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SCV-LEOS-IEEE

Recent Advances in Coherent Receiver Design for High Speed Long Haul Optical Communications

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WE *light* IT UP

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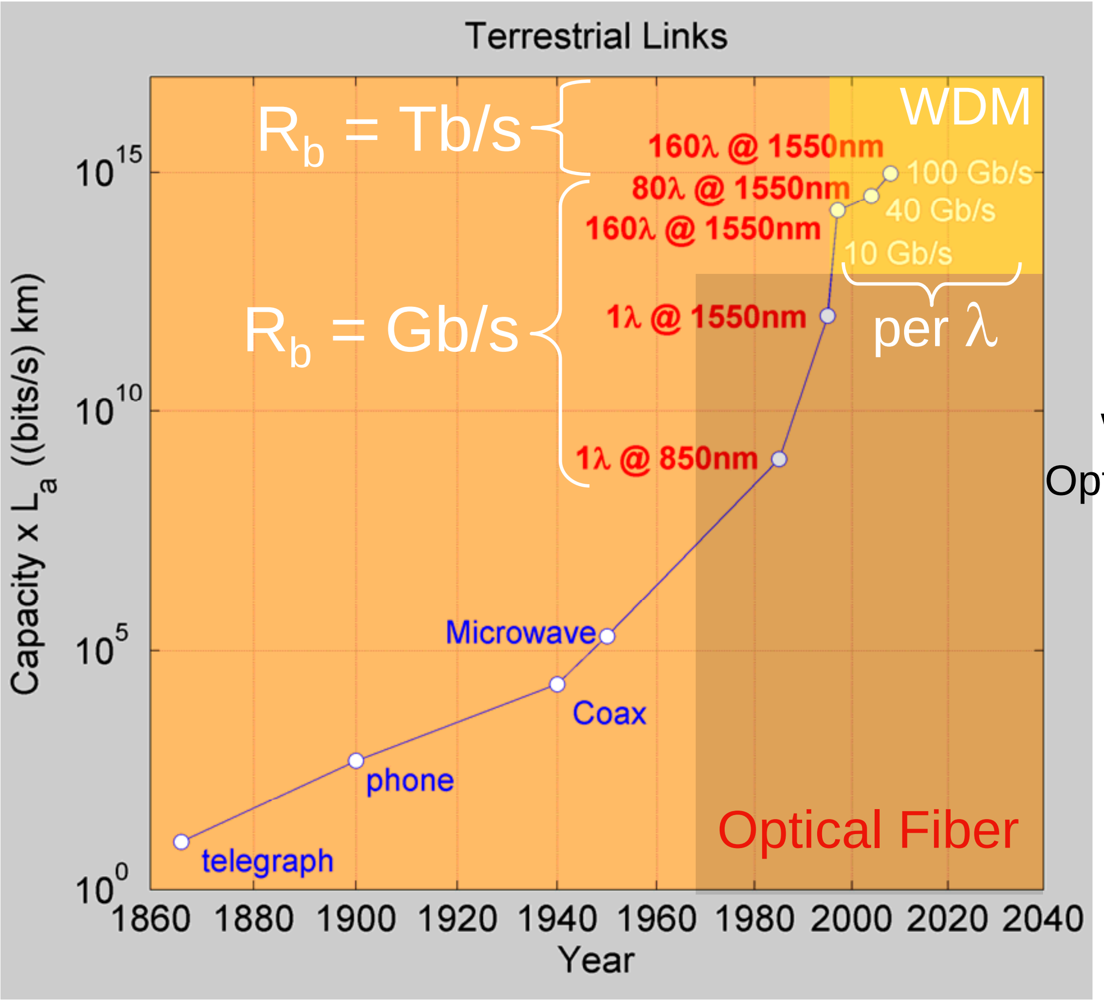
Abstract

Recent advances in coherent receiver design applied to high speed (40Gbps and 100Gbps) core optical communications networks will be presented, along with a brief historical overview. Specific modulation formats, combined with coherent detection and digital signal processing, will be shown to meet the requirements of modern optical communications networks. One such format receiving considerable attention is coherent polarization-multiplexed quaternary phase-shift keying (PM-QPSK). The theory of operation of PM-QPSK employing a polarization-diversity coherent receiver with digital finite-impulse-response equalizer and carrier phase estimation will be explained and the performance of state of the art R&D efforts will be discussed. Finally, we will review the importance of photonics integration in making mass production coherent products a reality.

Content

- Evolution of Telecommunication
- Evolution of fiber optics networks
- Evolution of coherent receivers
- Modern network requirements
- PM-QPSK theory of operation:
  - Transmitter and receiver architectures
  - Equalizer (EQ) description and adaptation algorithm
  - CPE and cycle slip
  - Performance:
    - CD and PMD tolerances
  - Special Design for large CD compensation
    - Time versus Frequency Domain
- Technology Options
- Photonics Integration

Evolution of Telecommunication



Capacity x L_a

↓ Total bit / s

↓ Amplifier spacing

WDM=Wavelength Division Multiplexing
Optical carriers (λ) used to transport channels

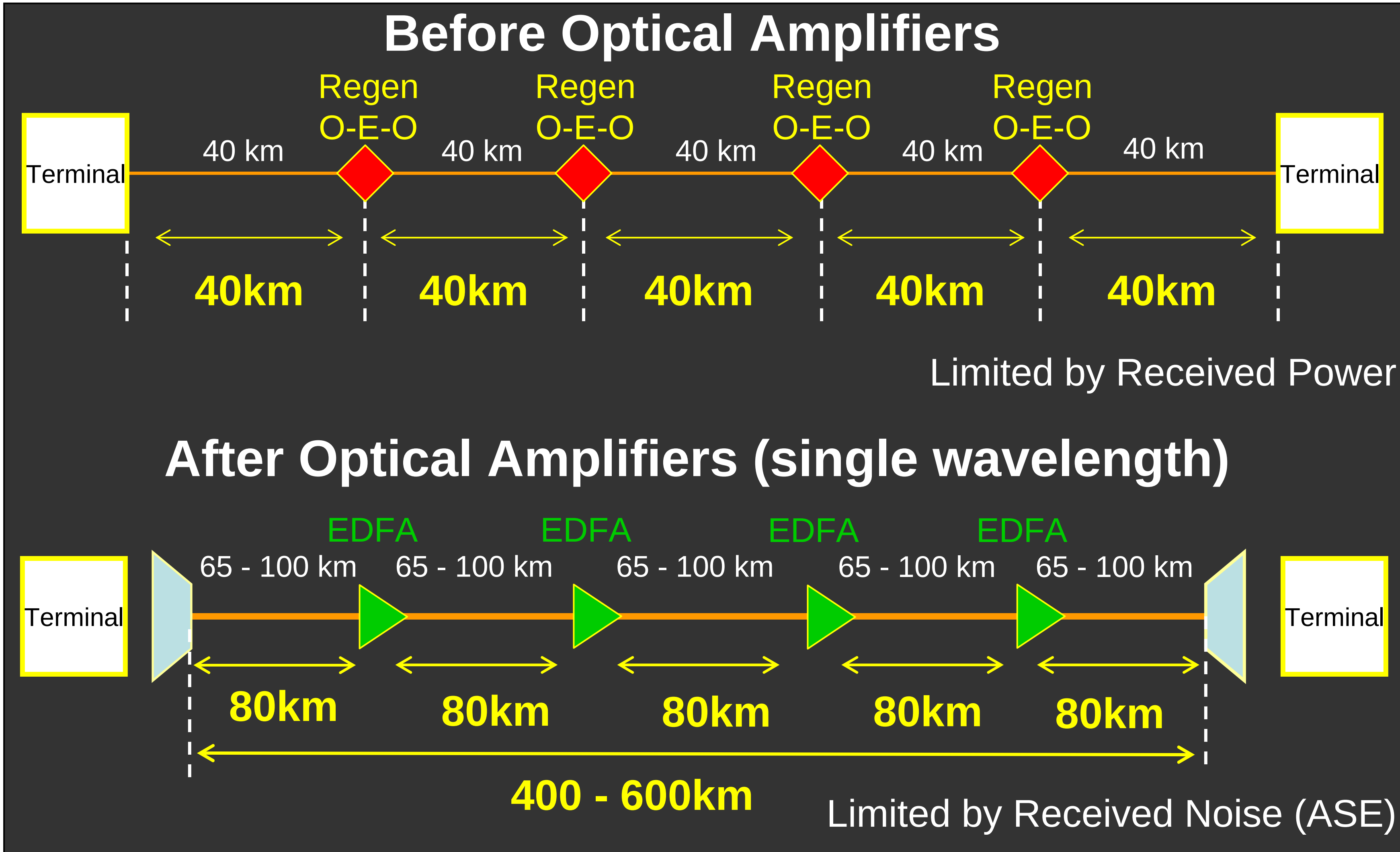
Capacity = # λ x Bit rate

Bit rate = Symbols/s x Bit/Symbol

↓ R_b

↓ Baud rate = R_s

Fiber Optics Network Evolution



Coherent and Direct Detection Receivers

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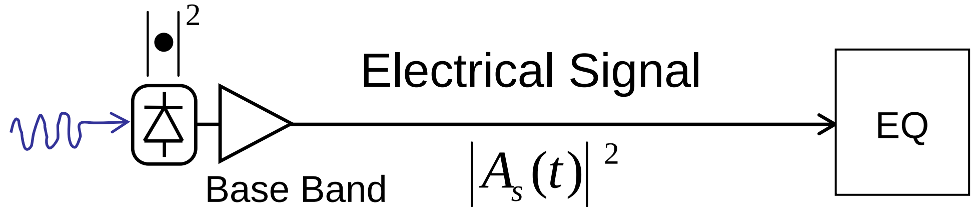
Direct-Detection

Optical Signal

$$A_s(t)\exp(j2\pi f_s t+\phi(t))$$



Coherent-Heterodyne

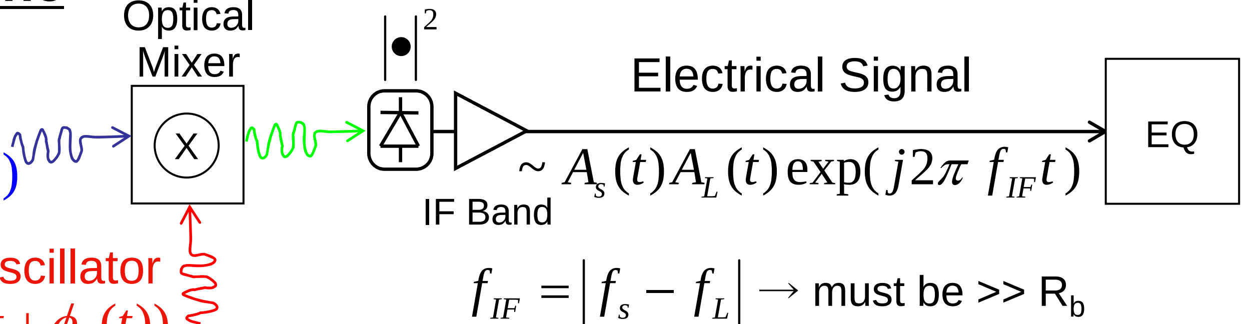
“downconverter” Optical Mixer

Optical Signal

$$A_s(t)\exp(j2\pi f_s t+\phi(t))$$

CW Local Oscillator

$$A_L(t)\exp(j2\pi f_L t+\phi_L(t))$$



$f_{IF} = |f_s - f_L| \rightarrow$ must be >> R_b

Coherent-Homodyne

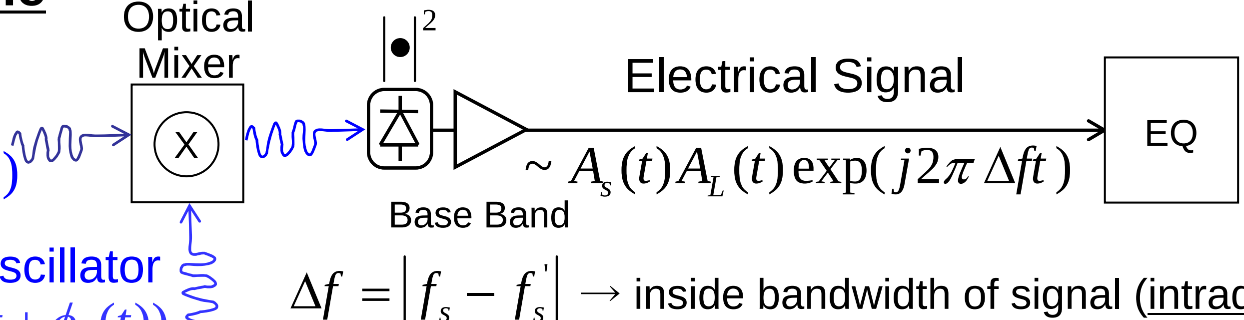
“downconverter” Optical Mixer

Optical Signal

$$A_s(t)\exp(j2\pi f_s t+\phi(t))$$

CW Local Oscillator

$$A_L(t)\exp(j2\pi f_s' t+\phi_L(t))$$



$\Delta f = |f_s - f_s'| \rightarrow$ inside bandwidth of signal (intradyne)

Coherent Receiver Evolution

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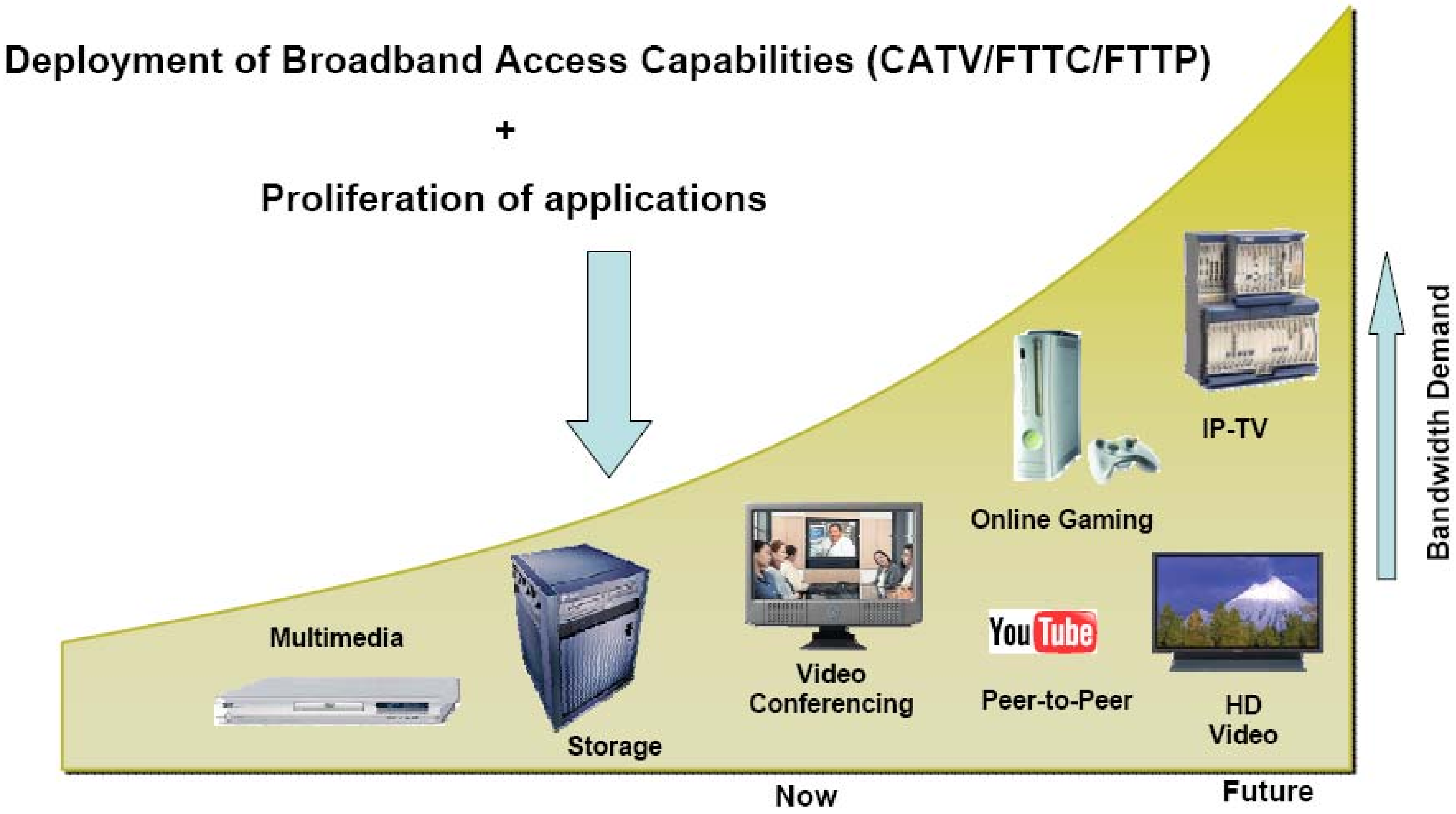
Research	WDM+DD Era Research Stopped	New Research
Japan Papers (1979); USA Papers (1980)	EDFA Invention	Why Coherent Rx Again?
1980 – 1990	1990 – 2000	Optical coherent communication time line (year)
• Un-repeated Links • Power sensitivity improvement (20dB) approaching Shot-noise limit	• Repeated Links • ASE limited (coherent Rx only gives 3 dB improvement) • Capacity improves by >100 x due to WDM • No need for coherent Rx	• 2004, Univ. College London, BPSK+coherent+DSP • 2005, Univ. Tokyo, QPSK+coherent+DSP • 2006, Univ. College London, PM-QPSK,coherent+DSP+blind EQ • 2007, Nortel, First “real-time” 40Gb/s PM-QPSK coherent Tx/Rx

Demand for Bandwidth is Growing



Household Bandwidth Needs in 2010 (U.S.)

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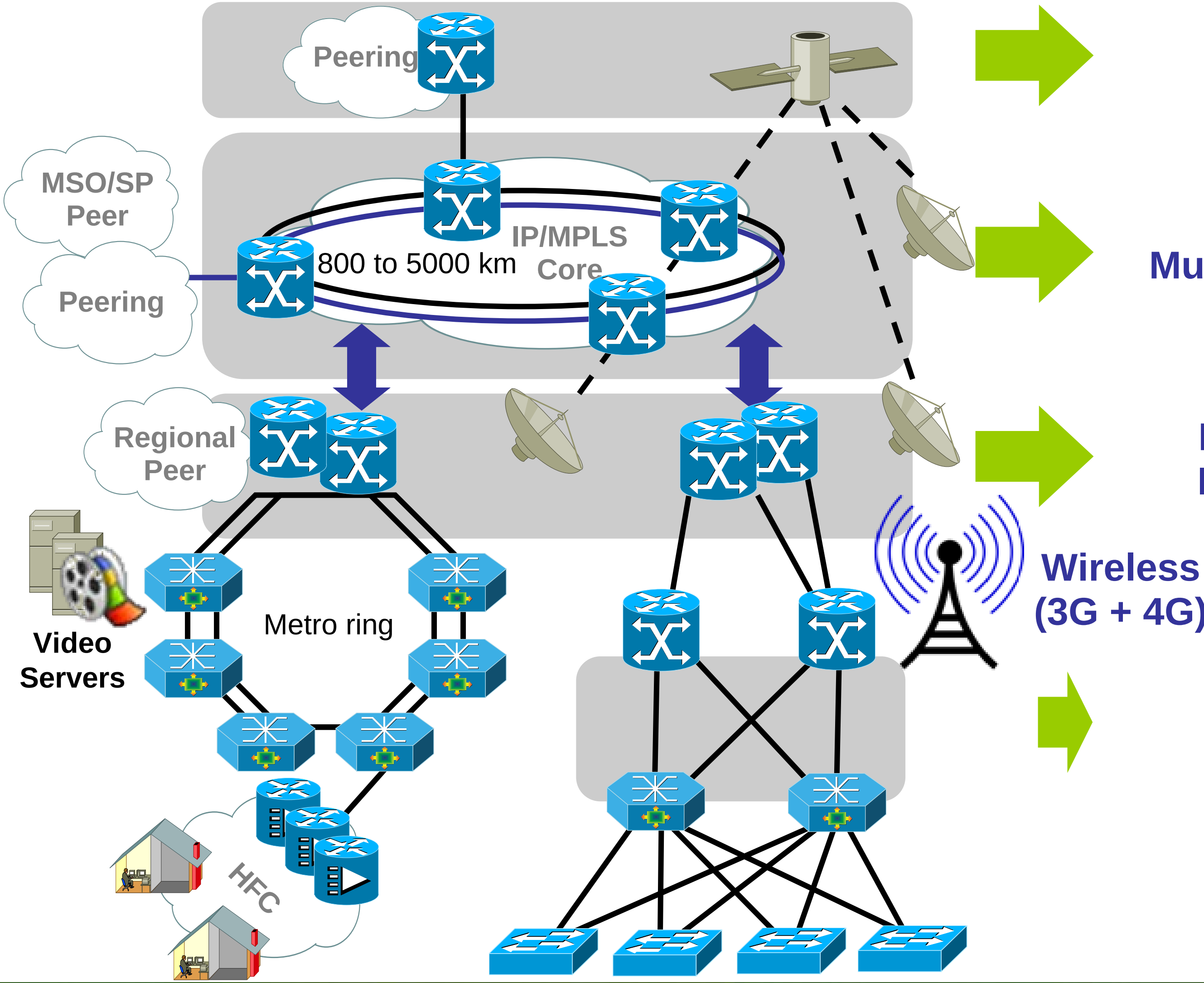
1x HDTV + 1x SDTV +
2x PVRs + 1x VoIP Phone + 1x HSD =
Overwhelming Capacity Requirements

Twenty such homes would generate more traffic than traveled the entire Internet backbone in 1995.

Why Coherent Receiver is Back?

- Better performance, support higher bit/symbol for ever increasing bandwidth demand
- Better technology availability:
  - Stable laser frequency
  - High speed digital signal processing
- Polarization diversity (shown previously)
  - Polarization tracking done in the DSP
  - No extra active components required
- Signal post-processing:
  - All complex amplitude information is preserved after detection
  - Can compensate linear impairments:
    - Residual Chromatic Dispersion (CD)
    - Polarization Mode Dispersion (PMD)
    - Polarization Dependent Loss (PDL)
    - Optical Filtering
- Limit to how much the coherent receiver can compensate is dictated by:
  - Speed of electronics (ADC sampling rate, analogue bandwidth of components)
  - Number of gates
  - Electrical power consumption
  - Nonlinear effects in the fiber

Modern Network Architecture



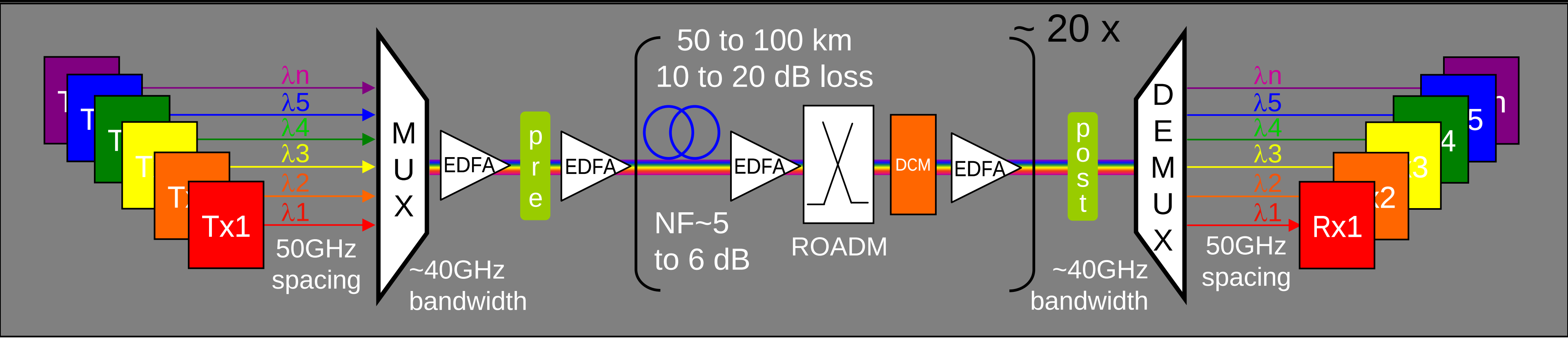
National Peering

Converged Multi-Service Backbone

Regional Peering / IPTV Deployments

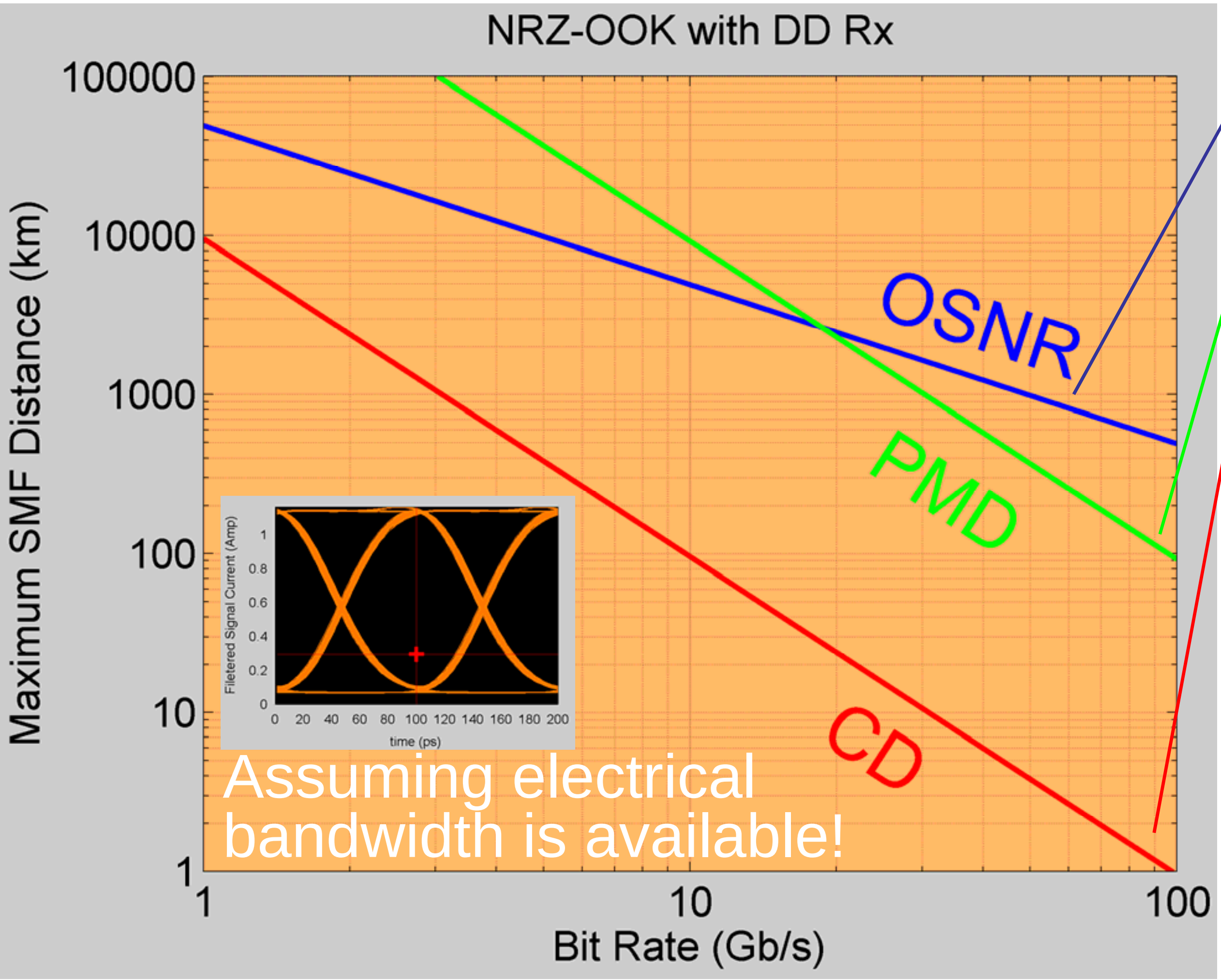
Data Center

Modern Core Network Requirements



- 10 Gb/s-NRZ-OOK per wavelength
- 80 wavelength in C-band per direction: 50 GHz spacing
- Span length 50 to 100 km
- Span loss 10 to 21 dB
- Fiber average launch power 0 to 2 dBm per channel
- Reach before O-E-O regeneration 1500 to 2000 km
- OSNR at Rx 16 to 18 dB (reported in 0.1 nm RBW)
- 90 to 98 % residual dispersion under compensated per span
- Fiber types SMF and NZDSF (LEAF)
- DWDM components (Mux, Demux, (R)OADM) have 40 to 50 GHz bandwidth (FWHM) per element

OSNR, CD and PMD Requirements of Serial OOK



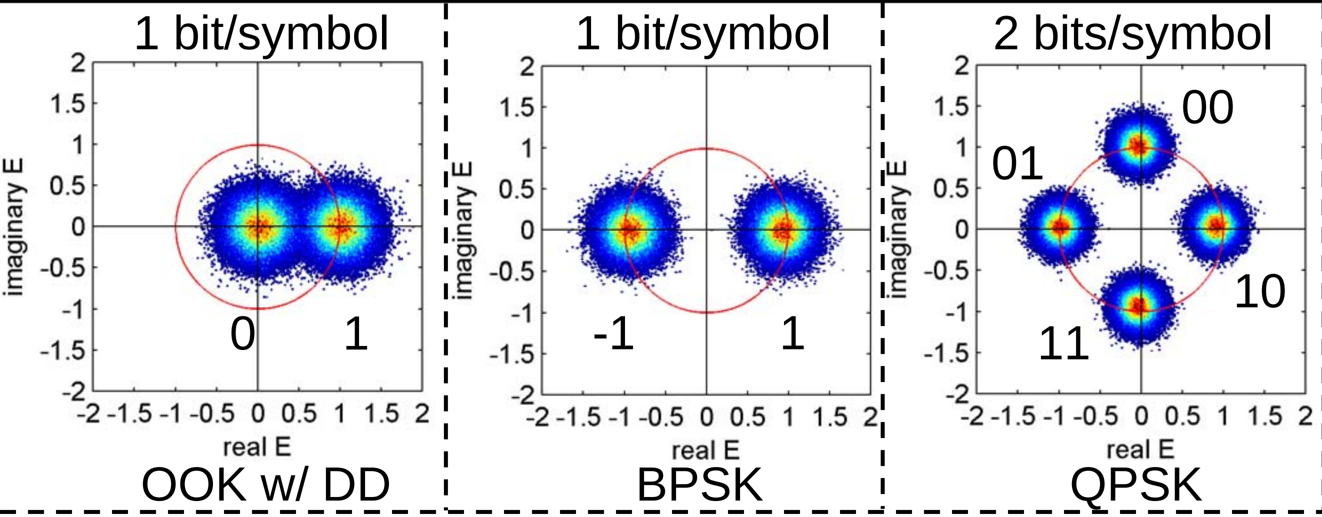
- 20 dB loss/span
- 80 km/span
- NF=5dB
- BER= 3 dB margin above 1e-3

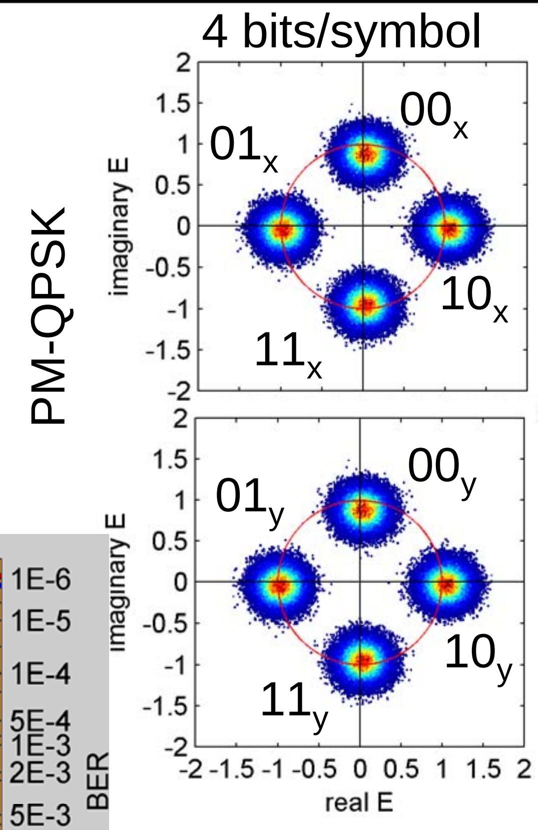
- 0.2 ps/km$^{1/2}$ all lumped in the fiber
- 3 dB OSNR penalty at BER=1e-3

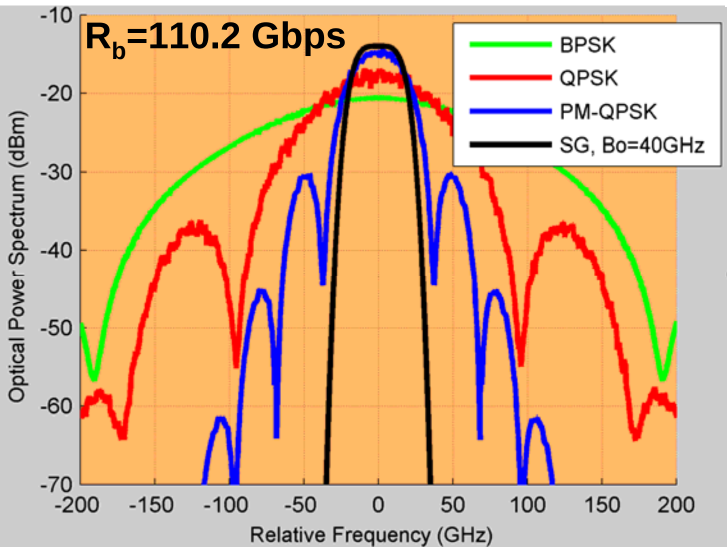
- 17 ps/nm/km
- 3 dB OSNR penalty at BER=1e-3

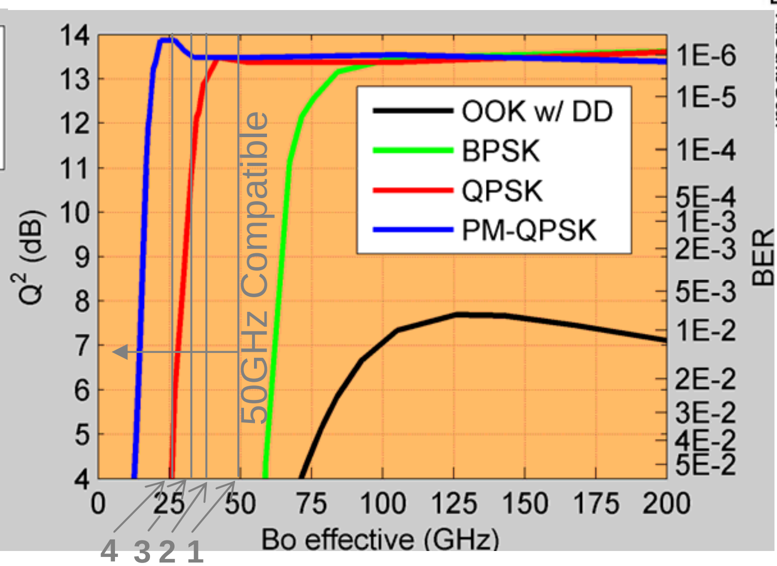
- **OSNR tol** $\propto 1/R_b$
  - At 100 Gb/s $\rightarrow$ 500 km
- **PMD Tol** $\propto 1/R_b$
  - Max Reach $\propto 1/R_b^2$
  - At 100 Gb/s $\rightarrow$ 100 km
- **CD Tol** $\propto 1/R_b^2$
  - At 100 Gb/s $\rightarrow$ 1 km
- Need more sophisticated modulation formats

Coherent Detection + Advanced Modulation Formats









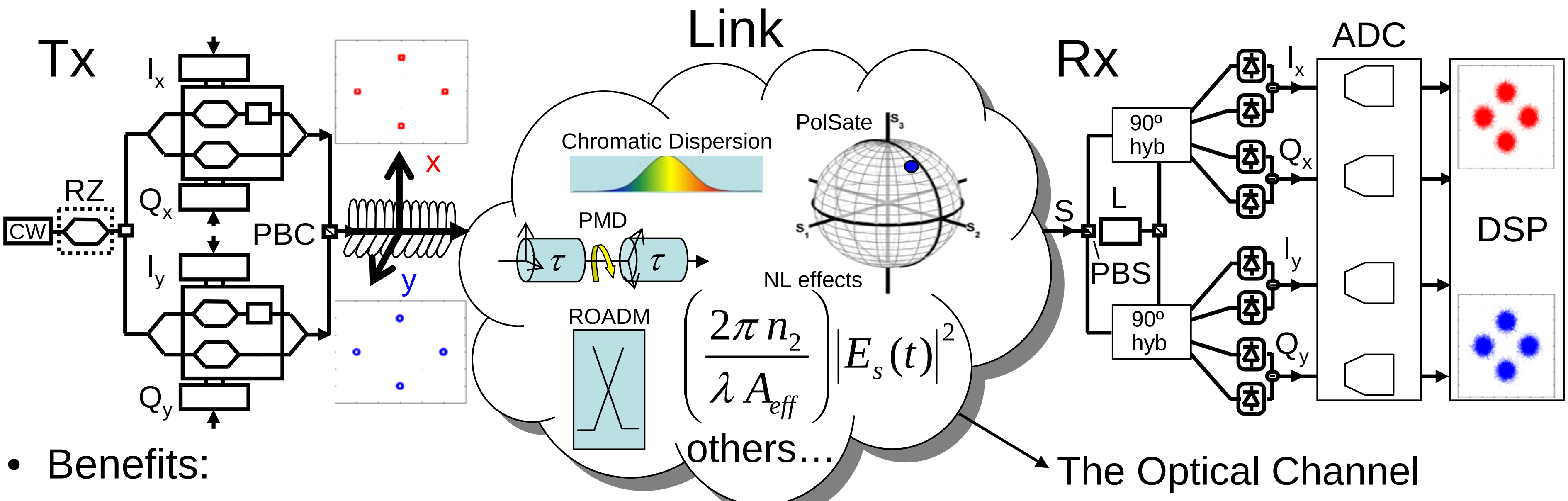
1) 2 x 50 GHz = 42 GHz

2) 4 x 50 GHz = 35 GHz

3) 6 x 50 GHz = 32 GHz

4) 16 x 50 GHz = 25 GHz

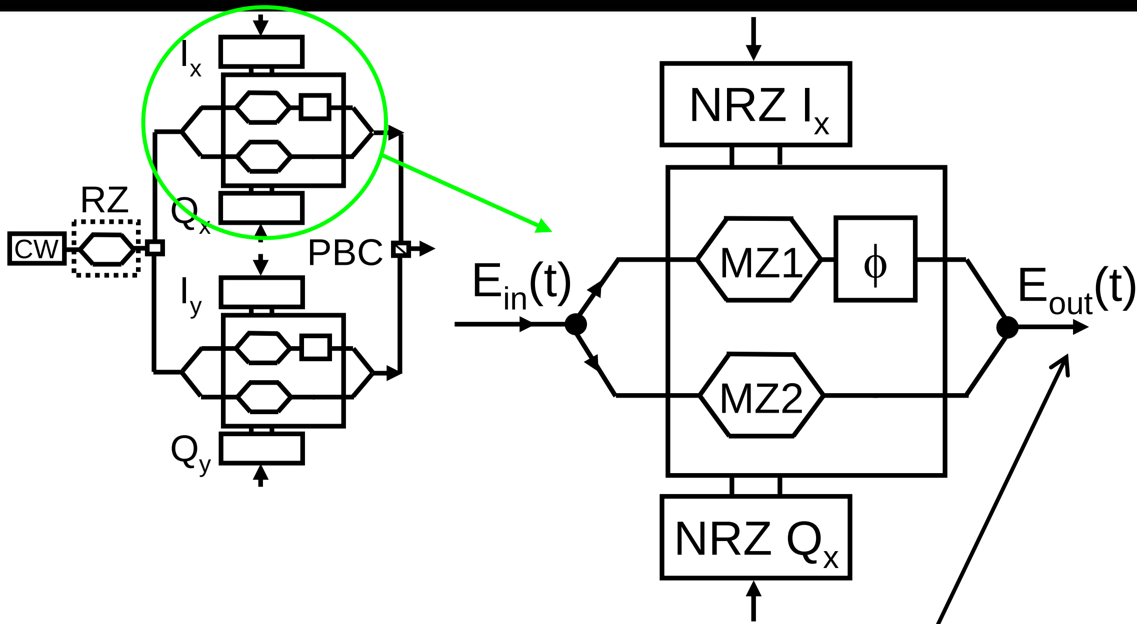
One Option: 100G PM-QPSK with 20% FEC OH



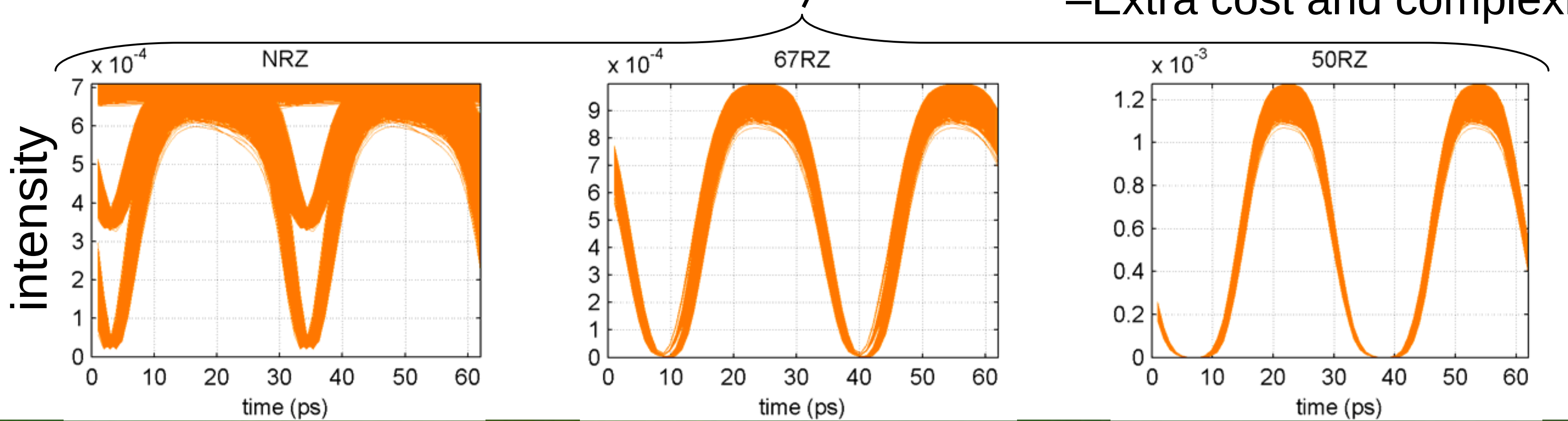
$$h(f) = \begin{pmatrix} h_{xx}(f) & h_{xy}(f) \\ h_{yx}(f) & h_{yy}(f) \end{pmatrix}$$

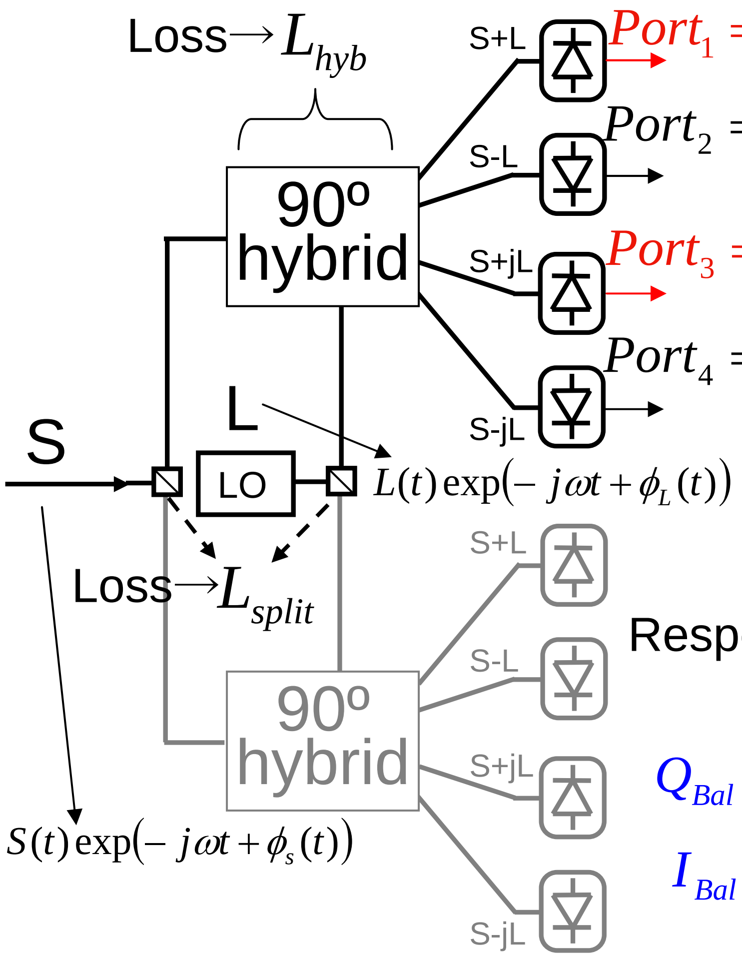
- Benefits:
  - Lowers baud rate by a factor of 4
  - Improved OSNR tolerance (compared to direct detection options)
  - Compensate linear impairments through DSP
- Challenges:
  - High speed ADC and DSP required
  - Significantly more complex transmitter and receiver optics
- High speed optics meets modem design ➡ exciting challenges
- Has been done in the wireless domain but not at these high data rates

PM-QPSK: Transmitter



- Two nested Mach-Zehnder modulators to form the IQ
- Phase between the I and Q should be maintained to 90 deg
- Two IQ modulators for x and y channels
- RZ carver option:
  - –Helps cleaning ISI in Tx chain
  - –Helps reducing NL effects
  - –Extra cost and complexity





$$Port_1 = R\,L_{split}L_{hyb}\left(|S|^2+|L|^2+2\,\mathrm{Re}\{SL^*\}\right)$$

$$Port_2 = R\,L_{split}L_{hyb}\left(|S|^2+|L|^2-2\,\mathrm{Re}\{SL^*\}\right)$$

$$Q_{Bal} = R\,L_{split}L_{hyb}\left(4\,\mathrm{Re}\{SL^*\}\right) + i_{thermal}$$

$$Port_3 = R\,L_{split}L_{hyb}\left(|S|^2+|L|^2+2\,\mathrm{Im}\{SL^*\}\right)$$

$$Port_4 = R\,L_{split}L_{hyb}\left(|S|^2+|L|^2-2\,\mathrm{Im}\{SL^*\}\right)$$

$$I_{Bal} = R\,L_{split}L_{hyb}\left(4\,\mathrm{Im}\{SL^*\}\right) + i_{thermal}$$

Total (x+y) average optical power in Watt

$$S(t)=\sqrt{P_s}A_s(t) \qquad L(t)=\sqrt{P_L}A_L(t)$$

Responsivity in A/W

$$\phi(t)=\phi_s(t)-\phi_L(t)$$

$$Q_{Bal} = 4R\,L_{split}L_{hyb}\sqrt{P_sP_L}\,\mathrm{Re}\left\{A_s(t)A_L(t)\exp\left(-j\phi(t)\right)\right\}+i_{thermal}$$

$$I_{Bal} = 4R\,L_{split}L_{hyb}\sqrt{P_sP_L}\,\mathrm{Im}\left\{A_s(t)A_L(t)\exp\left(-j\phi(t)\right)\right\}+i_{thermal}$$

Full complex amplitude information

Linear Transversal Equalizer Fractionaly Spaced

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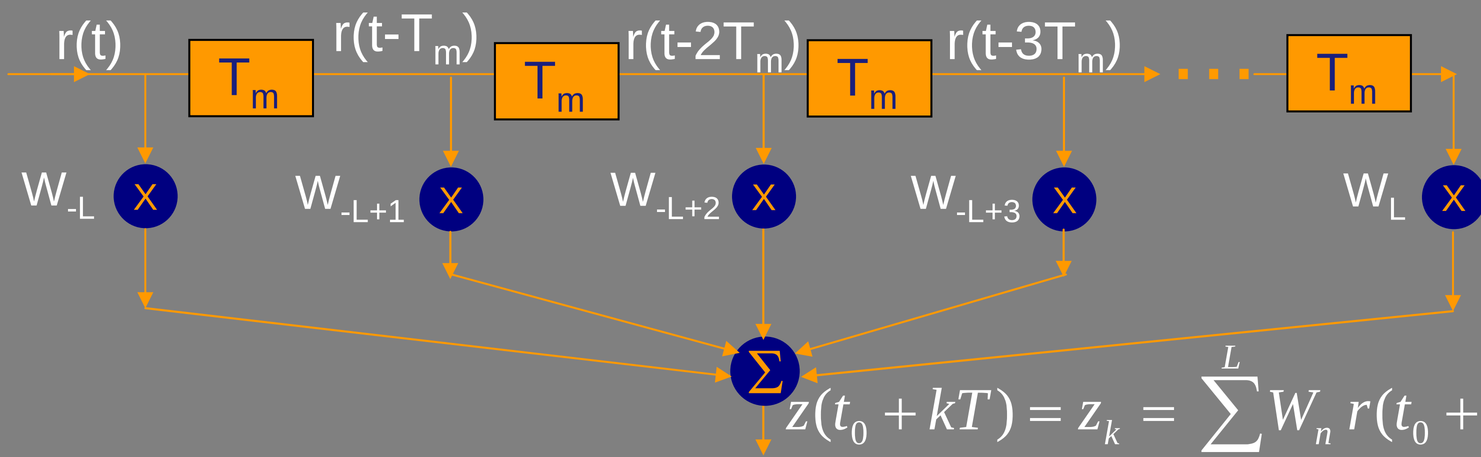
Linear transversal equalizer or Tapped-delay-line or Nonrecursive equalizer or Finite-Impulse Response (FIR) filter



$$z(t_0 + kT) = z_k = \sum_{n=-L}^{L} W_n \, r(t_0 + kT - nT_m)$$

- Over sampling rate M/K = T/T_m where T = 1 / R_s and T_m is the inverse of the sampling rate. EQ number of taps is N = 2L+1
- Samples (past and futur) of r(t) are linearly weighted by the taps coefficients (W) to produce the output
- Digital samples taken at M/K over sampling rate are stored in a digital shift register (or memory) and the EQ output estimations are produced at the symbol rate R_s
- The over sampling rate M/K=1,2,3,… or any rational number >1 (3/2,4/3,…)

EQ-2x2 Matrix Multiply Structure (MIMO)

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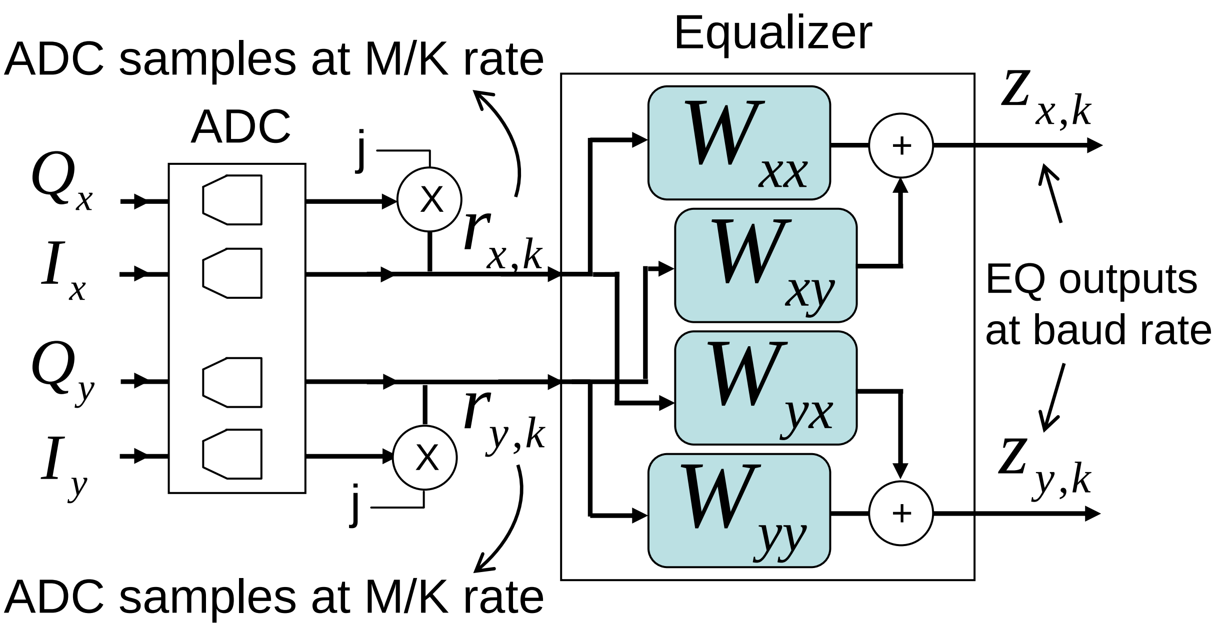
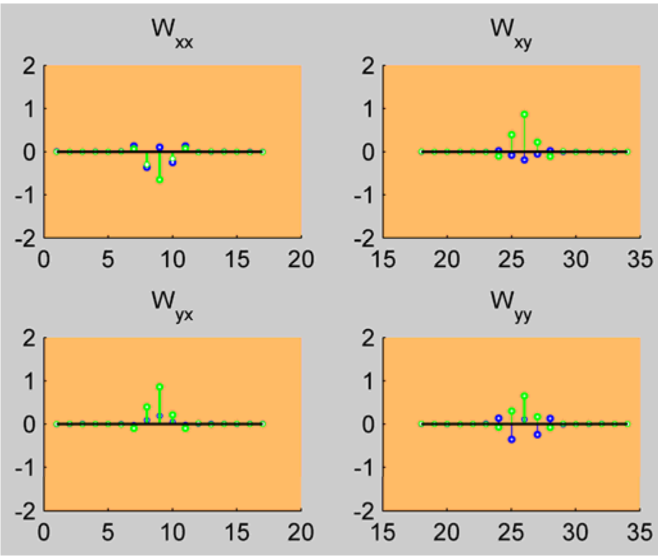




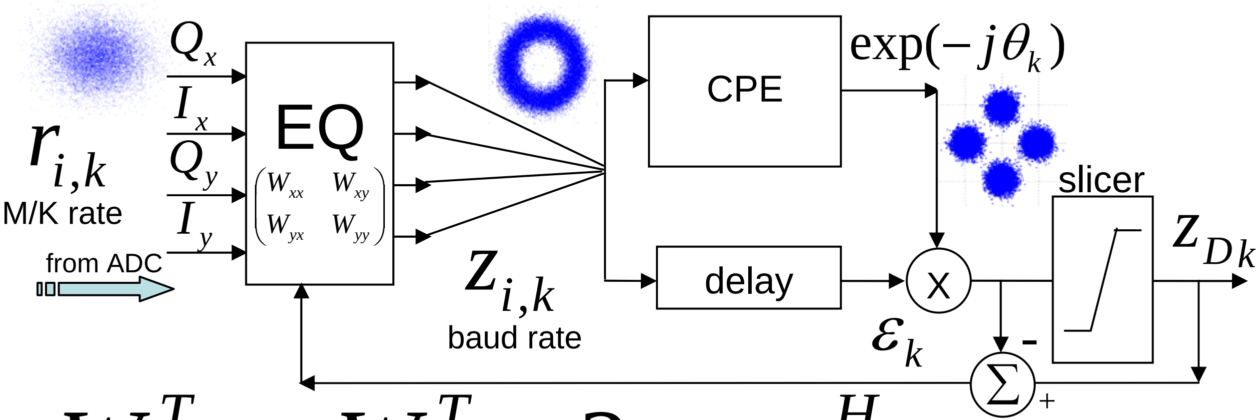
N Taps wide N Taps wide

$$\begin{pmatrix} z_{x,k} \\ z_{y,k} \end{pmatrix} = \begin{pmatrix} \mathbf{W}_{xx}^T & \mathbf{W}_{xy}^T \\ \mathbf{W}_{yx}^T & \mathbf{W}_{yy}^T \end{pmatrix} \begin{pmatrix} \mathbf{r}_{x,k} \\ \mathbf{r}_{y,k} \end{pmatrix}$$

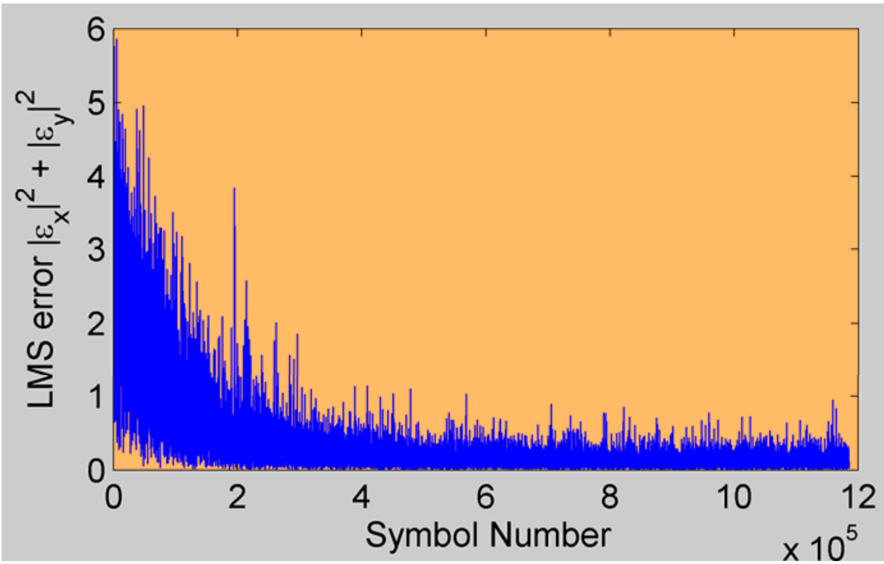
$$\mathbf{W}_{ij}^T = \left[W_{ij,-L}^T, W_{ij,-L+1}^T, \ldots, W_{ij,L}^T \right]$$

- 2L+1 taps (past and futur)
- *W* are complex (amp+phase)
- Cross-terms allow to remove the polarization coupling effects (pol demuxing/tracking, PMD, PDL)

Equalizer Adaptation Algorithm

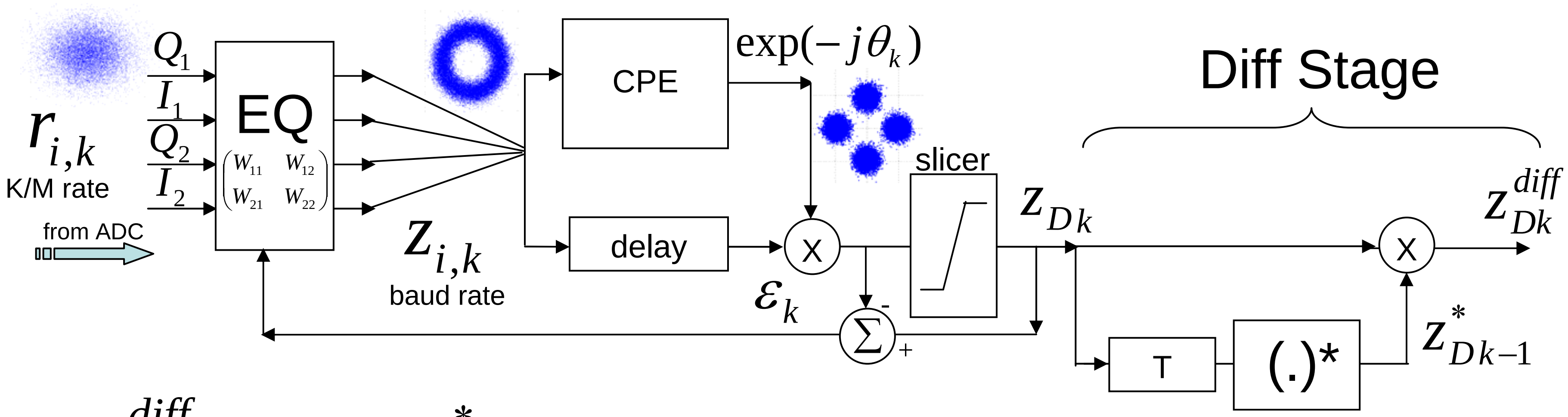


$$W_{k+1}^T = W_k^T + 2\mu\varepsilon_k r_k^H$$



- $r_{i,k}$ = ADC outputs at M/K rate
  i = x or y polarization
  k = symbol index
- $z_{i,k}$ = Constellation estimation at baud rate from EQ
- Slicer= Make decision to what constellation the signal belongs
- $\varepsilon_k = z_{Dk} - z_{i,k}$ LMS error
- z_{Dk} = Sliced constellation
  = "known" sequence when training is used

- Update equation using a steepest decent technique
- Error ε_k can be from LMS or CMA
- Updated every symbol *k* or by block of symbols
- Convergence speed, stability and accuracy are function of the gain μ
- Minimize ISI and noise enhancement



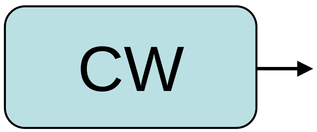
$$z_{Dk}^{diff} = z_{Dk}\, z_{Dk-1}^{*}$$

Δϕ (rad)	Symbol
0	00
π/2	10
π	11
3 π/2	01

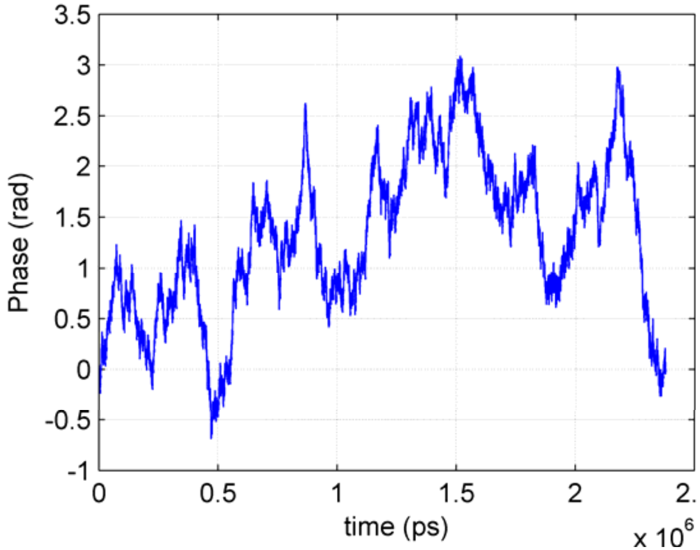
- Mapping of phase change between two consecutive constellations to 4 symbols
- Penalty of 2 BER (translates to ~0.5 dB of penalty)
- Robust to cycle slips

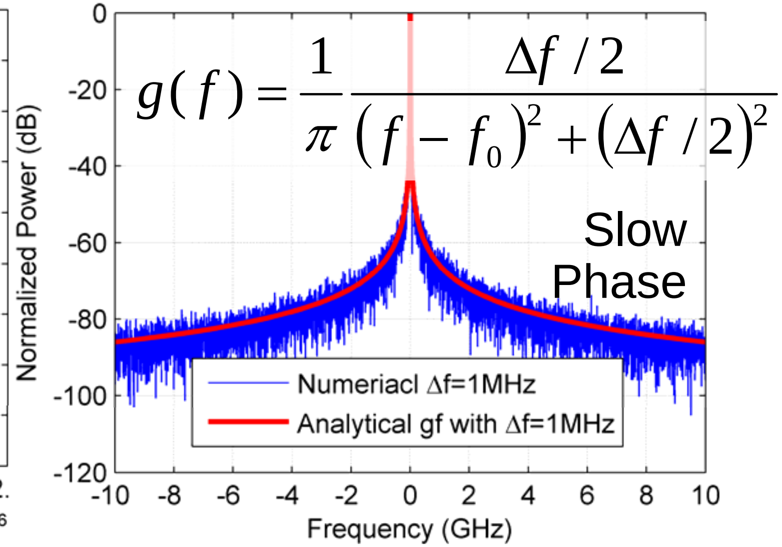
Received Phase Noise: Two Sources

1) Lasers



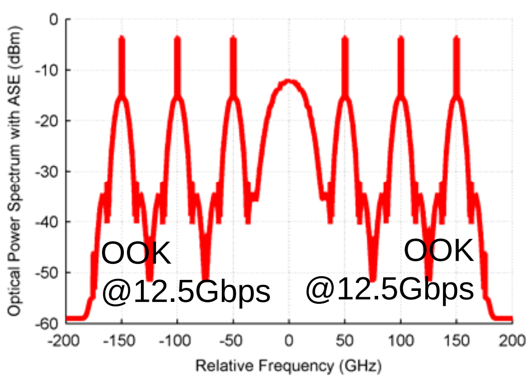
- Tx and LO CW laser
- LineWidth 200 kHz to 2 MHz

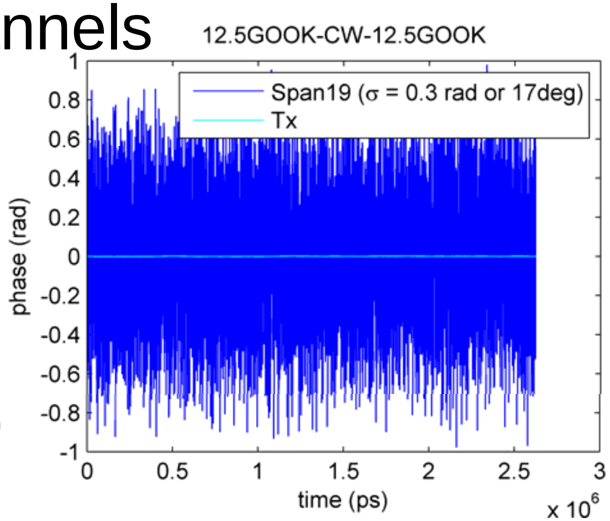


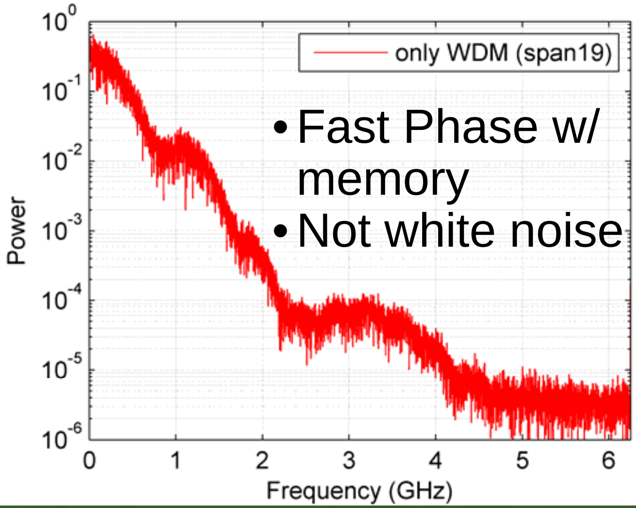


$$g(f)=\frac{1}{\pi}\frac{\Delta f/2}{\left(f-f_0\right)^2+\left(\Delta f/2\right)^2}$$

2) WDM OOK channels







- Fast Phase w/ memory
- Not white noise

Non-Data Aided CPE: Viterbi-Viterbi Technique

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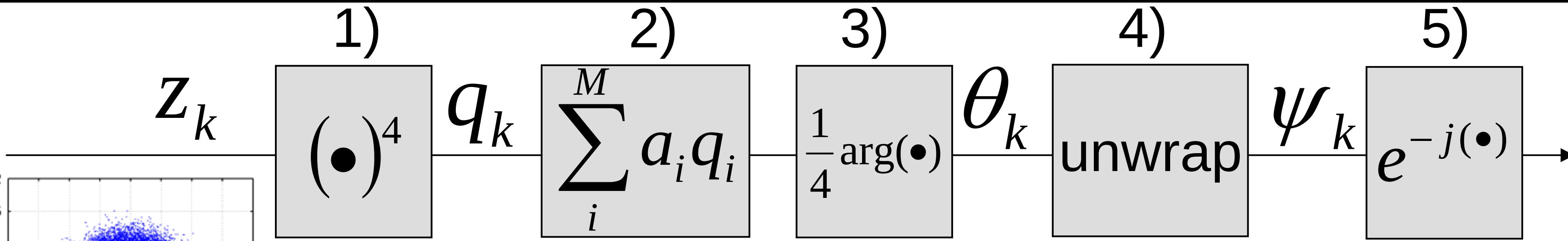
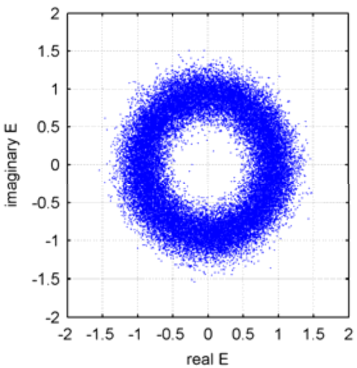
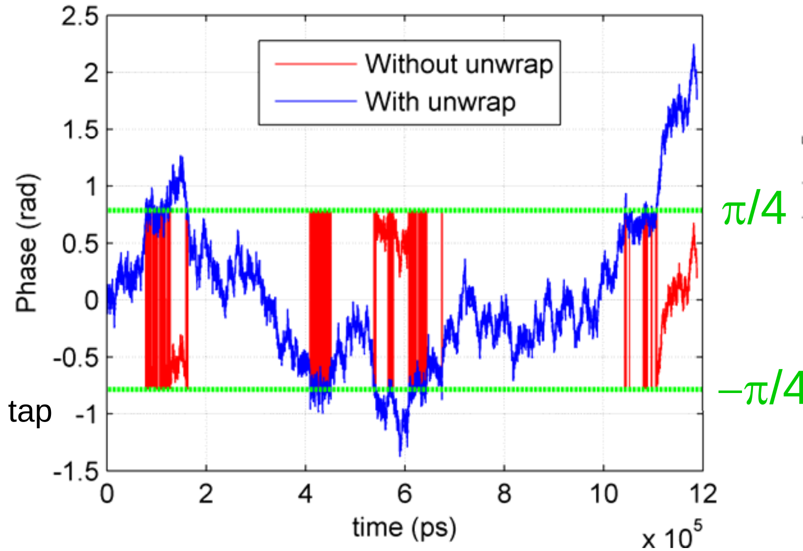
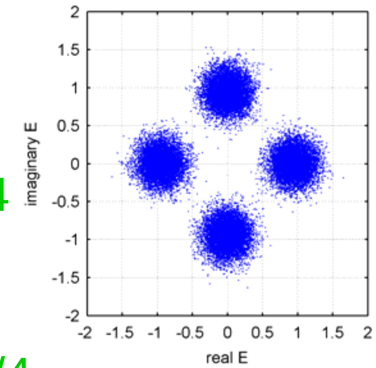


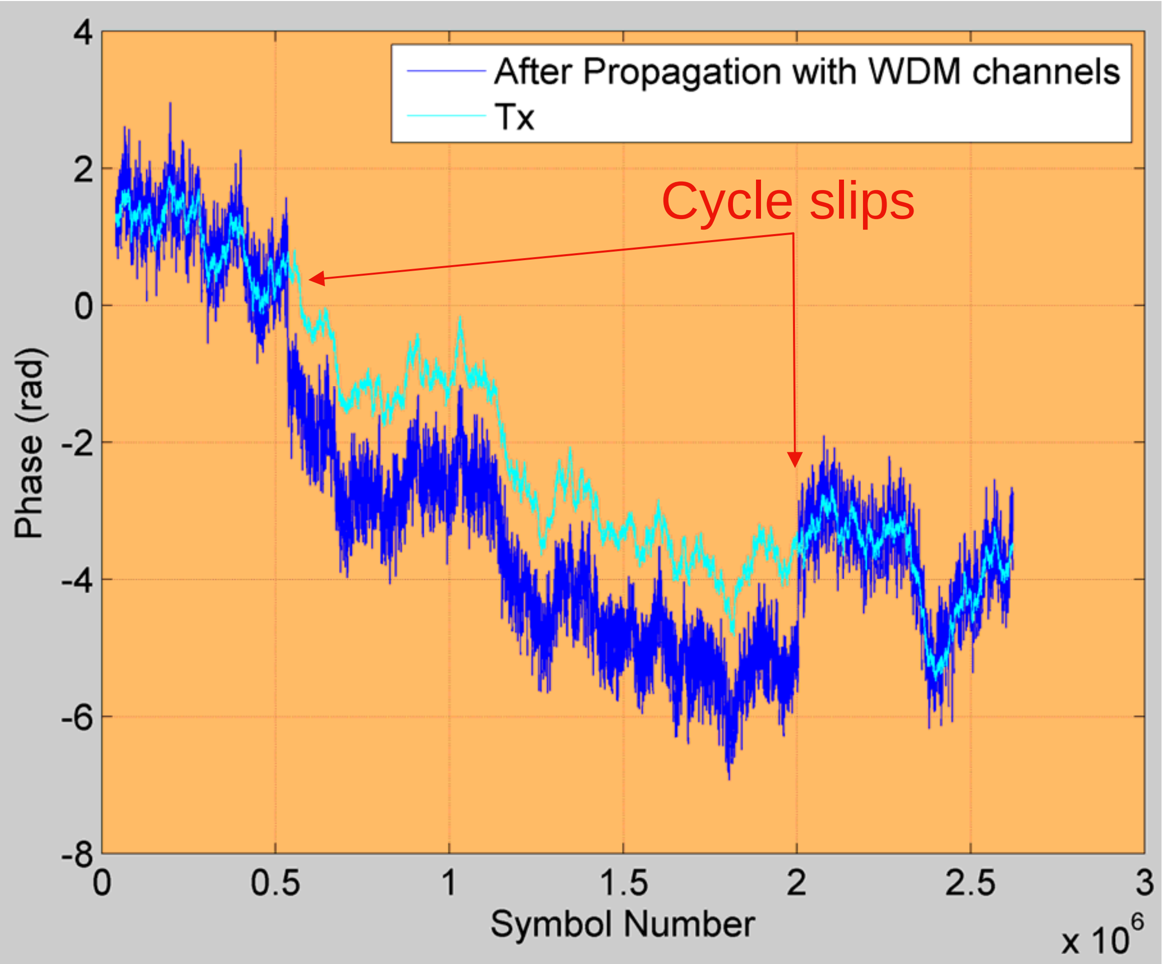






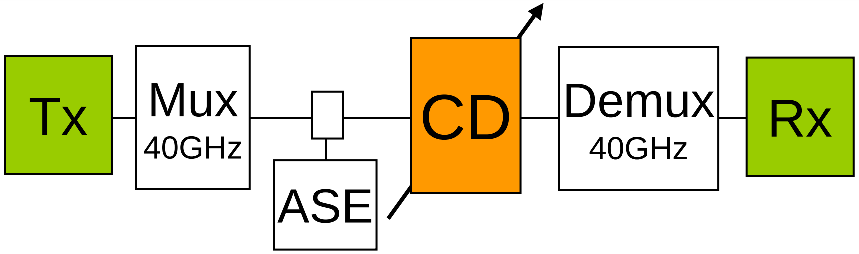
1. 4th power: Determine phase angle by "collapsing" the 4 constellations in one
2. Running average window (may have different tap weights)
3. "atan" function calculates the phase from the complex number q_k
4. Because the output of the atan goes only from –π to π (or the phase θ_k goes from –π/4 to π/4), the phase has to be unwraped, otherwise a phase slip will cause a n*π/2 angle rotation of the constellation and therefore a burst of error (from that point in time, all the sequences are not correctly decoded and unless the constellation are not rotated back, will last forever).
5. Once the correct phase has been estimated, simply multiply the incoming signal z_k by the inverse phasor

Cycle Slip

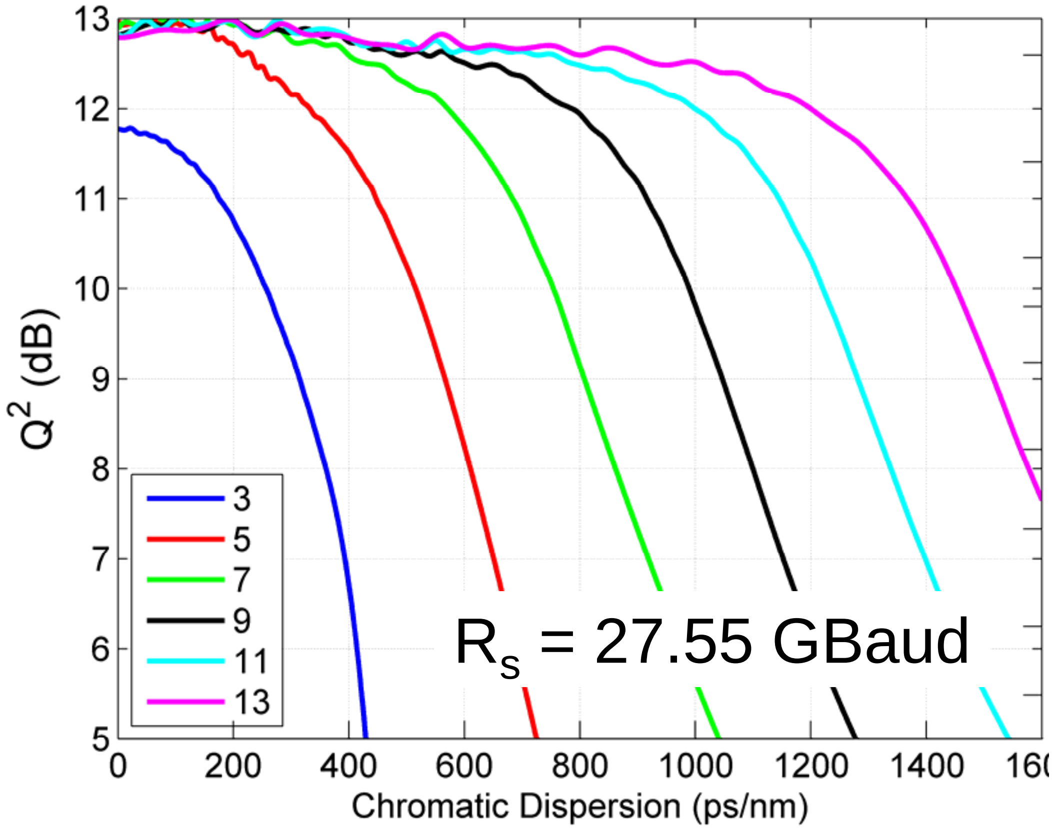


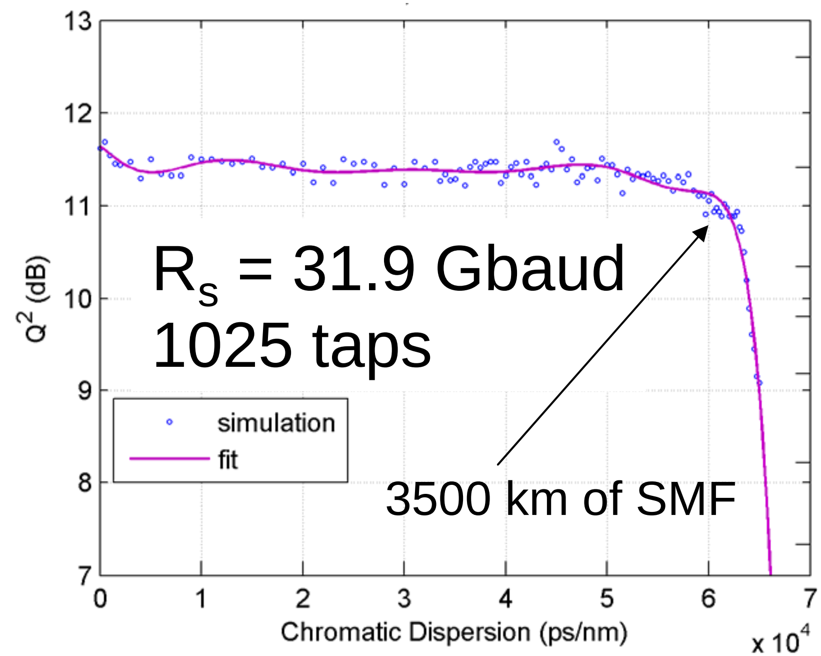
- Cycle slip is any rotation of n $\pi/2$ rad
- Cycle slip is an artifact of the CPE
- May happen under:
  - High peak-to-peak noise
  - Fast change
- Cycle slips lead to a catastrophic error propagation in non-differential mode (if no other precautions are taken like pilot symbols or interleaving)

Performance: Chromatic Dispersion

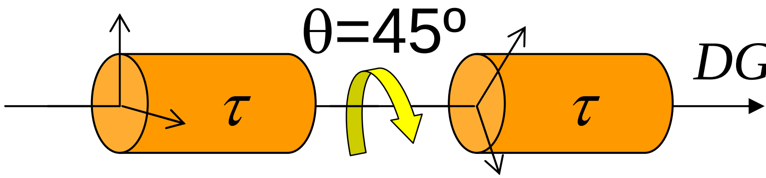


- $CD_{tol} \propto \frac{N}{R_s^2}$
- In principle, no limit to CD comp
- Limited by gate count and space considerations



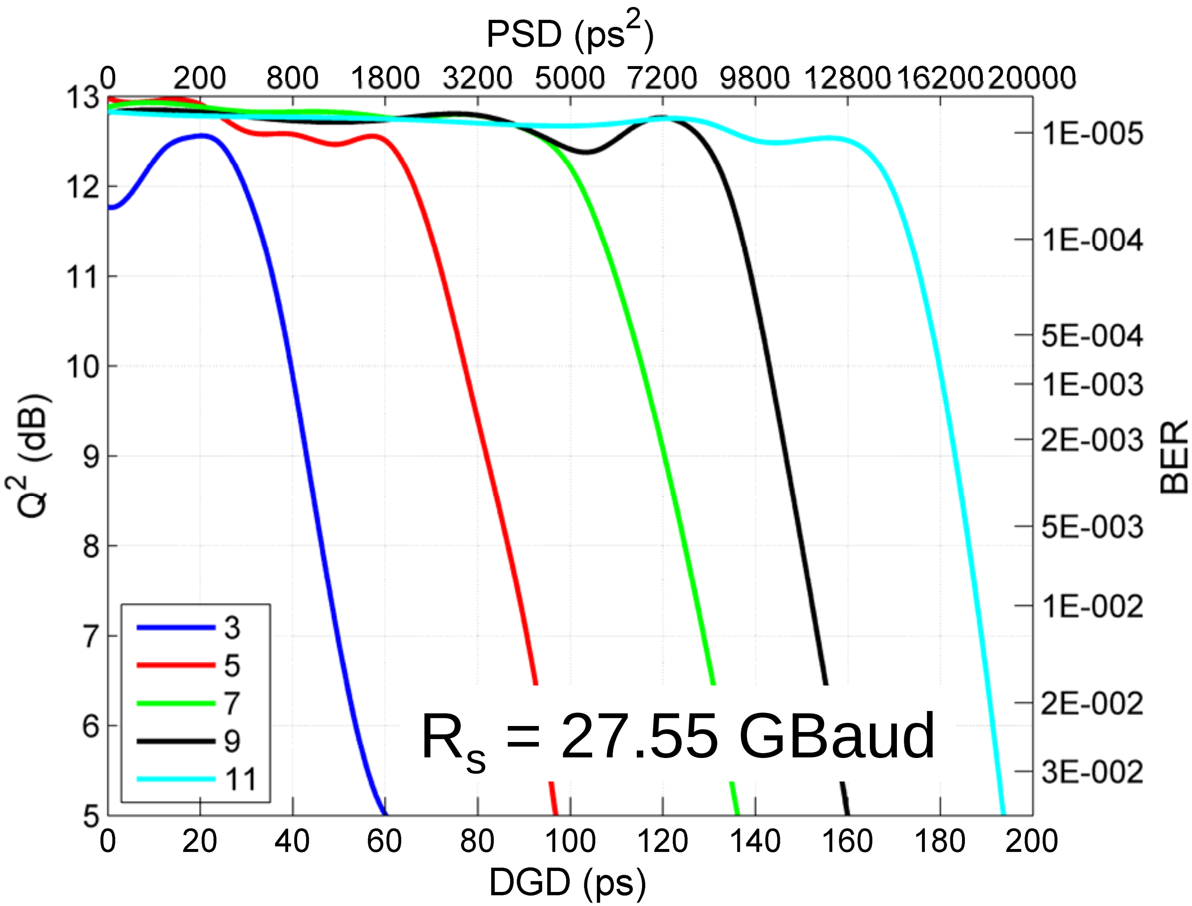


Performance: Polarization-Mode-Dispersion

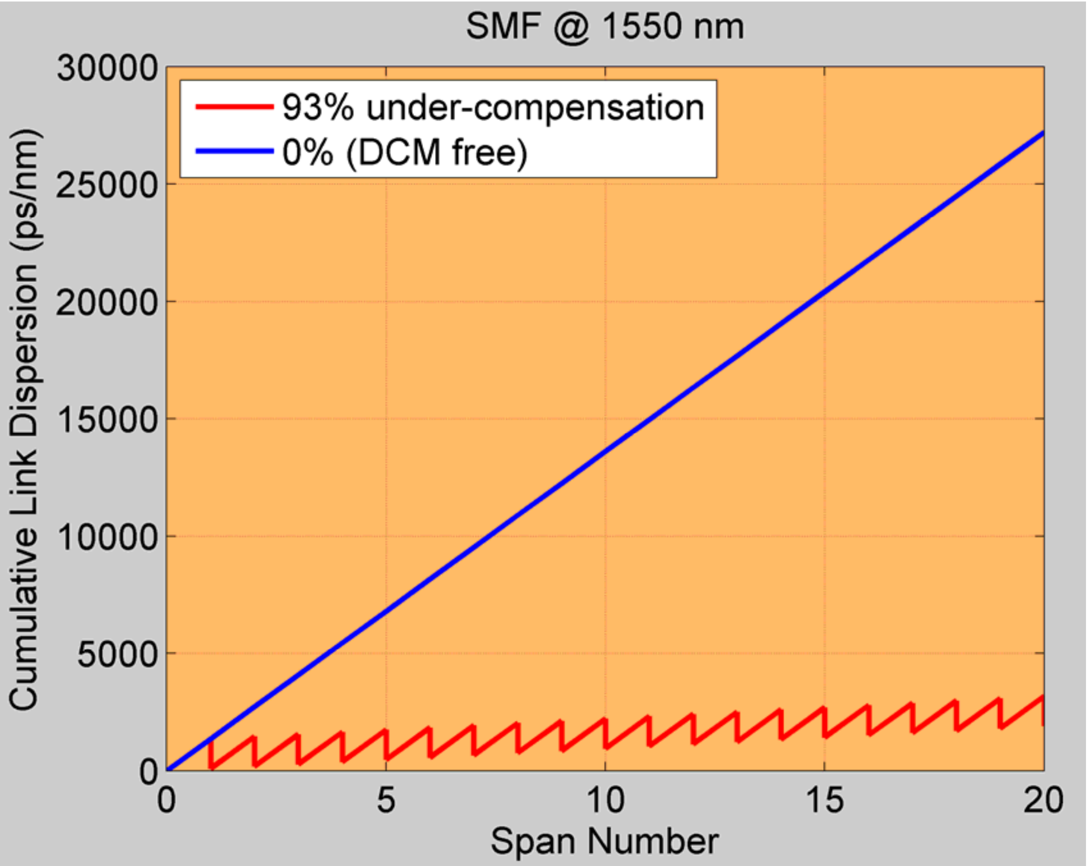


$$DGD(ps) = \tau\sqrt{2 + 2\cos 2\theta} \qquad PSD(ps^2) = \tau^2 \sin 2\theta$$

- Modeling DGD and PSD with 2 sections and 45deg rotation
- $DGD_{tol} \propto \dfrac{N}{R_s}$
- In principle, also no limit to PMD comp (second and higher orders)
- In practice, a few number of taps can compensate for maximum spec of 100 ps peak of DGD

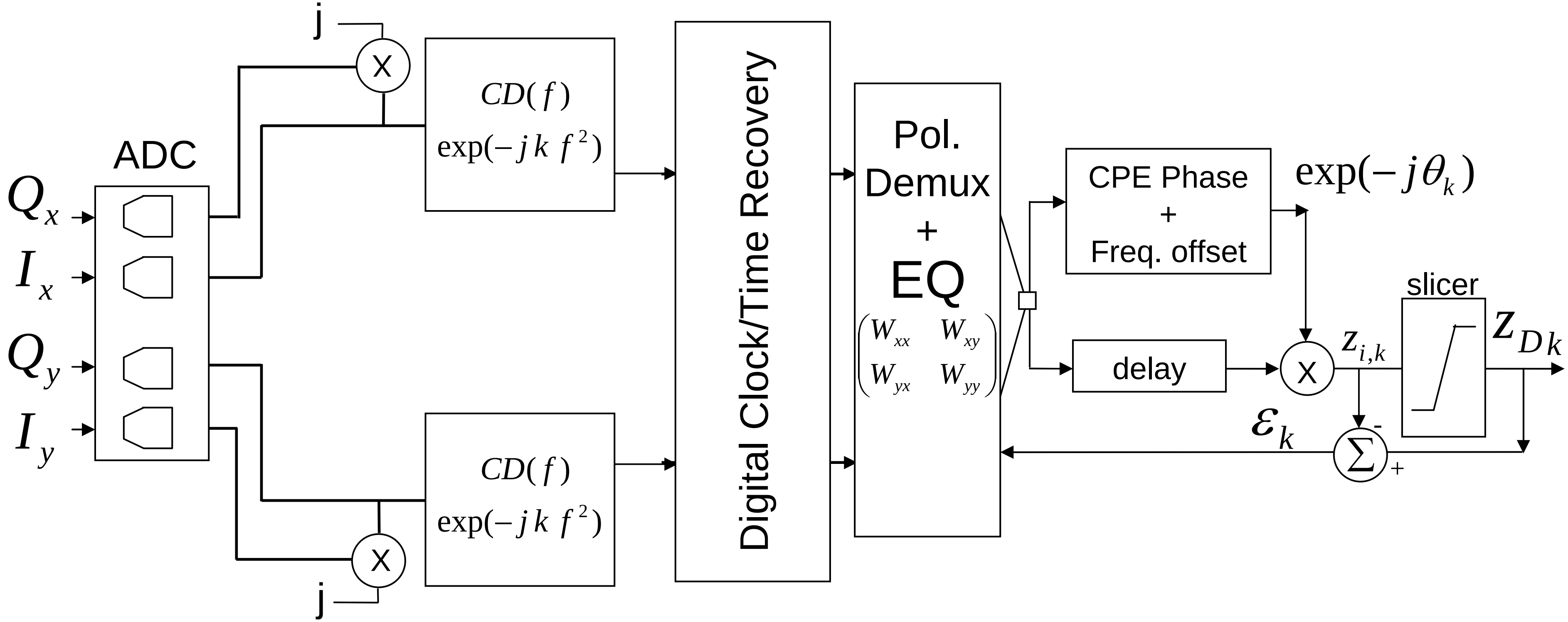


Is in-line dispersion comp. any more required?



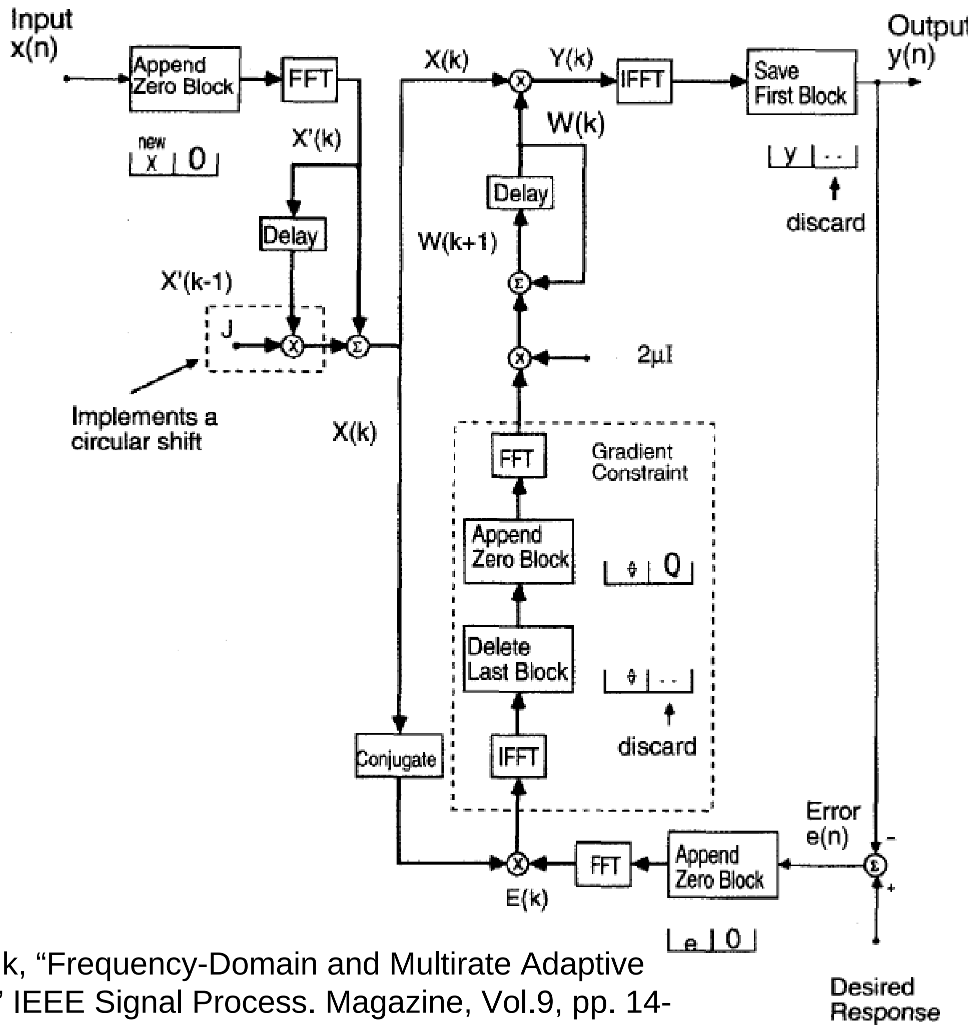
- Removing all the DCM: 18 ps/nm/km x 2000km = 36 000 ps/nm
- Why removing the DCM?
  - Less loss→better OSNR
  - No nonlinearity from DCM
  - Less nonlinearity from fiber
- Requires > 1000 taps
- Can it be done at 100Gb/s?
- Need a special design

Design to Accommodate Large CD Compensation



- One large "static" CD filter not updatable through the LMS
- One small adaptable EQ filter performing:
  - Polarization demux
  - Residual CD compensation
  - PMD compensation
  - Any other ISI compensation (optical filtering,…)

opnext



INITIALIZATION:

$$\mathbf{W}(0) = [0,\ldots,0]^T$$

$$P_m(0) = \delta_m, \quad m = 0,\ldots,N-1$$

MATRIX DEFINITION:

$$\boldsymbol{F} = N \times N \text{ DFT matrix}$$

FOR EACH NEW INPUT SAMPLE:

$$\mathbf{X}(n) = \text{diag}\{\boldsymbol{F}[x(n),\ldots,x(n-N+1)]^T\}$$

$$\mathbf{Y}(n) = \mathbf{X}(n)\mathbf{W}(n)$$

$$e(n) = d(n) - \mathbf{1}^T\mathbf{Y}(n)$$

$$\mathbf{E}(n) = \mathbf{1}e(n)$$

$$P_m(n) = \lambda P_m(n-1) + \alpha|X_m(n)|^2, \quad m = 0,\ldots,N-1$$

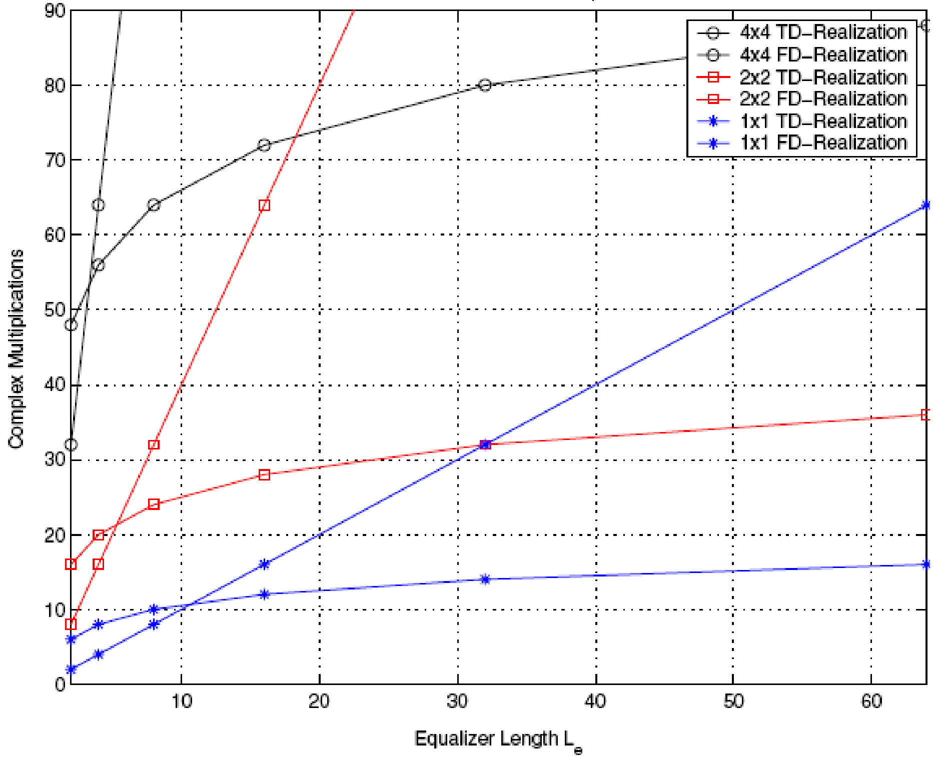
$$\boldsymbol{\mu}(n) = \mu\,\text{diag}\{P_0^{-1}(n),\ldots,P_{N-1}^{-1}(n)\}$$

$$\mathbf{W}(n+1) = \mathbf{W}(n) + 2\,\boldsymbol{\mu}(n)\mathbf{X}^H(n)\mathbf{E}(n)$$

J.J. Shynk, “Frequency-Domain and Multirate Adaptive Filtering,” IEEE Signal Process. Magazine, Vol.9, pp. 14-37, Jan. 1992

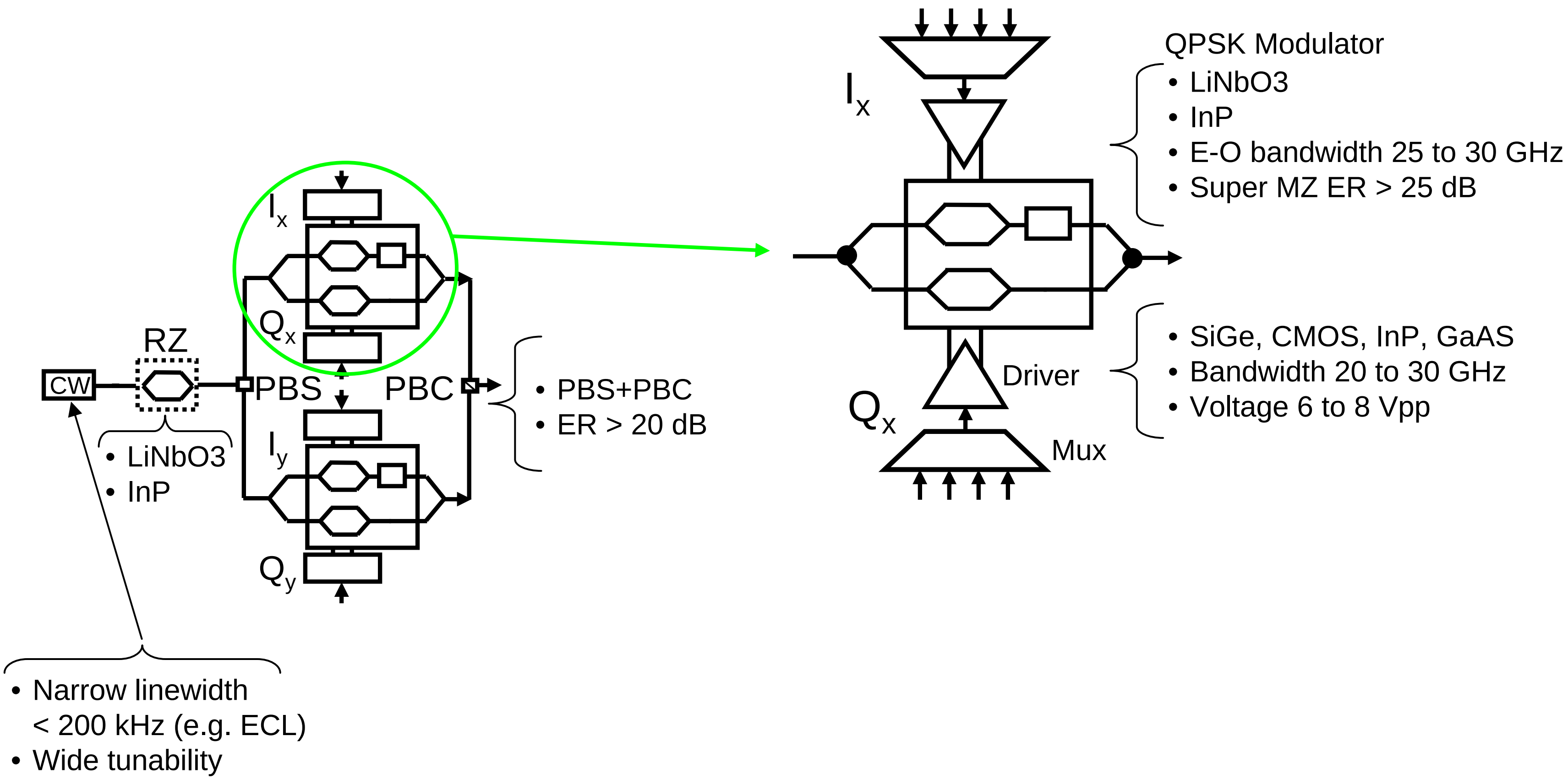
A. Burg, M. Rupp, s. Haene, D.Perels, N. Felber, W. Fichtner

Low Complexity Frequency Domain Equalization of MIMO Channels with Applications to MIMO-CDMA Systems

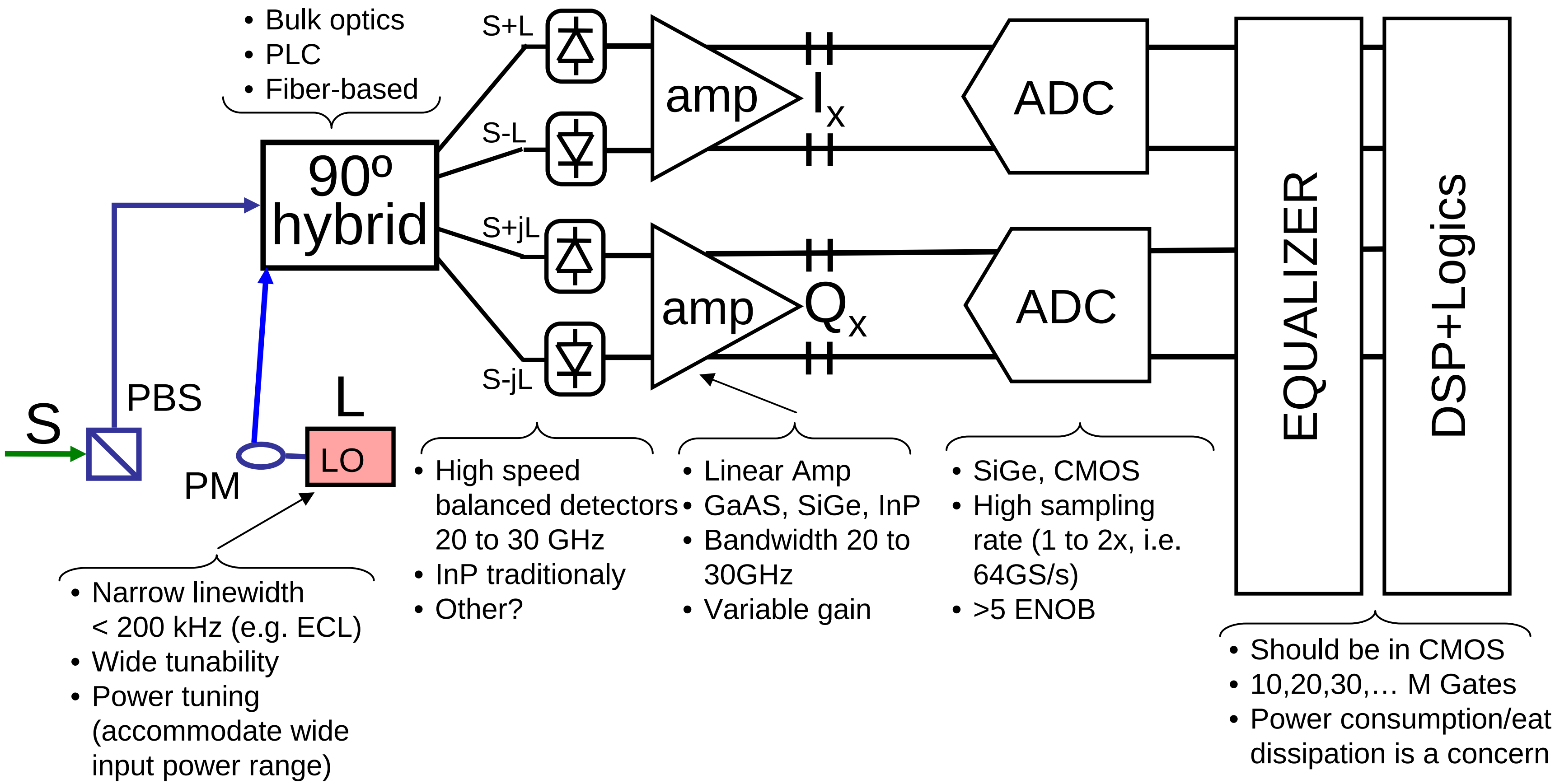


- Scaling rules on gates count:
  - N^2 for TD
  - $N \log_2 N$ for FD
- Break-even point:
  - 10 taps for 1x1
  - 4 taps for 2x2
- Anything beyond that, FD is much less complex

Technology/Material Options: Tx



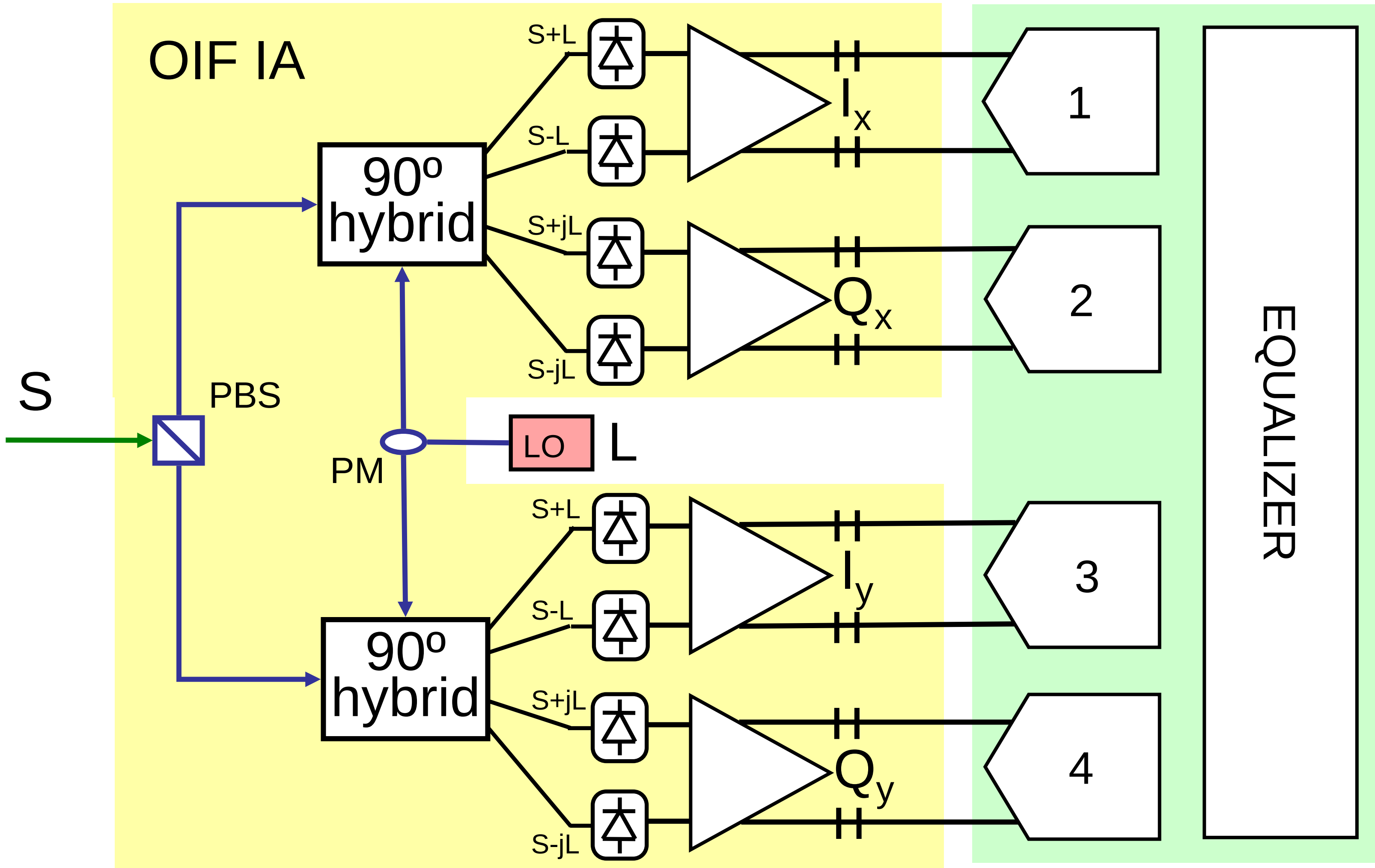
Technology/Material Options: Rx



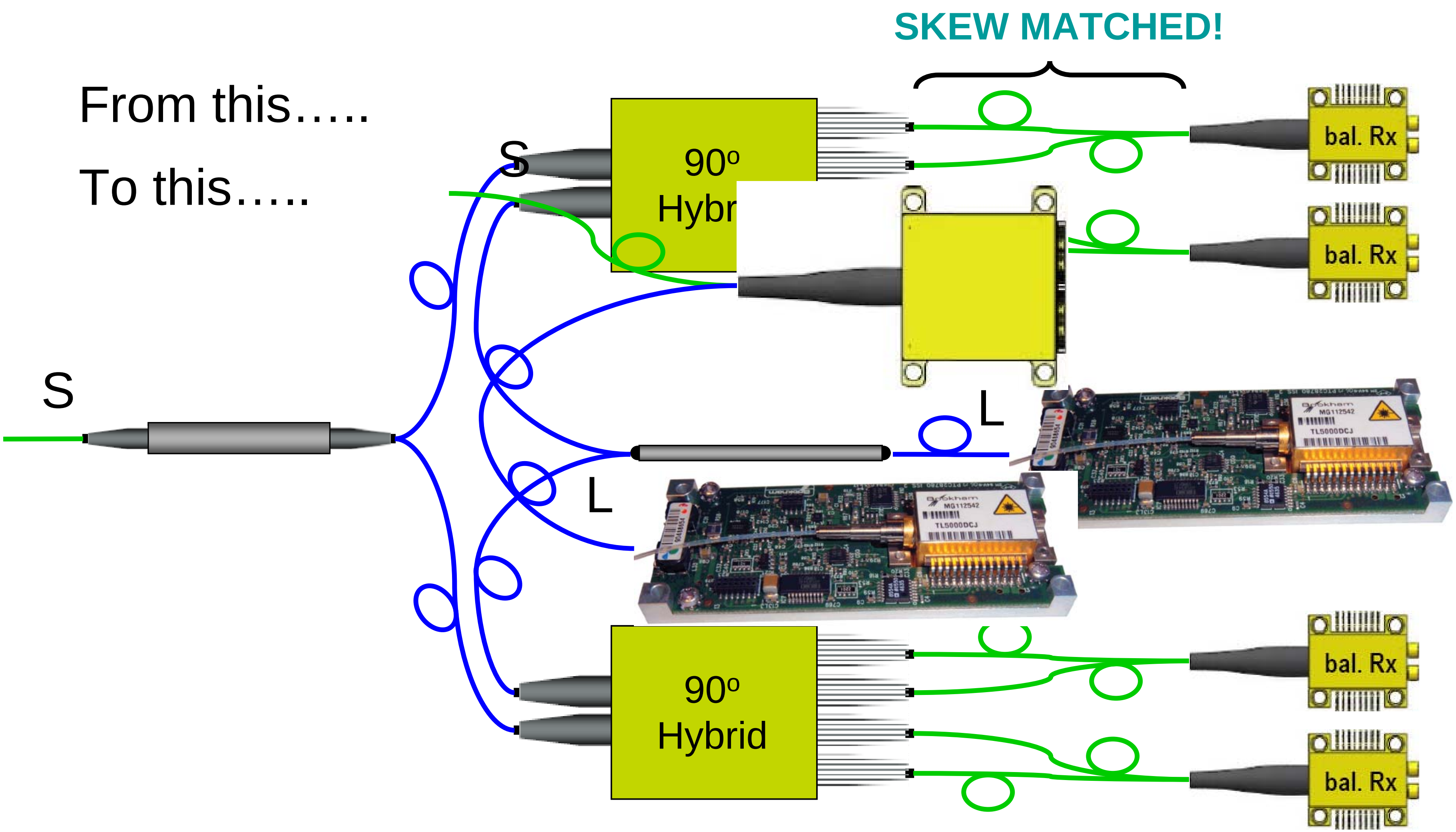
Making 100G DWDM a Reality

- Coherent systems exist on the market at 40G
- 100G coherent systems are under development
- Companies are actively funding 100G MODEM ASIC development
  - Required ADC and DSP functions are within current CMOS capabilities
- Optical functions exist on market
- Photonic integration is a key enabler
  - Manufacturability
  - Cost effectiveness
  - Size
- OIF PLL project currently underway defining Integrated TX and RX Photonics for 100 PM-QPSK applications (see www.oiforum.com)

Photonic Integration: A Key Enabler



Driving Home the Point



Conclusion

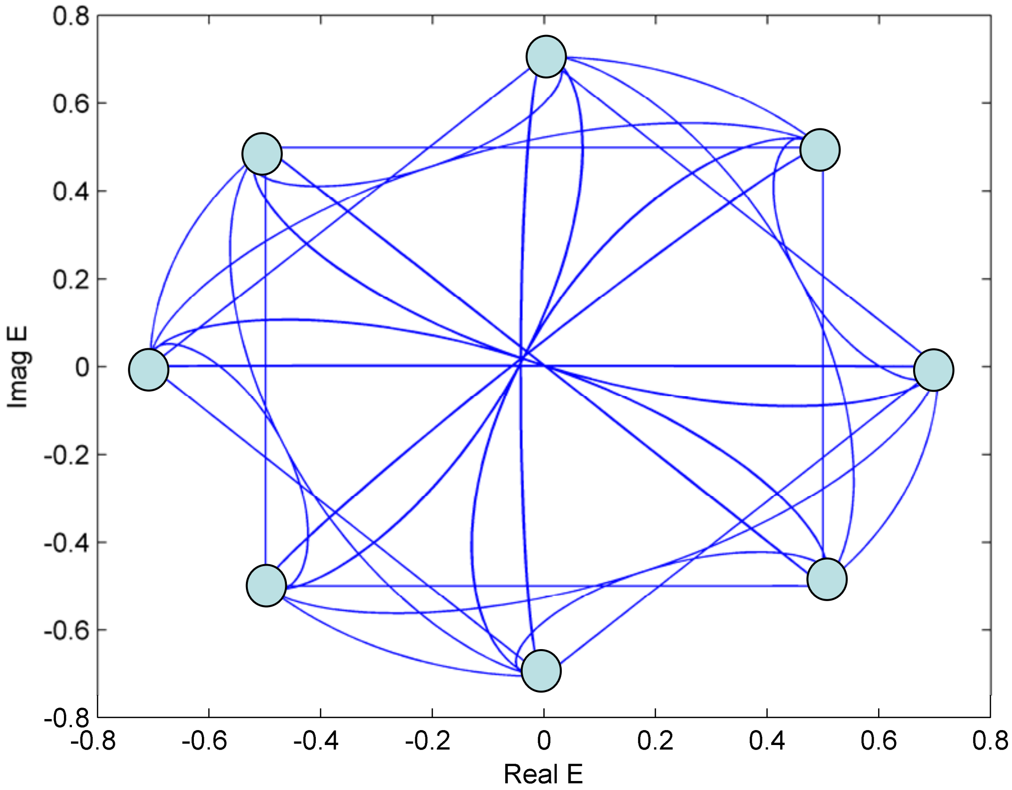
- To retro-fit existing 10Gb/s-optimized networks, 100Gb/s coherent PM-QPSK is one of the few modulation formats to meet the requirements:
  - Enough B2B OSNR margin at 16 to 18 dB of OSNR (in 0.1 nm RBW)
  - Launch power around 0dBm and reach above 2000 km
  - CD compensation of:
    - 1000 ps/nm for existing links
    - 36 000 ps/nm for new "green field" links
  - PMD compensation of <DGD> = 30 ps
  - Large number of (R)OADM/Mux/Demux filtering elements supporting 50 GHz spacing

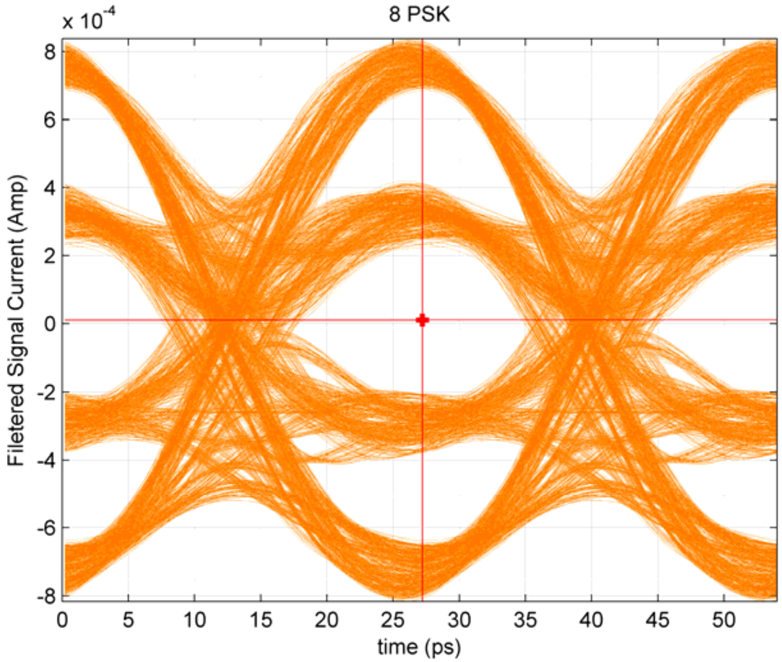
Path to Higher Data Rates

- High coding gain FEC already common
- Highest performing modulation formats being used
- Higher channel rates will require changes to fiber optics link to meet reach objectives:
  - Improve link OSNR
  - Lower noise figure amplifiers
  - Raman amplification
  - Reduced NL effects (new fibers)
  - Move to DCM free links

Backup Slides: 8 PSK

- M-ary reduces the symbol rate but reduces also the distance between symbols in the constellation diagram leading to…
- B2B 3 dB less OSNR





OTuN1.pdf

Modulation Formats For 100Gb/s Coherent Optical Systems

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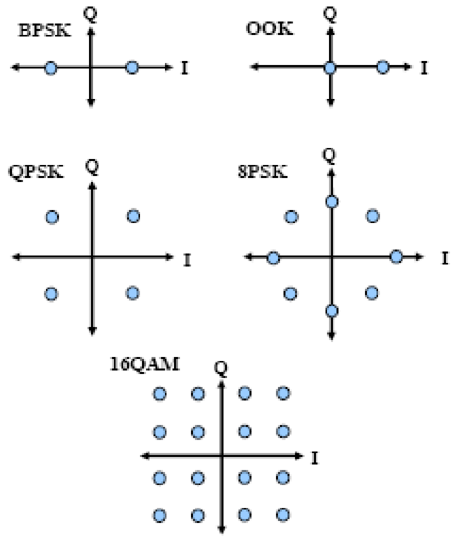


Fig. 1a Modulation formats under consideration

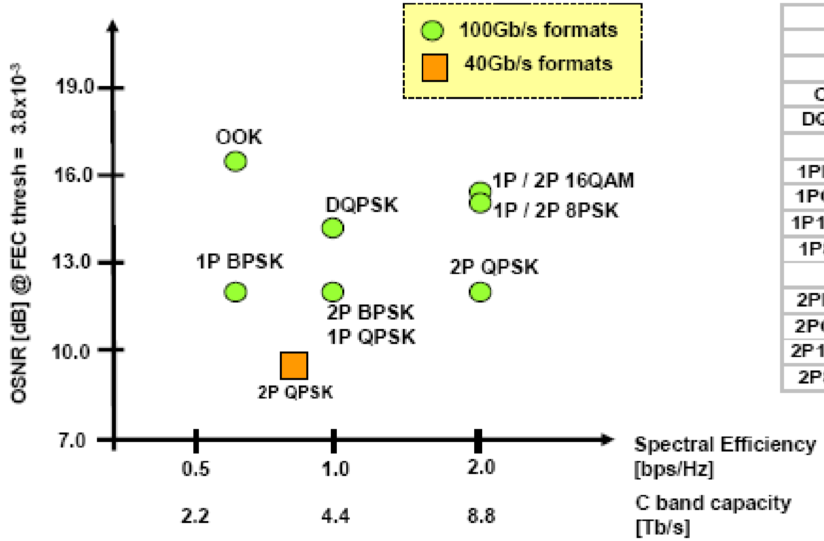
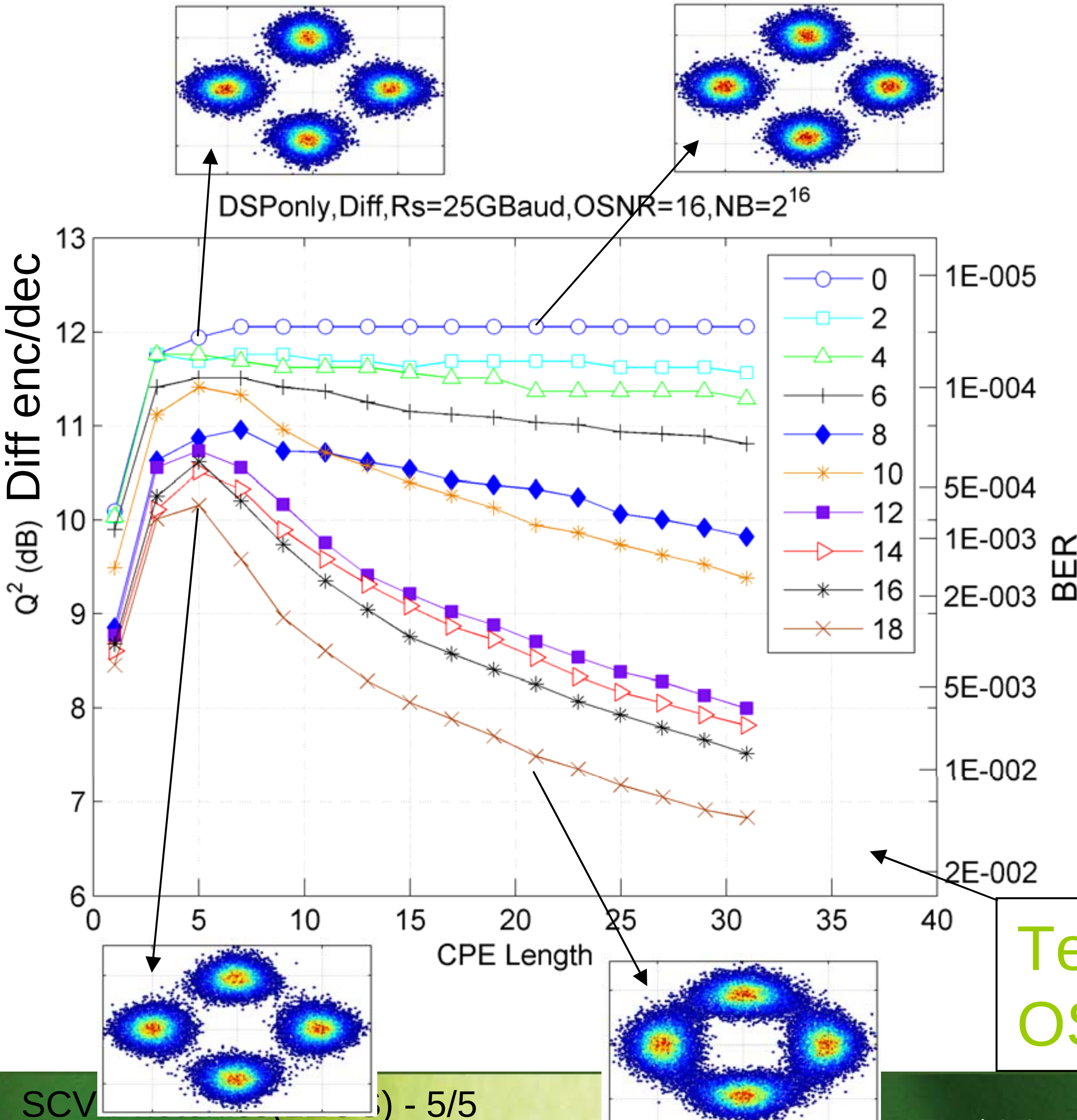


Fig. 1b Comparison based on OSNR tolerance and S.E.

	Fbaud [GHz]	OSNR Tol [dB]	ϕ margin [deg]
OOK	107.0	16.3	n/a
DQPSK	53.5	14.3	45
1PBPSK	107.0	11.8	90
1PQPSK	53.5	11.8	45
1P16QAM	26.8	15.4	16.9
1P8PSK	35.7	14.9	22.5
2PBPSK	53.5	11.8	90
2PQPSK	26.8	11.8	45
2P16QAM	13.4	15.4	16.9
2P8PSK	17.8	14.9	22.5

Backup Slides: CPE averaging window



- Laser linewidth Δf = 1MHz.
- Phase Noise for different SMF span number (legend)
- For only linewidth+ASE phase noise (span = 0), optimal CPE length is between 10 and 30 (assuming OSNR=16dB)
- For large WDM phase noise (span 18), optimal CPE length is between 5 to 7. In-line with [1]

Tested under OSNR=16dB

[1]


WE1.3 (Invited)
10.30 - 11.00

Effect of Carrier Phase Estimation for 111Gbit/s POLMUX-RZ-DQPSK Equalization in Presence of 10.7Gbit/s OOK Neighbours

Abstract: We optimize carrier phase estimation (CPE) to increase the XPM tolerance of 111-Gb/s POLMUX-RZ-DQPSK in the presence of 10.7-Gb/s OOK neighbours transmitted over an 1140 km EDFA-only link.

Introduction