with adapted electrical filter BW

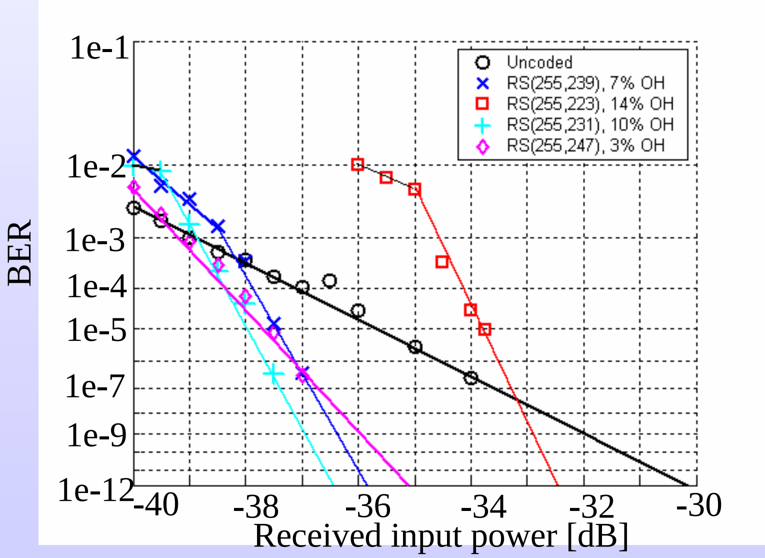


Investigation of Different Overheads in the presence of Dispersion

Various codes with Overheads from 3 to 14 %

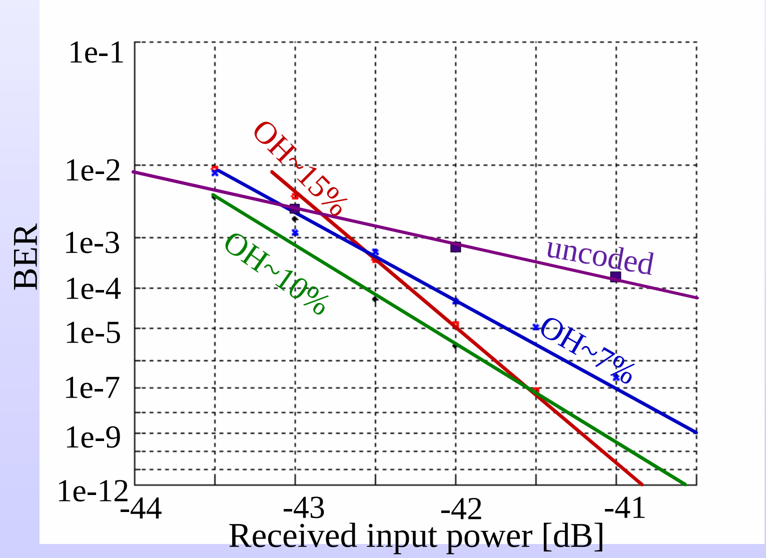
Reed-Solomon	Overhead
RS(255,247)	3.2 %
RS(255,239)	6.7 %
RS(255,231)	10.4 %
RS(255,223)	14.3 %

100 km SSMF



RS(255,231) with ~10% OH performs the best

60 km SSMF



RS(255,223) with ~15% OH performs the best

Conclusions: FEC

- FEC performance (block codes, convolutional codes, concatenated codes) evaluated by Monte Carlo simulations
- FEC performance varies between different modulation formats depending on the BER curve behaviour
- Influence of chromatic dispersion on FEC degrades performance due to OH and related coding loss

Thank You!