Introducing Spectrally Efficient Transmission over DWDM Optical Networks: Impact on Subsystems

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Outline

- Introduction: Modulation Formats
- Performance of Spectrally Efficient Modulation Formats
- Transceiver Design for DQPSK
- Upgrading DWDM Networks with Advanced Modulation Formats
- Performance of Electronic Equalizers for Different Modulation Formats
- Combining FEC and Modulation Formats

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: 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**

Spectrally Efficient Transmission: Impact on Subsystems

- Use alternative Modulation formats
- Impact of these new modulation formats on:
  - Robustness towards channel impairments
  - Upgrading existing DWDM systems
  - Equalizer Design
  - FEC performance

Modulation Formats: Some Options

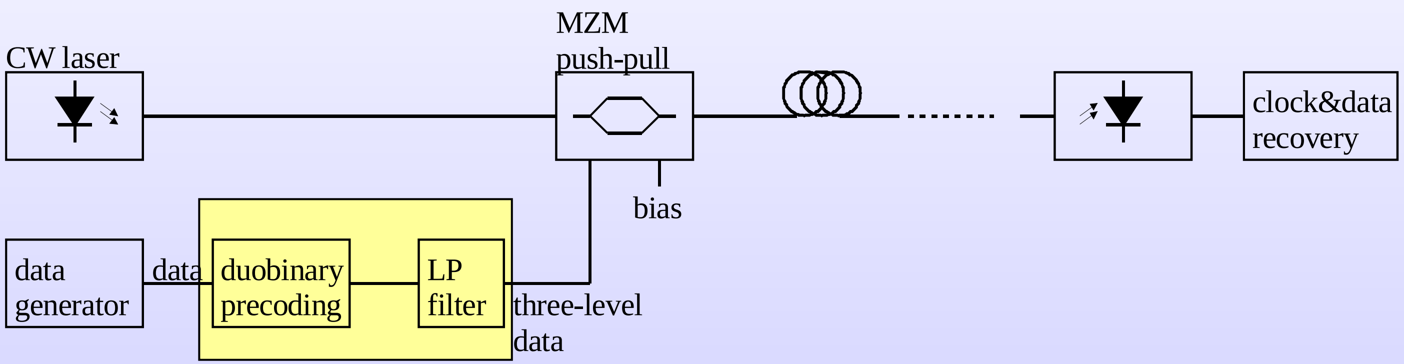
- Amplitude
  - RZ/NRZ (2-ASK with different pulse shape)
  - VSB/SSB
  - Multilevel (4-ASK, 8-ASK)
- Phase
  - DPSK
  - DQPSK
  - Multilevel PSK
- Frequency
  - MSK/FSK = minimum shift keying/ frequency shift keying
- Hybrid
  - CS-RZ, chirped RZ/NRZ, partial response (e.g. duobinary)
  - ASK-DPSK
  - QAM
  - Multiring-QPSK

Innovative Formats: Duobinary Signaling

- ✓ Reduced bandwidth (approx. Factor of 2 against NRZ)
- ✓ Highly dispersion tolerant → increase uncompensated transmission reach
- ✓ Increased spectral efficiency
- ✓ Carrier suppressed format: relaxed SBS suppression requirements
- ✓ Low implementation complexity → upgrade of conventional IM/DD possible
- \- Reduced back-to-back performance

Duobinary Signaling - Implementation

- Duobinary precoder = differential encoder → IC-solution
- Duobinary filter: LP with cut-off frequency of $f_b/4$



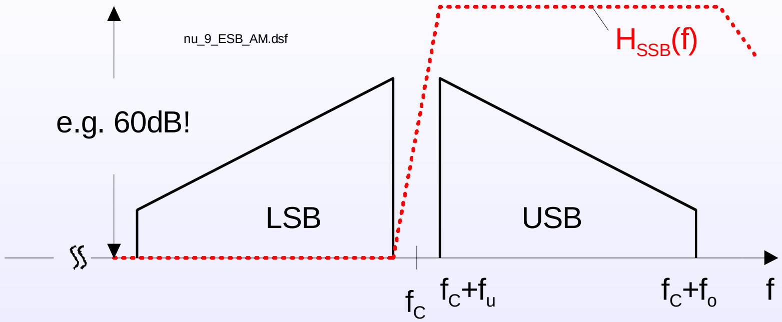
Duobinary Encoding

Innovative Formats: SSB/VSB

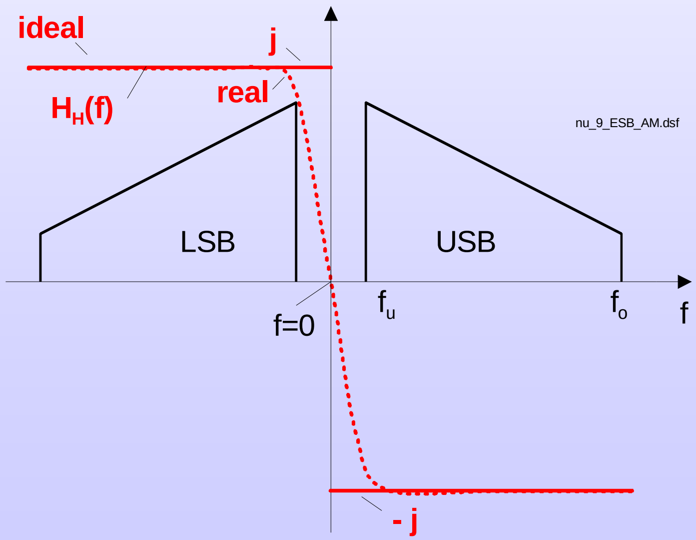
- ✓ Single Side Band (SSB) or Vestigial Side Band (VSB)
- ✓ Reduced bandwidth (approx. factor 2) →Highly dispersion tolerant →Increased spectral efficiency
- \- Medium to high implementation complexity
- \- For direct detection: carrier required →Extinction ratio problems! → reduced receiver sensitivity

SSB/VSB – Sideband Suppression

- Optical SSB/VSB filter
- Filtering in **optical** (band-pass) domain

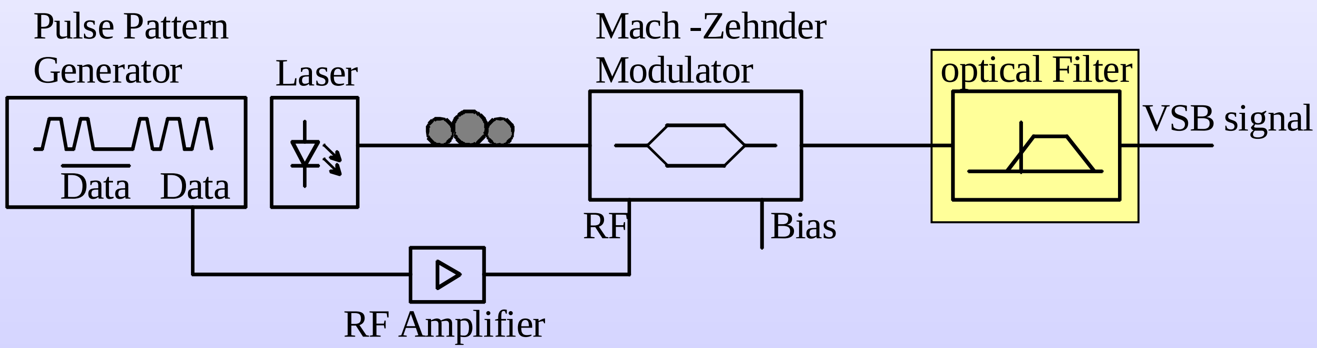


- Hilbert Transformer = Phase response Filter
- Filtering in **electrical** (base-band) domain



SSB/VSB – Implementation: Optical Filter

- Optical filtering of conventional IM (DSB) signal
- Steep filter slope required



Binary Differential PSK (D-2-PSK)

- ✓ Symbols: +1, -1, NRZ or RZ pulse shape possible
  - ✓RZ: → advantage in XPM environment
- ✓ Improved noise performance vs. conventional IM/DD , if balanced receiver used (3dB)
- ✓ Differential scheme → avoids coherent detection
- \- Differential scheme → noise penalty: 0.2dB (binary), 2dB (quaternary)
- \- Additional DPSK receiver (MZDI) necessary & Differential precoder necessary!

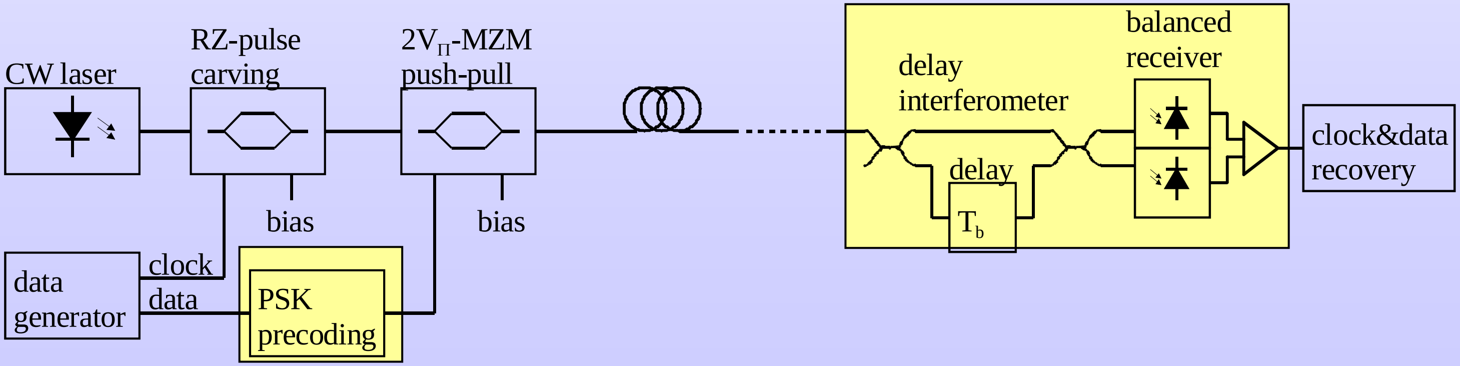
Binary DPSK

- DPSK precoder = differential encoder (same as for duobinary)
- Functionality of MZDI receiver. Phase $\phi(k) \in \{0, \pi\}$

$$\left[\cos(\omega_c t + \phi(k)) + \cos(\omega_c t - \alpha + \phi(k-1))\right]^2 = \underbrace{\ldots + 2\cos(\ldots)\cdot\cos(\ldots) + \ldots}_{\cos\left[\phi(k) - \phi(k-1) - \underbrace{\alpha}_{=0}\right]}$$

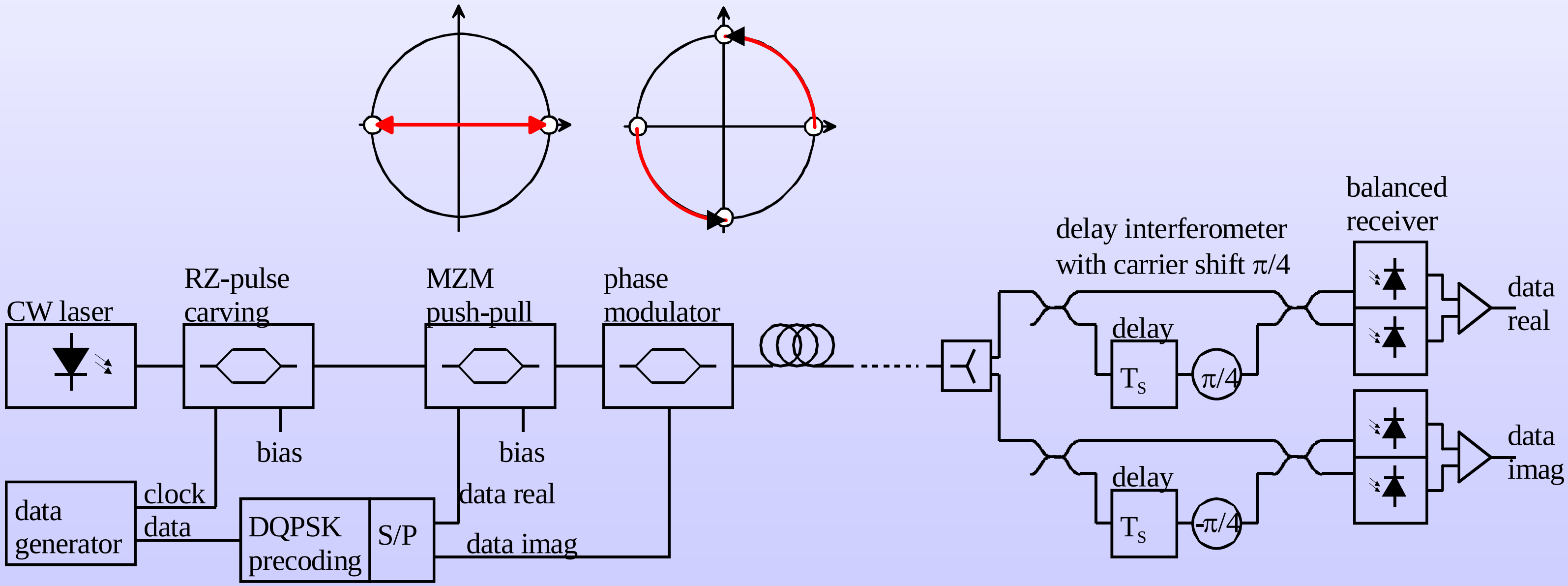
"High" if $\phi(k) = \phi(k\text{-}1)$,

"Low" if $\phi(k) \neq \phi(k\text{-}1)$



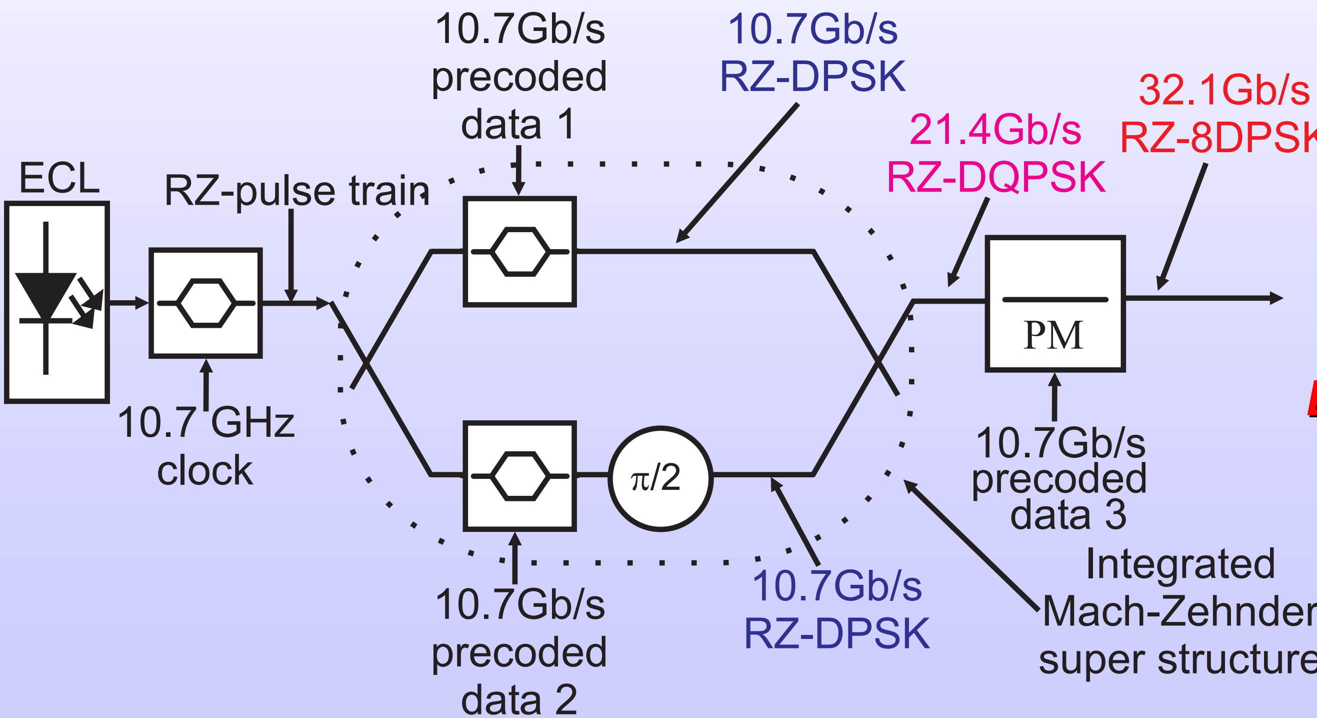
Quaternary DPSK (DQPSK)

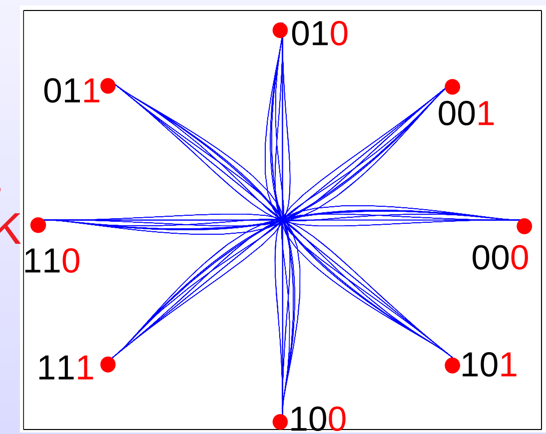
- Our solution: serial DQPSK-transmitter → reduced complexity, relaxed phase control
- 2 parallel data streams (real & imaginary) with speed and bandwidth requirements of single data stream!
- Quaternary differential precoder required



Eight level RZ-DPSK (RZ-8DPSK)

- Upgrade from parallel RZ-DQPSK to RZ-8DPSK by cascaded phase modulator
- Driving amplitude of the phase modulator corresponds to ¼Vπ
- No additional control loop required !
- Considering 7% FEC overhead





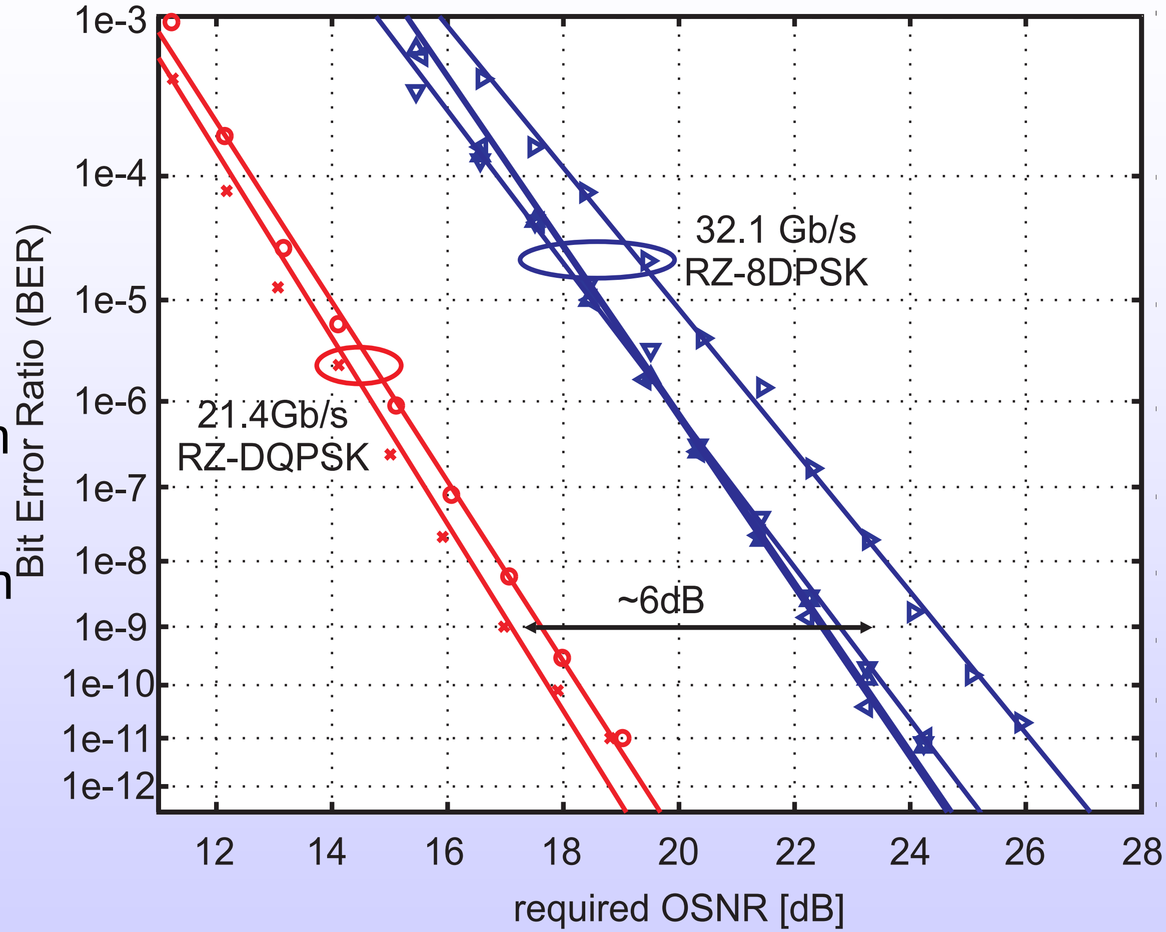
Eight possible symbols i.e. 3 bits per symbol →Data-rate increase by 50% at same spectral width!

8-DPSK Experimental Results: OSNR-requirements

OSNR Requirements at 1e-9:

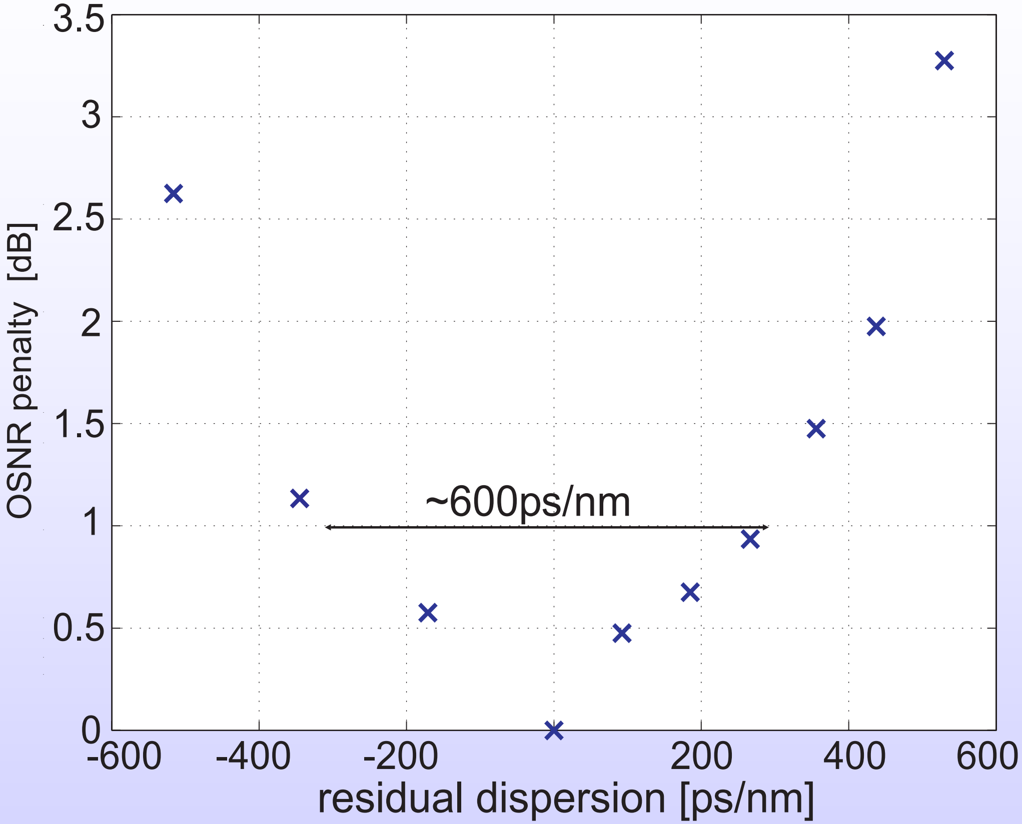
- RZ-DQPSK: 17.7dB
- RZ-8DPSK: 24.4 dB

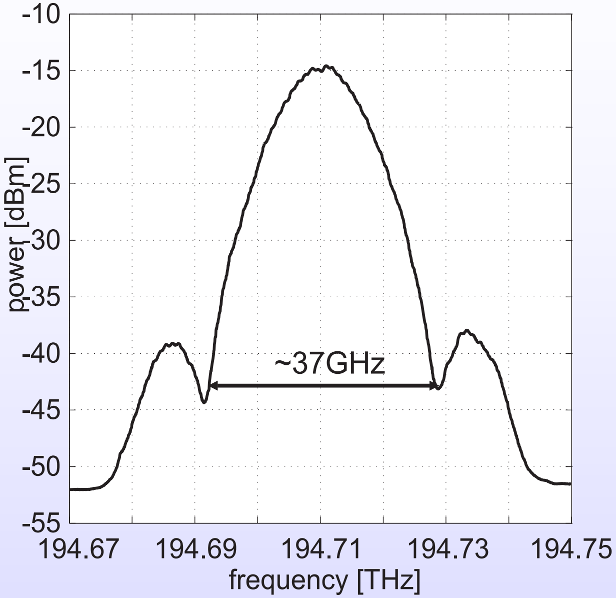
→At most 6.7dB penalty due to narrower distance between adjacent symbols in the complex plane in combination with incoherent detection.



- Difference between tributaries due to imperfect receiver implementation

Measured dispersion tolerance



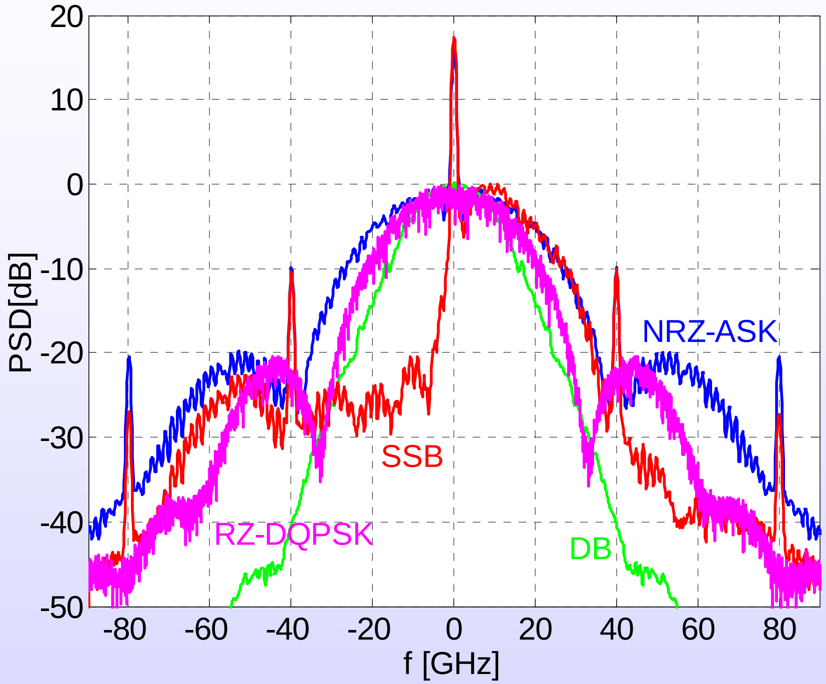


Narrow spectral width of 37GHz for 32.1Gb/s

- Measured dispersion tolerance of 600ps/nm at 32.1 Gb/s.
- Equivalent to 35km SSMF

Modulation Formats in WDM Transmission

- Power Spectral Density of various modulation formats at 40Gb/s
- DB,SSB,RZ-DQPSK suitable for 0.8b/s/HZ i.e. 50GHZ channel spacing

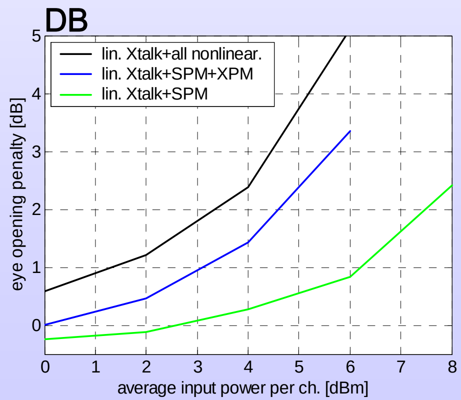


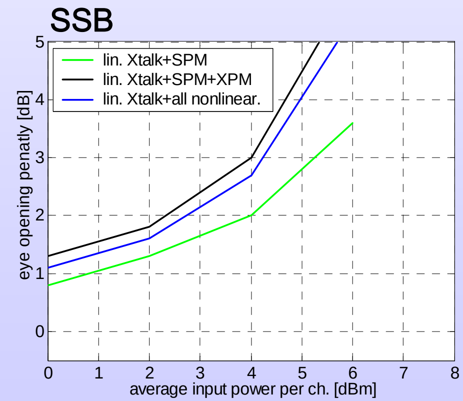
	SSB	DB	RZ-DQPSK	NRZ-ASK
Δf [GHz]	40	48	56	70

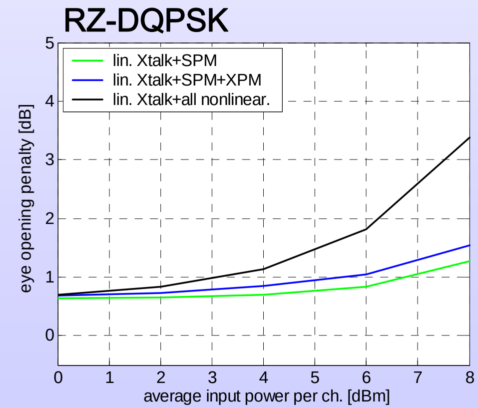
Two-sided spectral width for a decay of 20dB at 40Gb/s data rate

Narrowband Modulation Formats in WDM: Intermodulation

	Linear cross-talk	SPM	XPM	FWM
DB	☺		☹	
SSB		☹		☺
RZ-DQPSK		☺	☺	☹







Sensitivity to nonlinear fibre effects, SSMF, 40Gb/s, Δf=50GHz, 0.8b/s/Hz

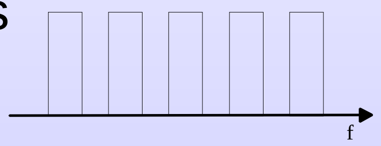
Conclusions: Performance vs. Complexity

- Duobinary: low complexity, high benefit through spectral narrowing → promising candidate for system upgrade now!
- SSB/VSB: solution with optical filtering → moderate system improvement for reasonable additional complexity
- DPSK: medium complexity → high benefit through improved receiver sensitivity and WDM intermodulation robustness
- DQPSK: medium to high complexity → but doubles channel capacity
- Other advanced formats: (MSK, CPM, M-PSK, M-QAM) worth investigating in optical environment! → constraints: complexity and chirp!

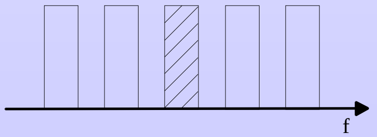
Upgrading DWDM Networks with advanced Modulation Formats

Upgrade Scenario: Individual channels(groups) with advanced modulation formats coexist with "old" NRZ-ASK channels

- WDM Network with uniformly modulated channels RZ-DPSK, RZ-DQPSK, NRZ-ASK (uniform system)



- WDM Network with NRZ-ASK and individual channels upgraded with RZ-DPSK and RZ-DQPSK (mixed system!)



Investigations

Robustness of Modulation format

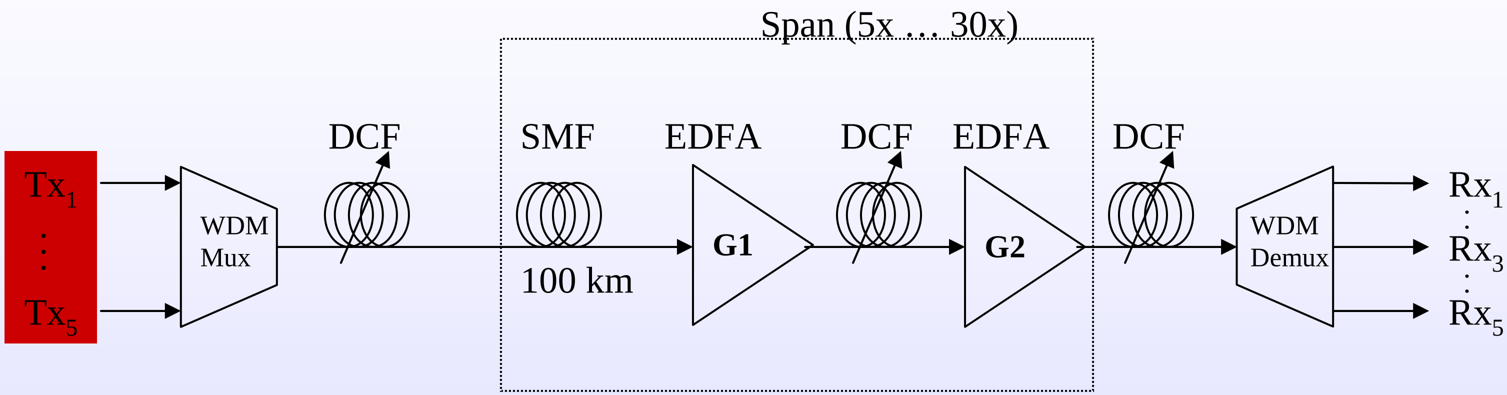
→ **Dispersion tolerance**

- Variation of Parameters:
  - Power
  - Transmission Distance
  - Pre compensation
  - In-line compensation
  - Post compensation

- Compute Eye Opening Penalty (EOP)

- Dispersion tolerance as a function of pre- and inline-compensation

Simulation set-up

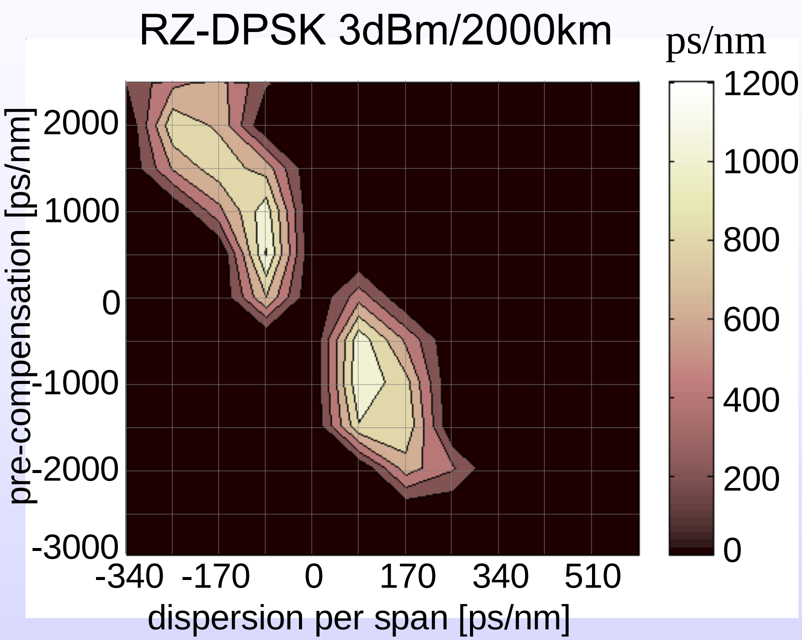


Mixed WDM-System:

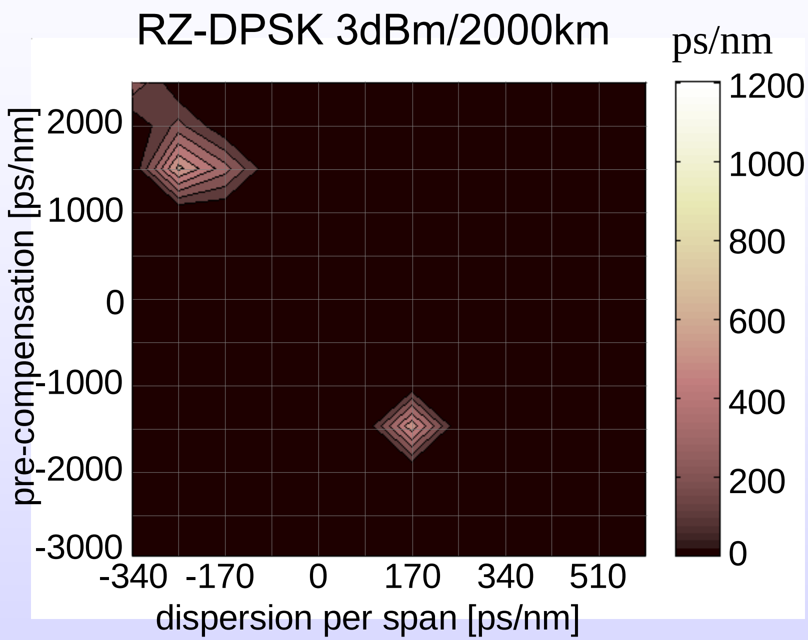
- One channel RZ-DQPSK or RZ-DPSK
- All other channels NRZ-ASK

Results for RZ-DPSK

uniform WDM-System:



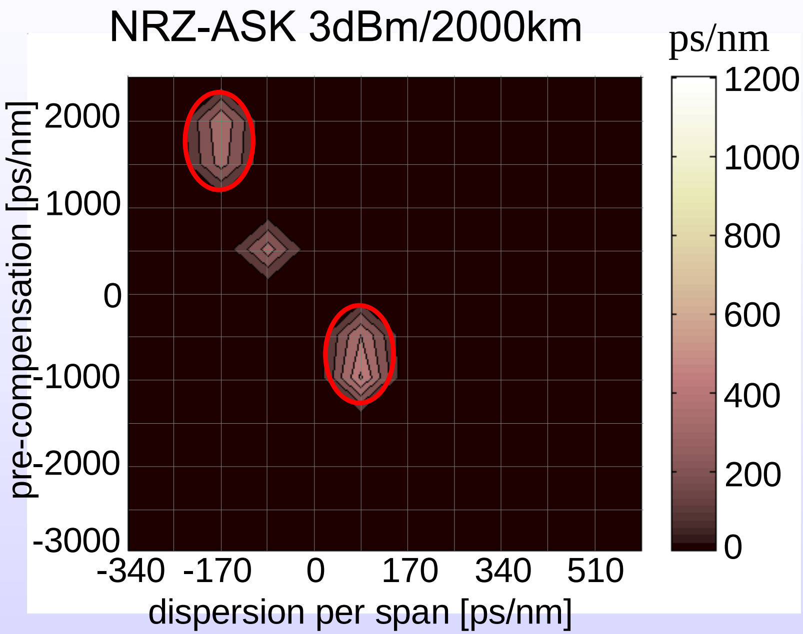
mixed WDM-System:



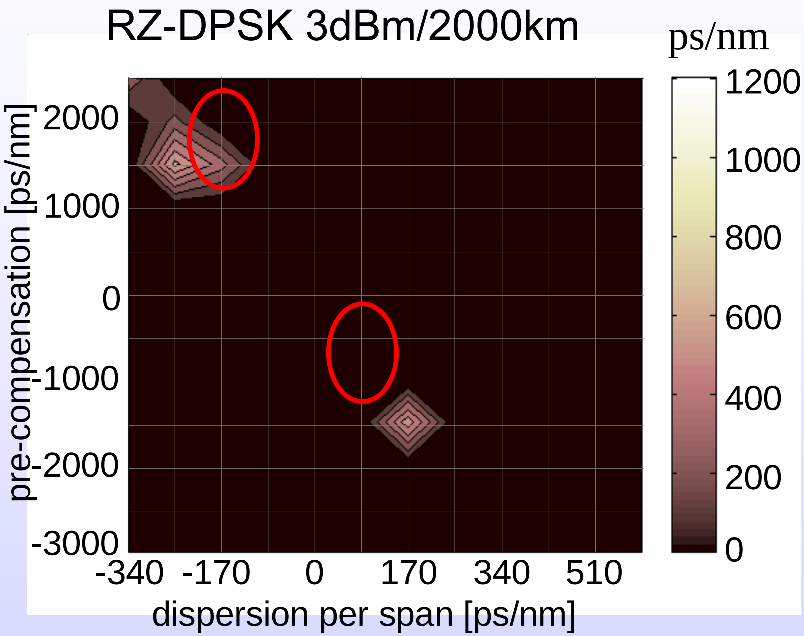
- Mixed WDM system: RZ-DPSK exhibits reduced dispersion tolerance

Results for RZ-DPSK

Uniform "old" WDM-System:



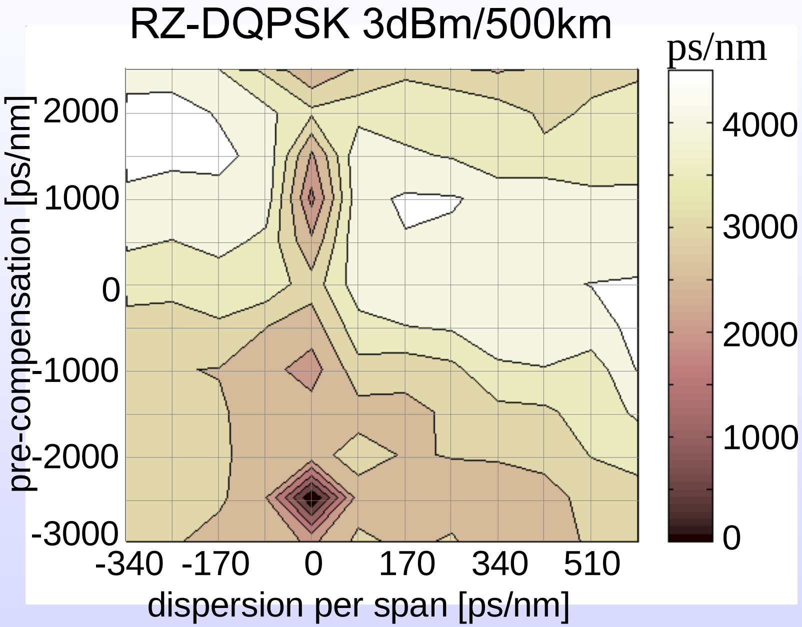
Mixed "upgraded" WDM-System:



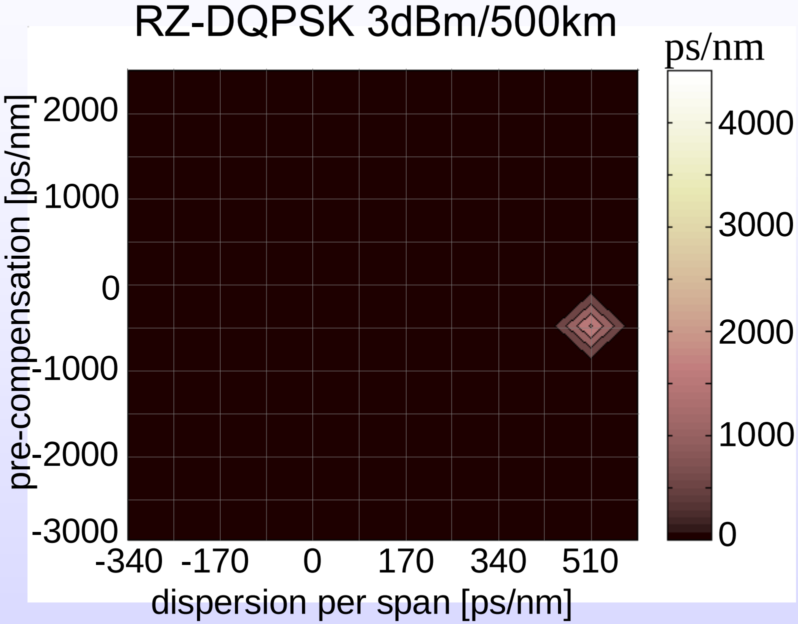
- Optimized Dispersion map for NRZ-ASK is sub-optimum for RZ-DPSK

Results for RZ-DQPSK

uniform WDM-System:



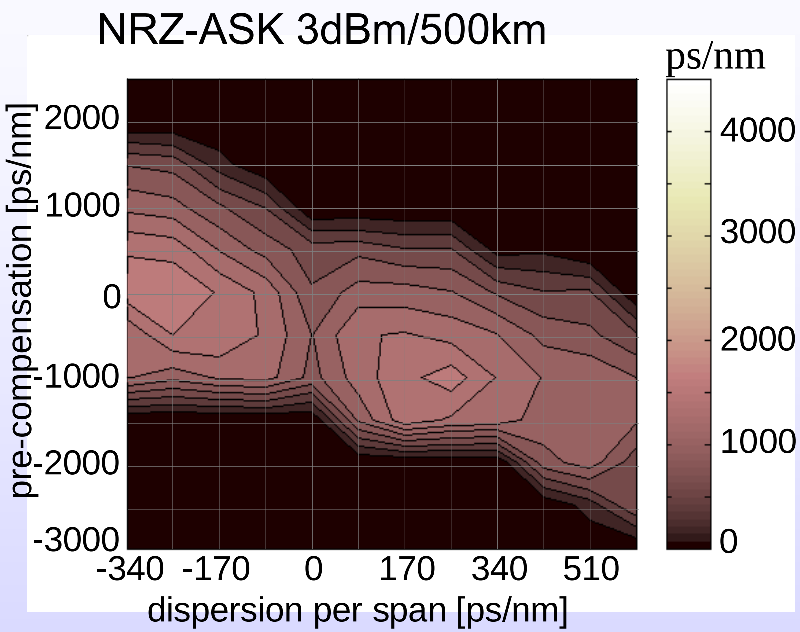
mixed WDM-System:



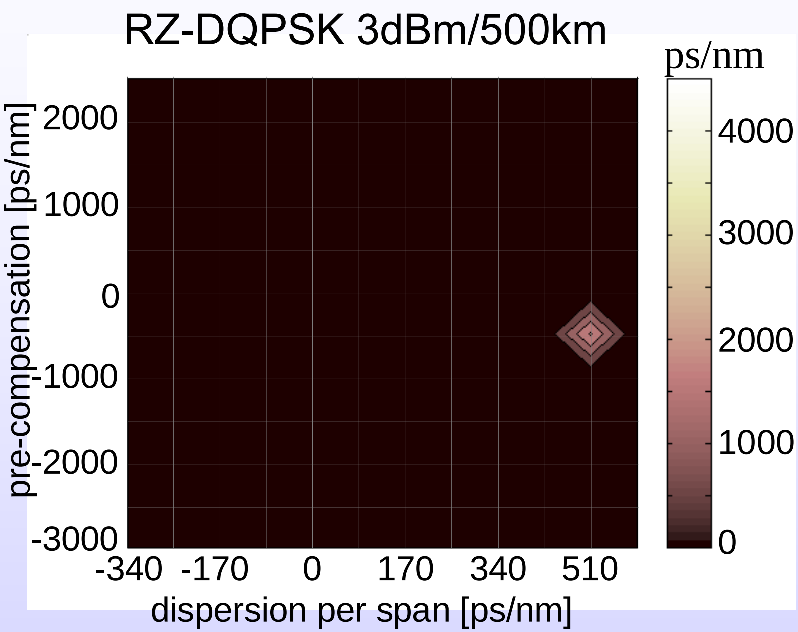
- Mixed WDM system: RZ-DQPSK exhibits strongly reduced dispersion tolerance

Results for RZ-DQPSK

uniform WDM-System:



mixed WDM-System:



- Optimized Dispersion map for NRZ-ASK is not suitable for RZ-DQPSK

Conclusions: Upgrading DWDM

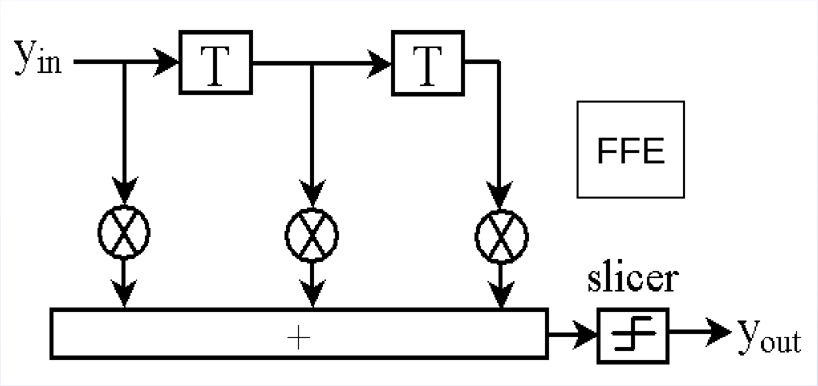
- In NRZ-ASK mixed modulated WDM-Systems strong degradation of RZ-DPSK and RZ-DQPSK
- RZ-DQPSK is degraded more than RZ-DPSK
- Transmission of RZ-DPSK and RZ-DQPSK in a mixed modulated NRZ-ASK WDM-System requires adaptation of Dispersion scheme

Electronic Equalizers (EDC) & Modulation Formats

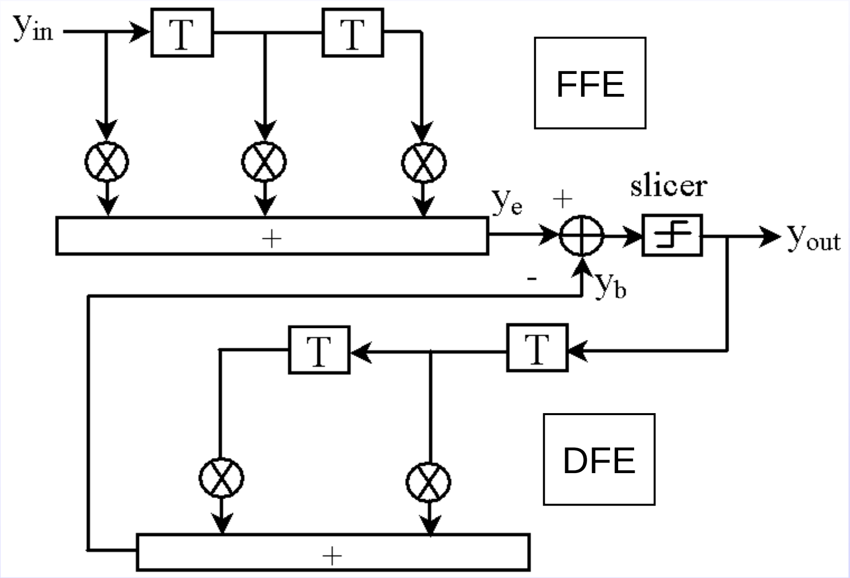
- Introduction of different EDC setups
- EDC on CD and PMD mitigation for advanced modulation formats
    - Optical duobinary modulation (ODB)
    - Differential-phase-shift-keyed (DPSK)
    - Optical single side band modulation (OSSB)
- Conclusions

EDC setups (1)

FFE



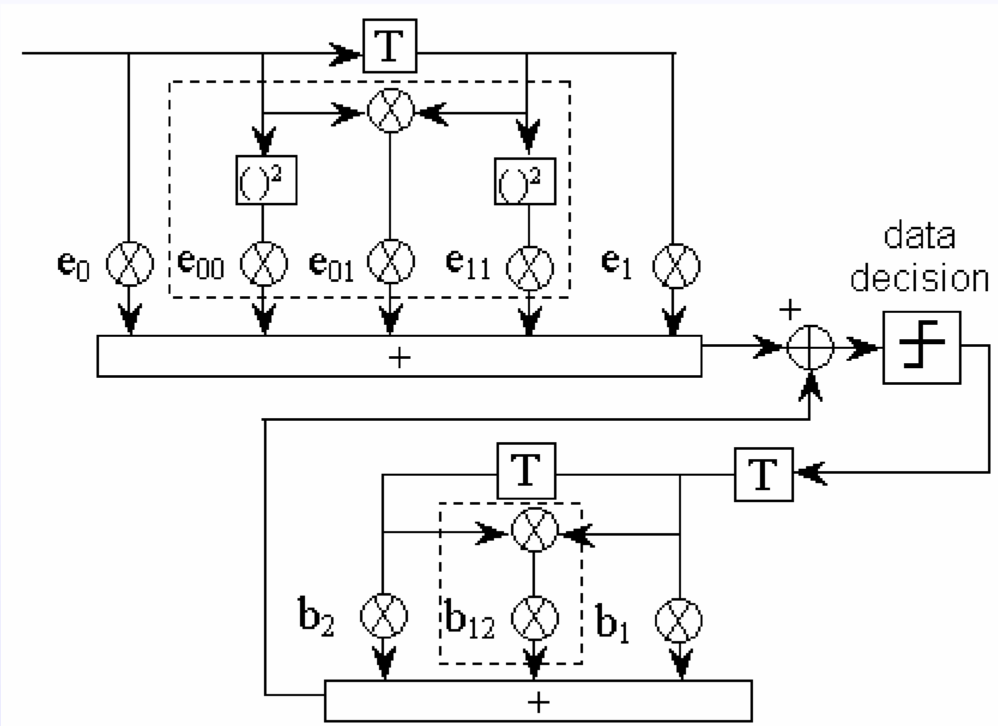
FFE-DFE



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

EDC setups (2)

Nonlinear-FFE-DFE



Nonlinear order of FFE

Nonlinear order of DFE

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

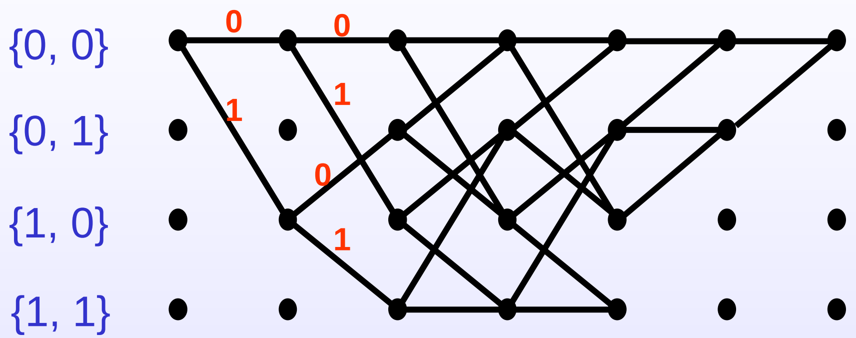
Order of FFE

Order of DFE

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

EDC setups (3)

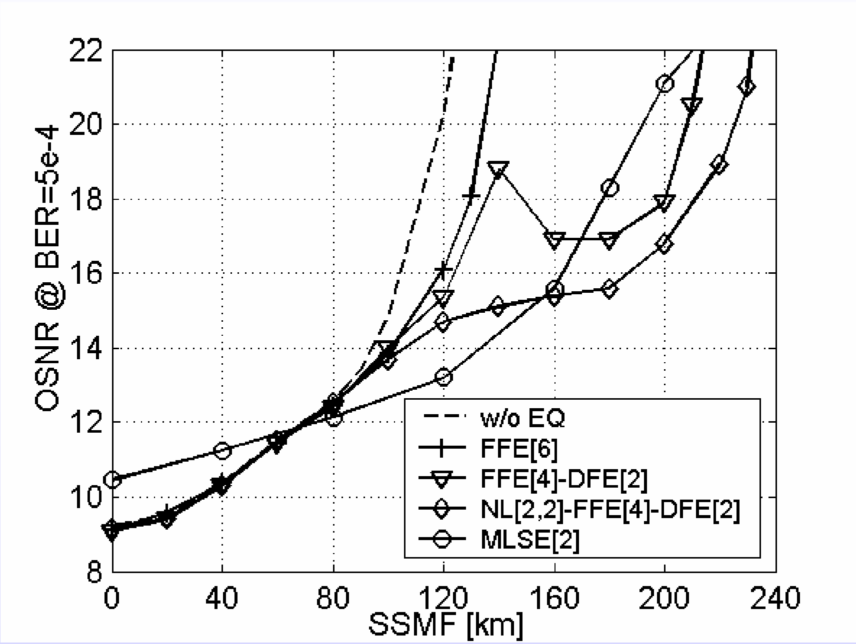
MLSE



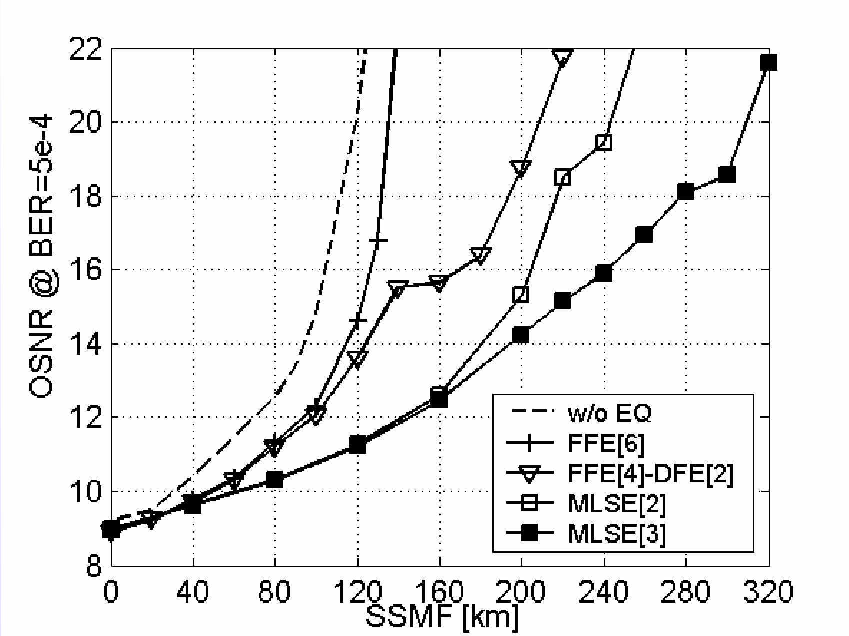
- Optimum receiver based on Viterbi algortihm
- Channel estimation (based on Lookup table method where PDF is estimated) first with training symbols.
- High speed A/D Converter required
- Memory: 2 or 3 (ISI from 2 or 3 previous bits)

EDC on CD mitigation for OOK

1 sample/bit, 10 Gb/s



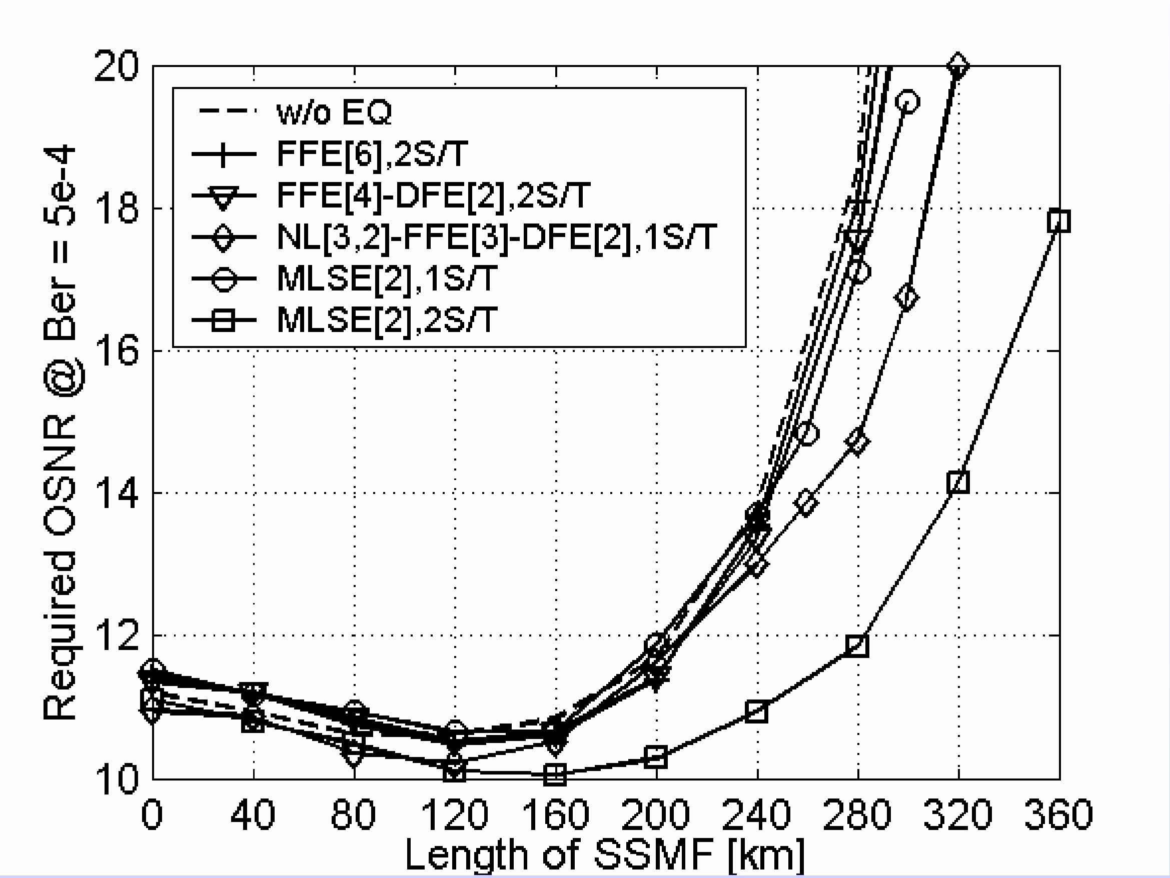
2 samples/bit, 10Gb/s



- FFE[4]-DFE[2] exhibits advantage over FFE[6] at longer distance
- NL[2,2]-FFE[4]-DFE[2] outperforms MLSE[2] at longer distance (>160km)

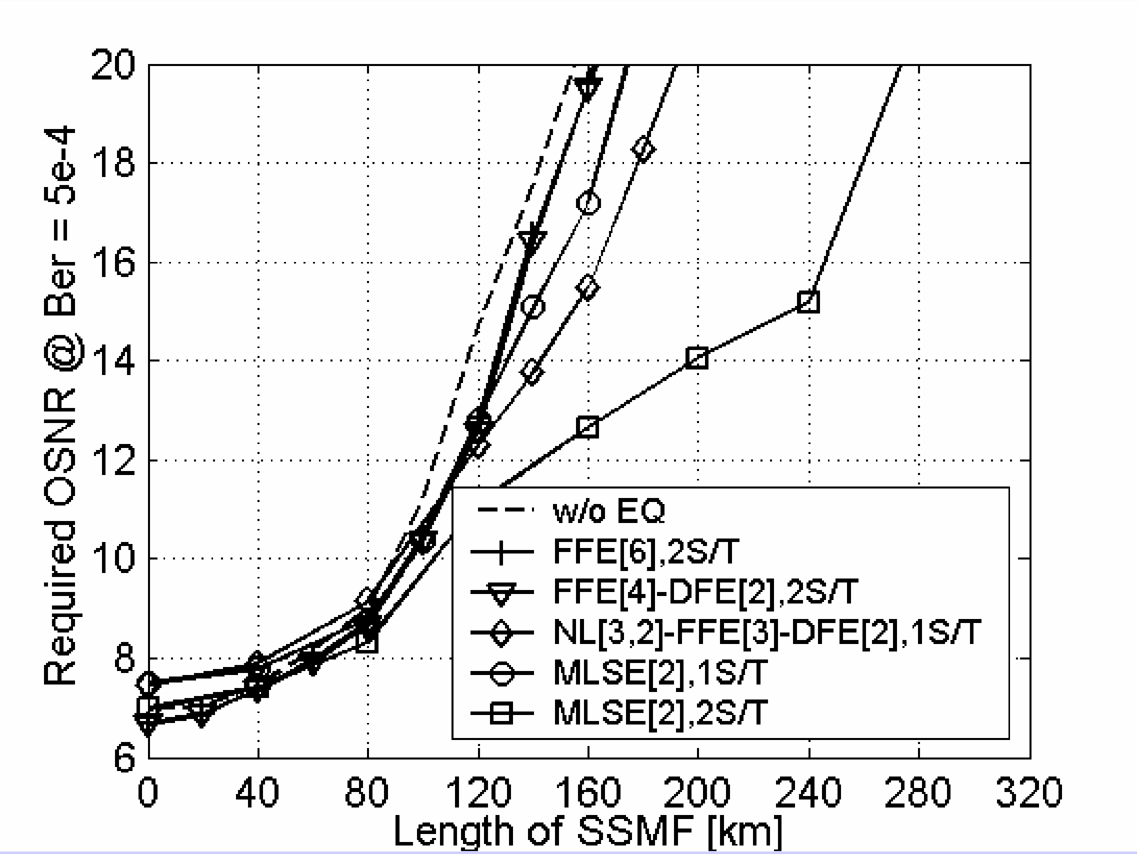
- Improvement through oversampling (fractionally spaced equalizer)

EDC on CD mitigation for Optical Duobinary



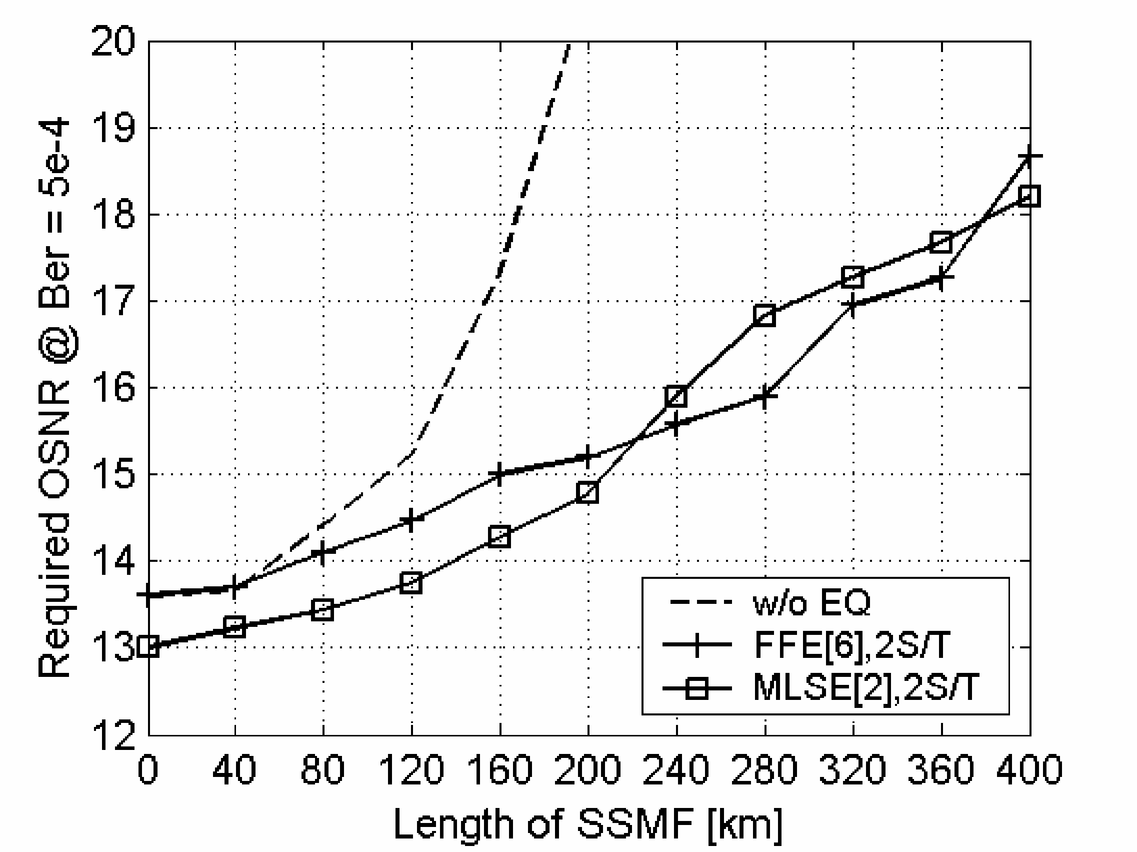
- ODB: larger dispersion tolerance, B2B penalty
- FFE and FFE-DFE very little performance improvement
- NL-FFE-DFE (1S/T) can achieve sub-optimum performance
- MLSE[2] with 2 sample/T required for better performance

EDC on CD mitigation for NRZ-DPSK



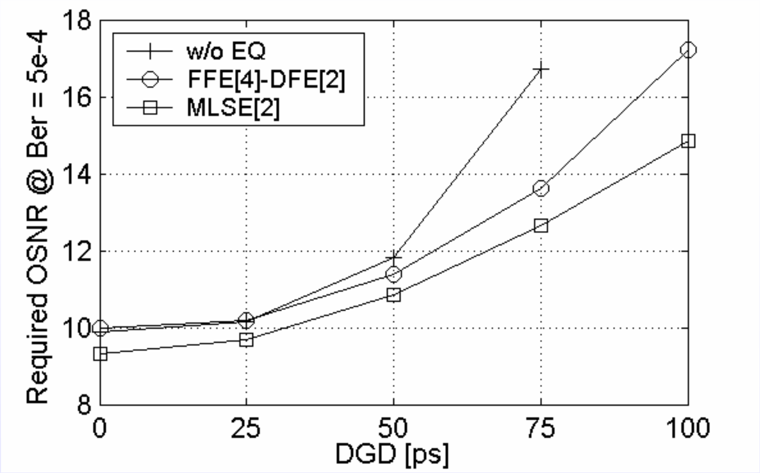
- NL-FFE-DFE outperforms MLSE[2] with 1sample/Bit
- MLSE[2] with 2samples/bit required for better performance
- All the EDC are limited at short distance due to the balanced detection

EDC on CD mitigation for OSSB

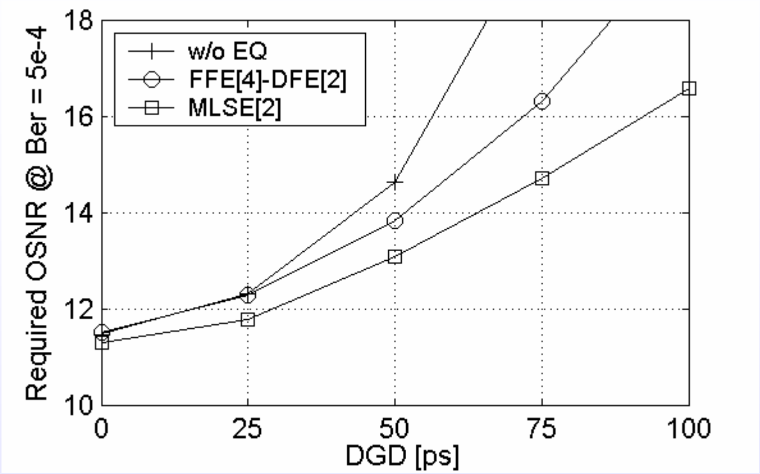


- CD results in Linear distortion in OSSB systems
- FFE[6] can achieve the similar performance to MLSE[2] up to 400km
- FFE alone can achieve very good compensation, DFE &MLSE are unnecessary

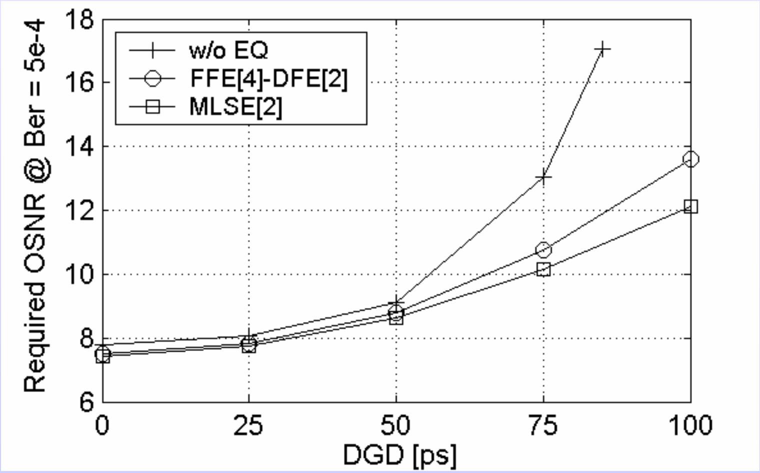
EDC on PMD mitigation for different modulation formats



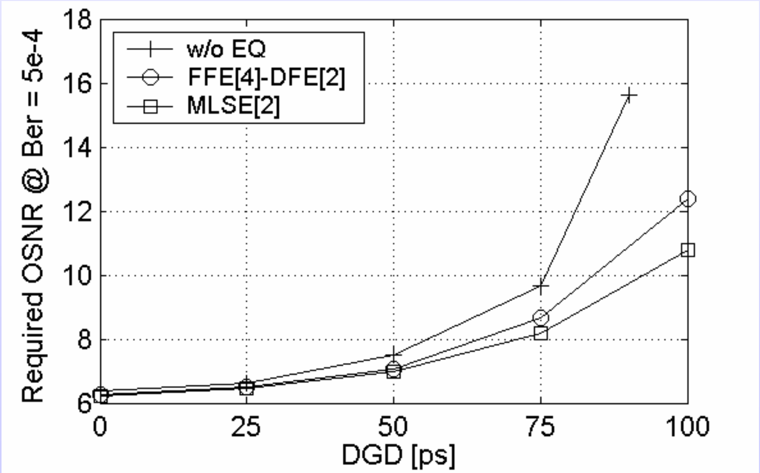
NRZ-OOK



NRZ-Duobinary



NRZ-DPSK



RZ-DPSK

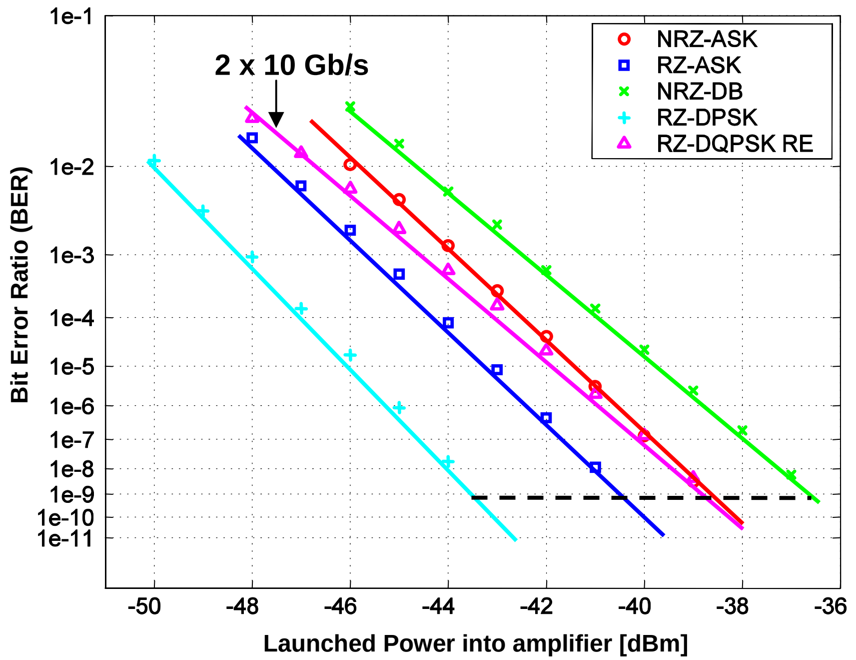
Conclusions:
EDC on CD/PMD mitigation in SMF links

- EDC performance reduced for ODB and DPSK
- EDC with 2-fold oversampling better performance
- Nonlinear FFE-DFE shows nearly as good performance as MLSE.
- Good performance of EDC on PMD mitigation for all modulation formats

FEC & Modulation Formats

- Receiver Penalties and Net Coding Gain (NCG) for different Modulation Formats and FEC
- RZ-DQPSK + Concatenated FEC Codes

Receiver Penalty of Various Modulation Formats



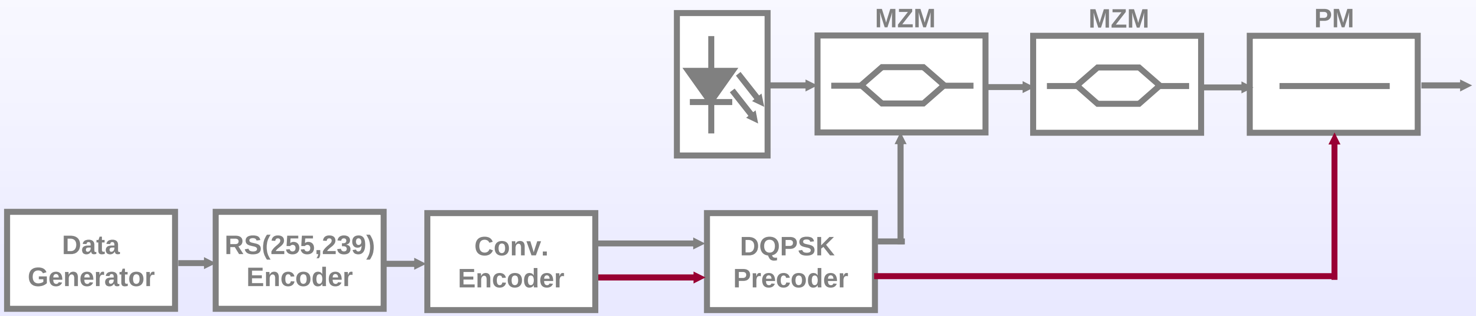
Modulation Formats	Receiver Penalty without FEC at BER=10^{-9}	Receiver Penalty with FEC RS(255,239) NCG~4.8 dB	Receiver Penalty with FEC BCH(255,239) NCG~3.4 dB
NRZ ASK	0 dB (reference)	- 4.8 dB	- 3.4 dB
RZ ASK	- 1.8 dB	- 6.6 dB	- 5.2 dB
NRZ DB	+ 2 dB	- 2.8 dB	- 1.4 dB
RZ DPSK	- 4.5 dB	- 9.3 dB	- 7.9 dB
RZ DQPSK	- 0.2dB	- 5 dB	- 3.6 dB

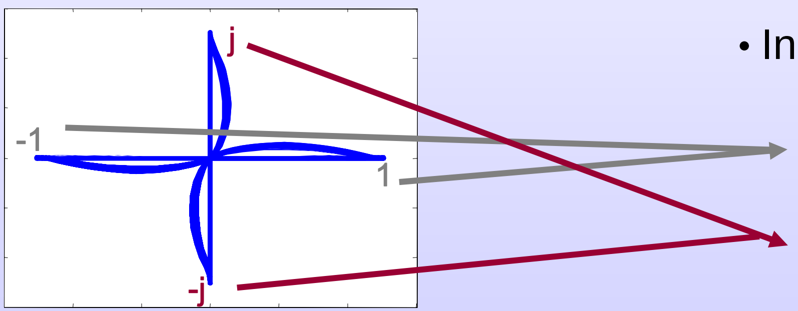
- Monte Carlo Simulation, ASE noise
- NRZ ASK with FEC: 4.8dB NCG
- Modulation formats with different receiver sensitivity
- Coding Gain is added to all other Formats

RZ-DQPSK + Concatenated Codes

Standard RS(255,239) + R=1/2 Covolutional Code + RZ-DQPSK

- Serial concatenation of RS(255,239) (outer-code) and R=1/2 Convolutional (inner-code)





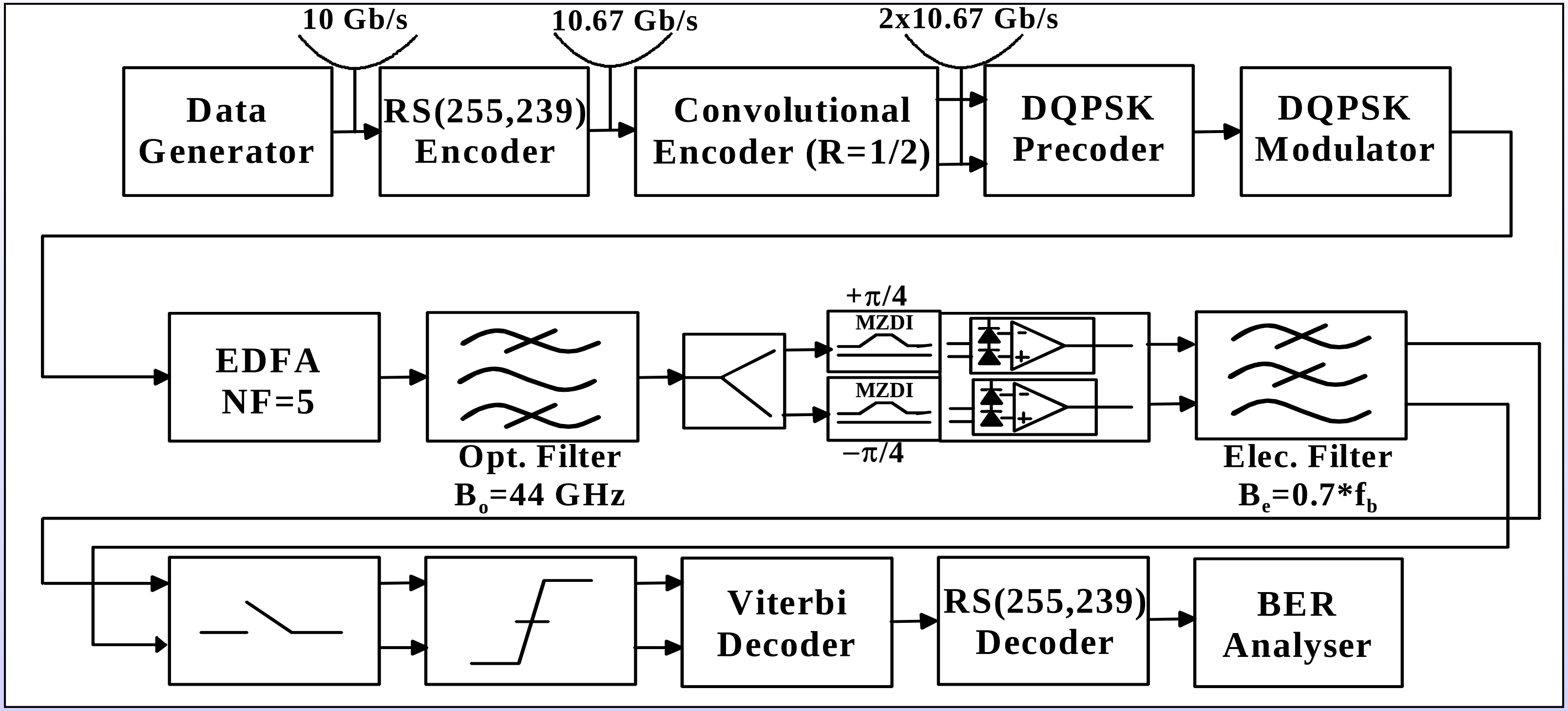
Signal Constellation of RZ-DQPSK

- In-phase and Quadrature Components
  - Data Signal
  - Overhead

- Data signal was allocated to the in-phase component
- Overhead was allocated to the quadrature component

Simulations System Setup

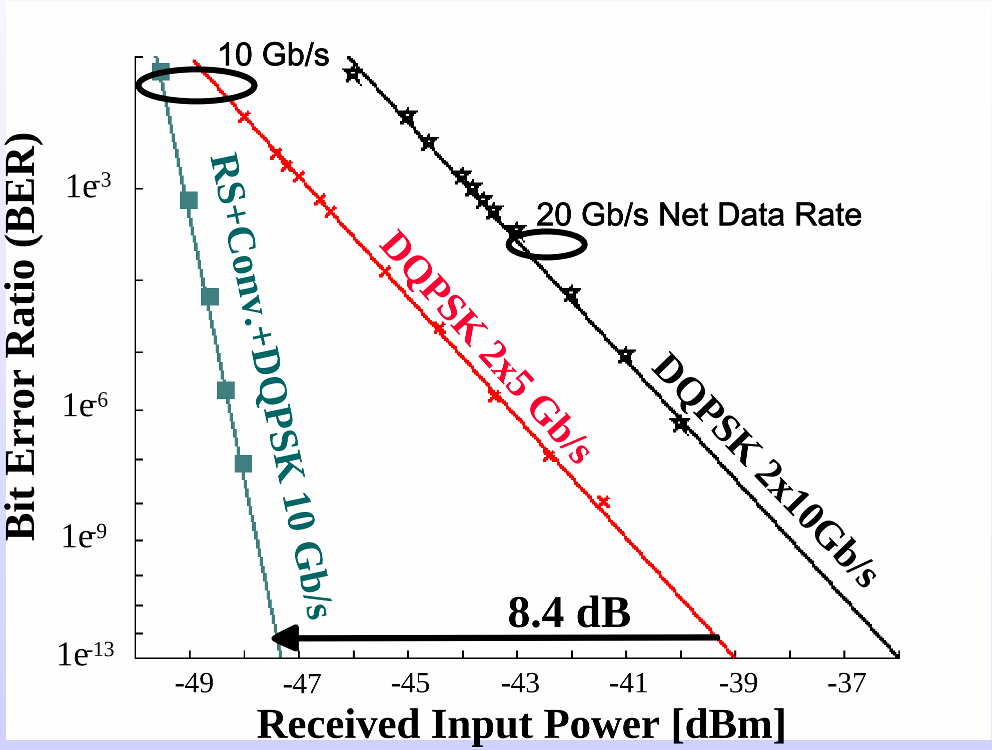
- Monte-Carlo simulations of a b2b optically preamplified system with dominating ASE noise
- RZ-DQPSK with serial concatenation of block and convolutional codes



- Interleaving was omitted in this concatenated scheme to simplify the simulations
- Hard-input hard-output Viterbi decoder was used

Bit Error Ratio Results

- Performance measured using BER-curves at 10^{-13}
- 6.7% OH → Increase of bandwidth due to the standard RS(255,239) code
- 100% OH → Increase of modulation levels (2 to 4) due to R=1/2 convolutional code



Results:

RS+RZ-DQPSK:	6.5 dB
Conv.+RZ-DQPSK:	5.2 dB
RS+Conv.+RZ-DQPSK:	8.4 dB

8.4 dB Net Coding Gain with only 6.7% excess bandwidth over 2x5Gb/s DQPSK

Summary and Comments

- Comparison of several modulation formats
- Differences in Performance and Complexity
- Introducing advanced Modulation Formats in DWDM Networks:
  - Critical upgrade into existing IM/DD DWDM networks
  - Review equalizer design & performance
  - Enhanced capacity of multilevel modulation (as QPSK) may be used as overhead for error correction