Bell Labs

Transmission cohérente sur fibre optique

CFOR: Technologies des réseaux à fibres optiques multi-terabit/s

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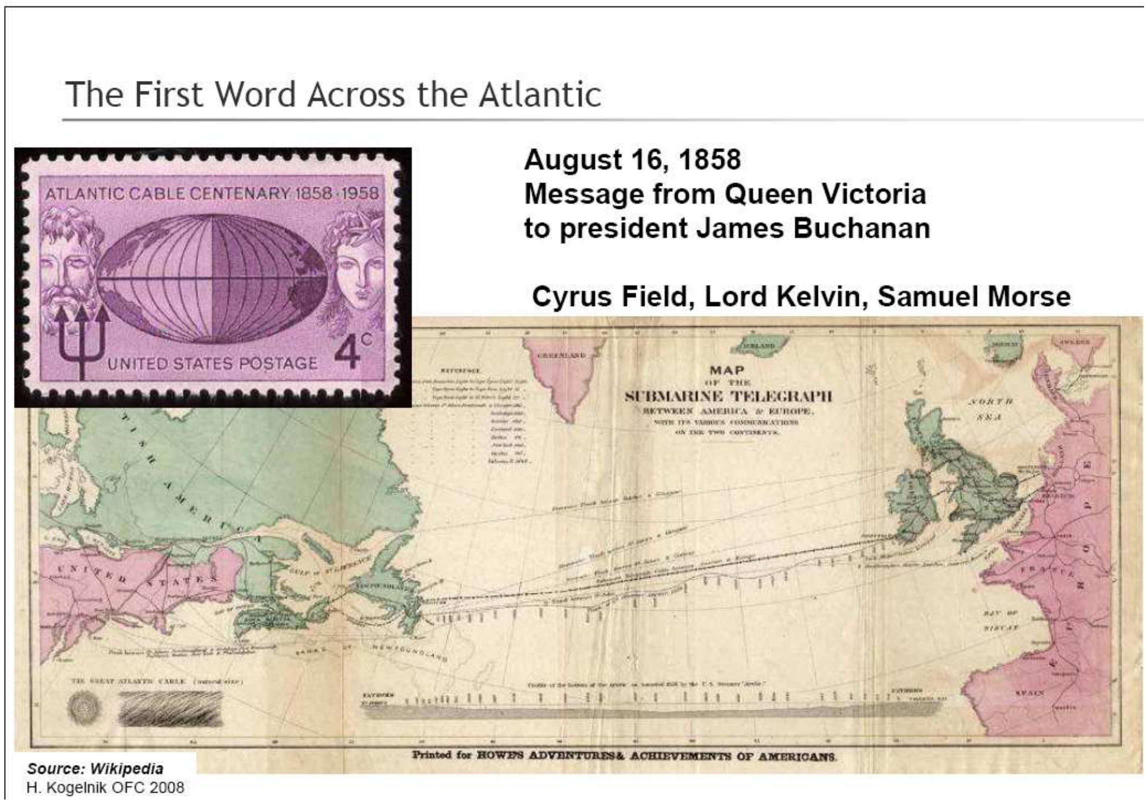
- 1er Dec. 2016

Introduction

- Long haul optical systems transport almost all data traffic (>99%).
- Undersea optical systems are the successor of the first telegraphic undersea cables !
- Transport data, video, internet, voice (fix & mobile) over a single network.
- Initial deployment of optical networks in the 1980s.

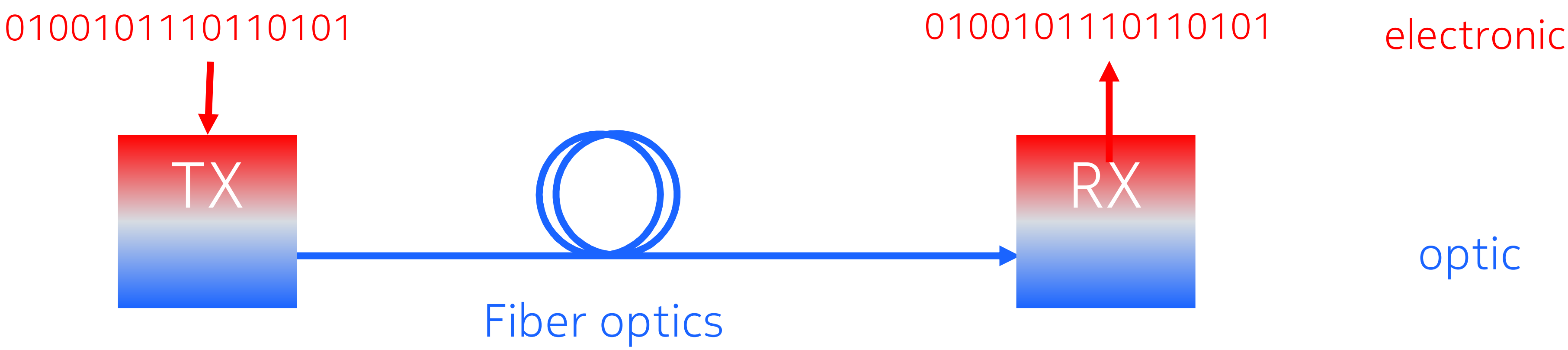


OUTLINE

- **Direct detection**
- Basics of coherent detection
- Implementation of coherent transponder
- System performances obtained thanks to coherent
- Conclusion

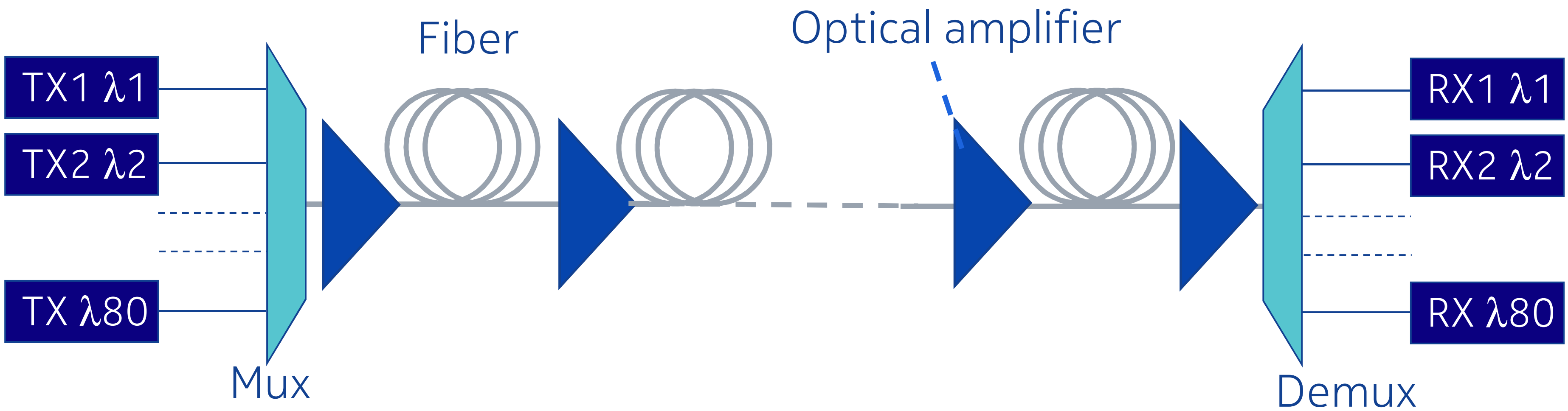
Optical data transmission

Encoding bits on an optical signal, fiber transmission and reverse operation



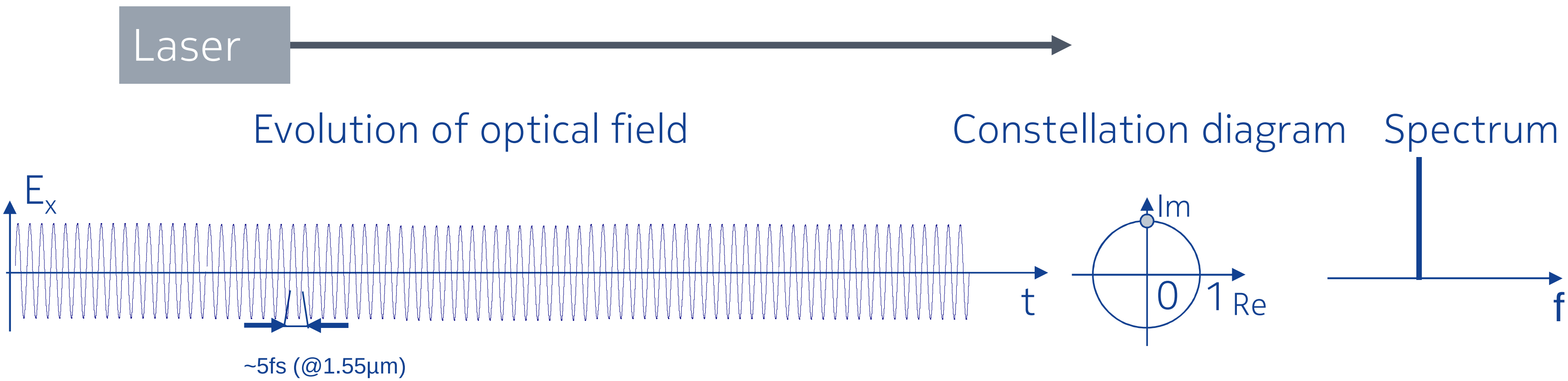
- Benefits from fiber optics:
  - Low attenuation ~0.2dB/km
  - Wide bandwidth with low attenuation (>>10THz)
  - Efficient optical amplification (Erbium doped fiber amplifier over 2 x 5THz)

Point to point WDM system



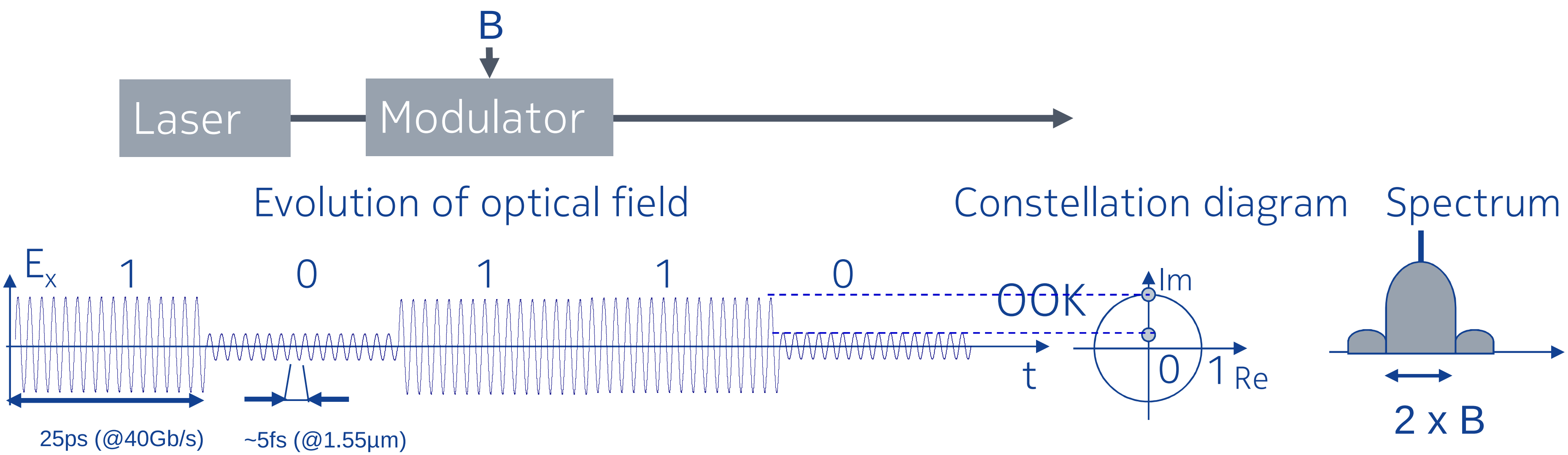
- Typically 80 to 100 channels (wavelengths) with 50GHz spacing
- 100-200Gb/s per channels typical in 2016
- Span length : 50 to 100km (10 to 30dB span loss typically)
- 10-20 amplifiers for terrestrial systems, up to 200 for undersea systems !

Electrical field and spectrum of laser



- 1.55µm used in long distance telecom industry to benefit from the lowest attenuation of fiber and of optical amplification from EDFA.
- This wavelength corresponds to a frequency of ~200THz

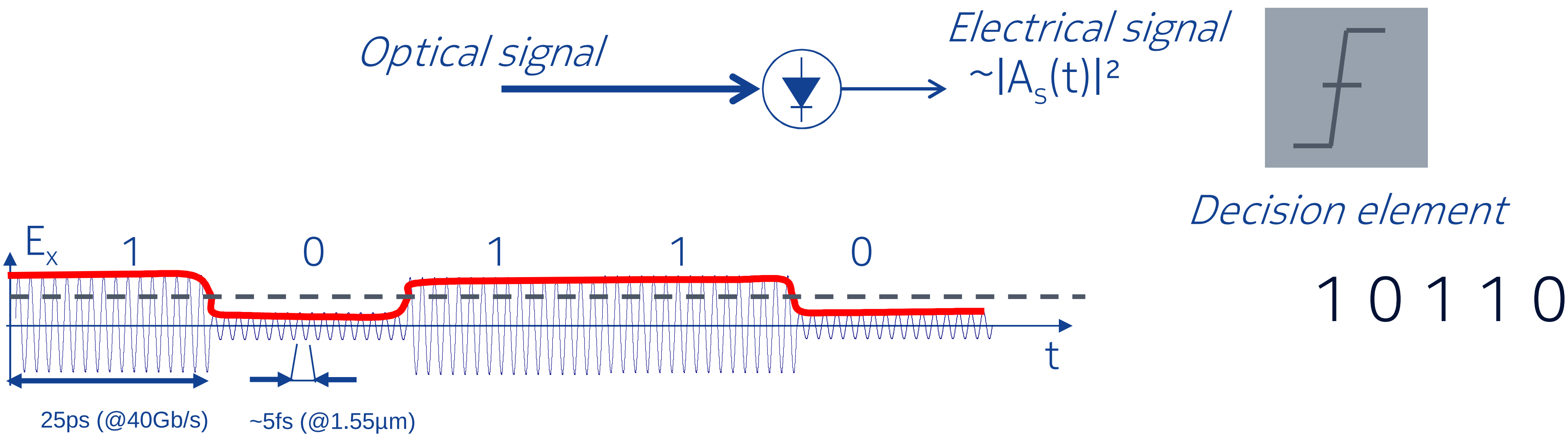
Modulation format, constellation diagram, spectrum



- Constellation diagram represents the field of the electrical signal at the center of each symbol.
- Spectrum width (of first lobe) is twice the modulation speed

Direct detection

Direct detection is the conventional way to detect optical signal.
= QUADRATIC detection of electric field,



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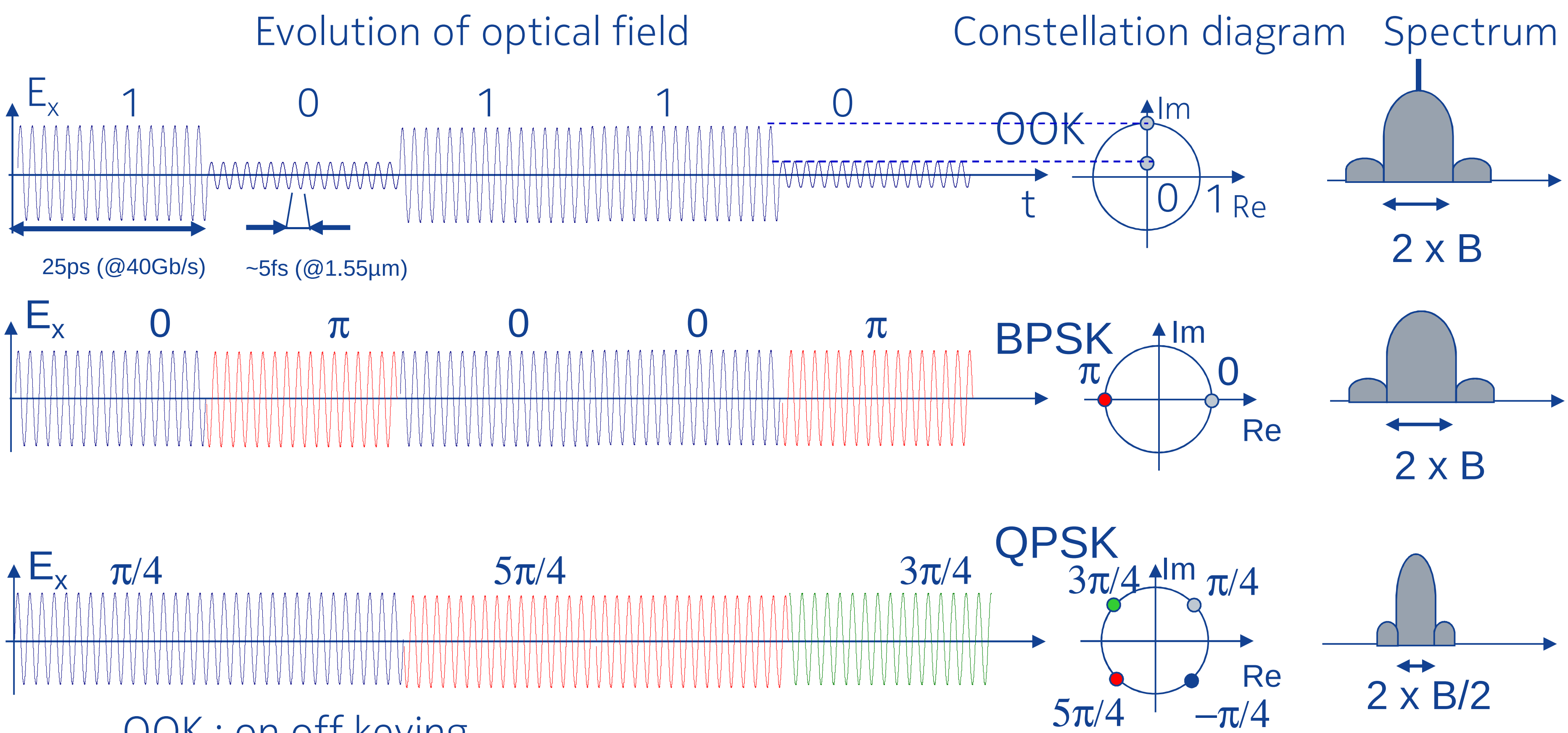
Modulation format and constellation diagram

Phase shift keying

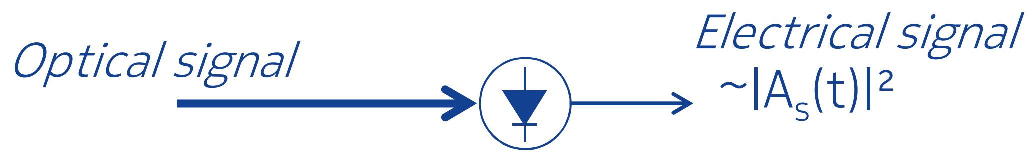


OOK : on off keying
BPSK : binary phase shift keying
QPSK : quadrature phase shift keying

Differential detection

Direct detection is the conventional way to detect optical signal.

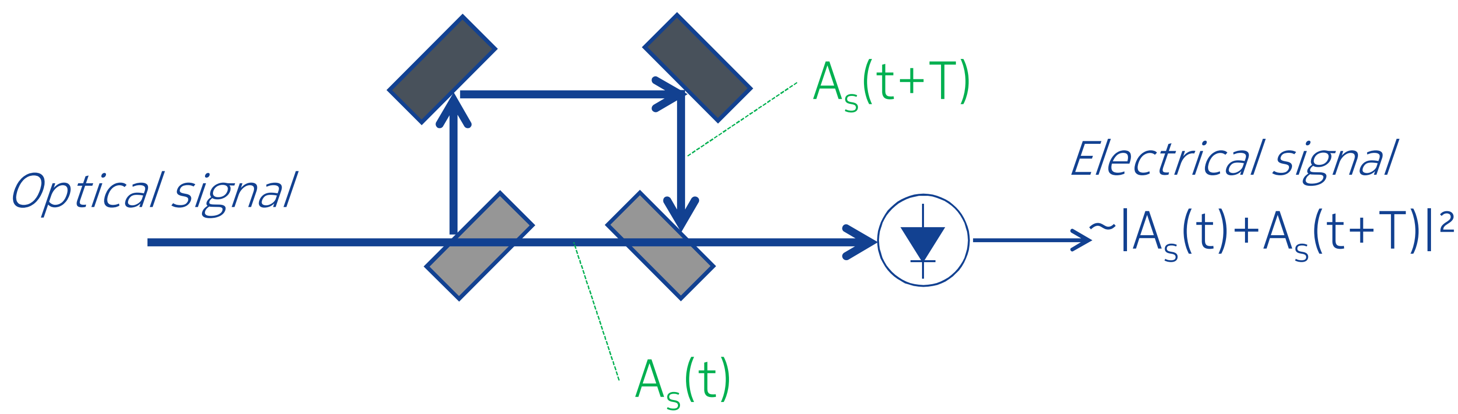
= QUADRATIC detection of electric field,



Differential detection

= Optical demodulator + direct detection

- Suited for detection of phase modulated signal

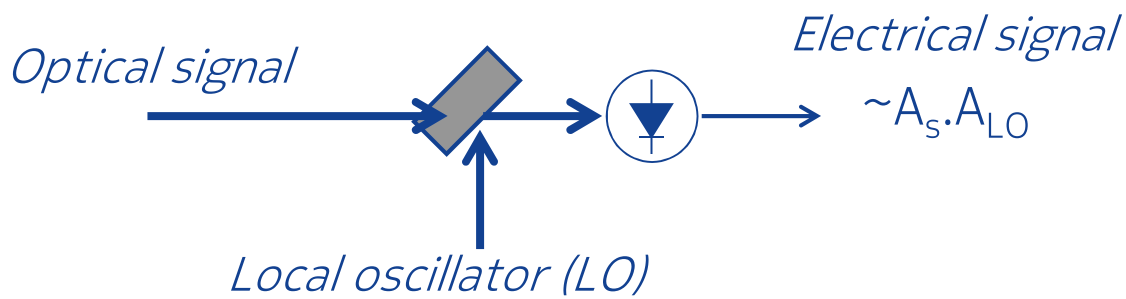


Coherent detection

Coherent detection

= LINEAR detection of the electric field, by beating with local oscillator (LO)

- LO frequency = Signal frequency → homodyne detection
- LO frequency ≠ Signal frequency → heterodyne detection
- LO frequency ≈ Signal frequency → intradyne detection



Motivation for coherent detection in the 1980's

- No optical amplifier available at that time.
- Transmission distance was mostly limited by fiber attenuation.
- « Amplification » provided by strong local oscillator. $A_s.A_{LO}$ vs $A_s.A_s$

- Amplitude shift Keying (ASK) vs Phase shift Keying (PSK) ?

Table 2.2. Number of photons per one signal bit required to achieve $BER = 10^{-9}$.

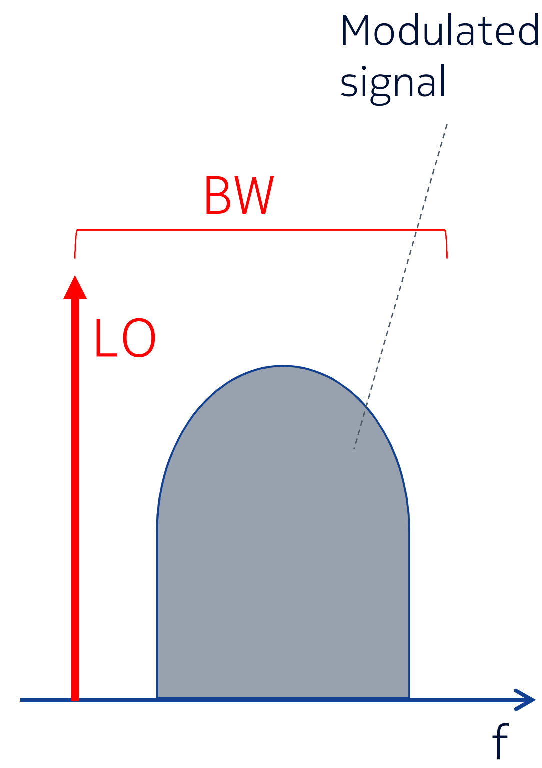
Coherent schemes		$N_{required}$
Heterodyne	ASK	80
	FSK	40
	PSK/DPSK	20
Homodyne	ASK	40
	PSK	10

Coherent detection in the 1980's

Homodyne or heterodyne ?

Table 5.1. *Comparison of heterodyne and homodyne systems (after Kazovsky[1])*.

Item	Heterodyne	Homodyne
Receiver sensitivity	3 dB worse than homodyne	3 dB better than heterodyne
Optical phase stability	Not needed unless coherent postdetection is employed	Needed
Optical frequency stability	Needed. The requirement is not stringent unless coherent postdetection is employed	Needed. The requirement is very stringent
Polarization stability	Needed	Needed
Required detection bandwidth (highest amplifier frequency)	5~6 times that of homodyne system	Equal to baseband



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Coherent detection in the 1980's

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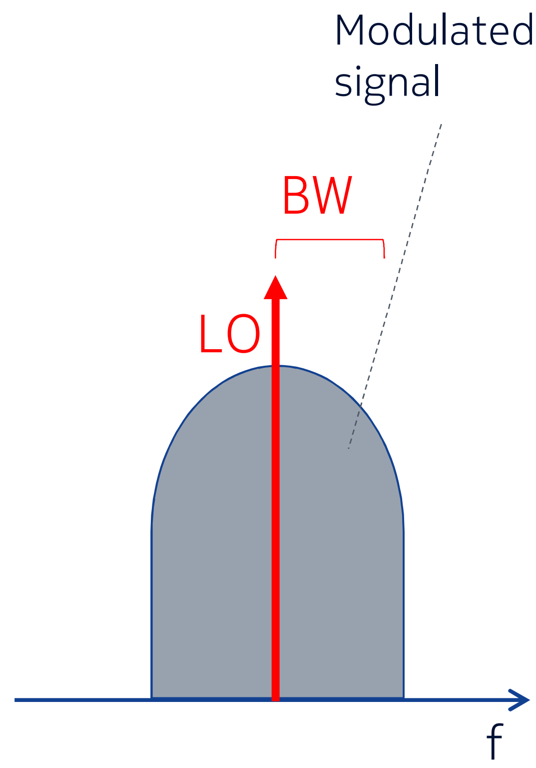


But EDFA was invented...

Renewal interest for coherent detection ~2005

- Technological evolutions:
  - Availability of high speed ADC (high bandwidth, high sampling rate)
  - Strong progress of CMOS digital signal processing capabilities

- Optical transmission landscape
  - Phase shift keying modulation used again! (with differential detection) DPSK, DQPSK
  - Electronic Signal processing (FFE, DFE,… for chromatic dispersion, PMD… mitigation)
  - Willingness to increase spectral efficiency

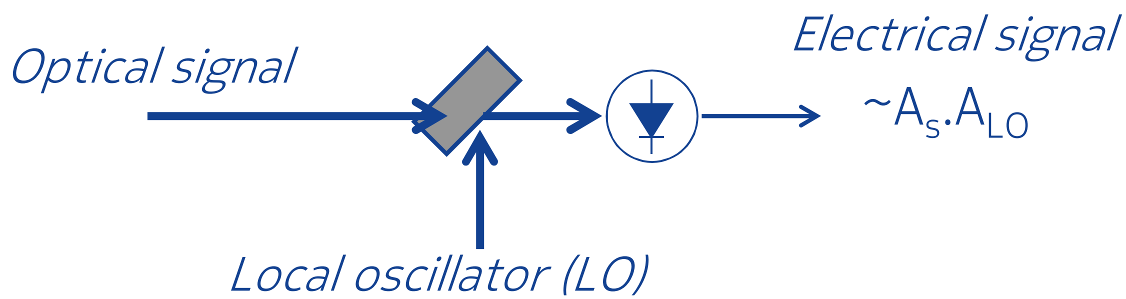
First “modern” coherent detection experiment in 2004-2005

Intradyne coherent detection

Coherent detection

= LINEAR detection of the electric field, by beating with local oscillator (LO)

- LO frequency = Signal frequency → homodyne detection
- LO frequency ≠ Signal frequency → heterodyne detection
- LO frequency ≈ Signal frequency → intradyne detection



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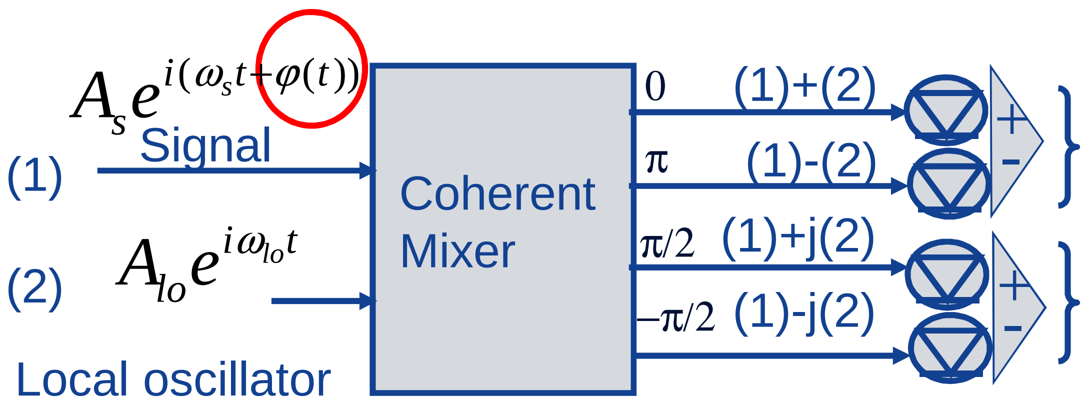
Interference at coherent mixer output

Coherent mixer or 90° hybrid



$$I_1(t) = PD_1(t) - PD_2(t)$$

$$I_2(t) = PD_3(t) - PD_4(t)$$

$$PD_1 = (E_s + E_{ol}).(E_s + E_{ol})^* = |A_s|^2 + |A_{ol}|^2 + 2A_sA_{ol}\cos[(\omega_s - \omega_{ol})t + \varphi(t)]$$

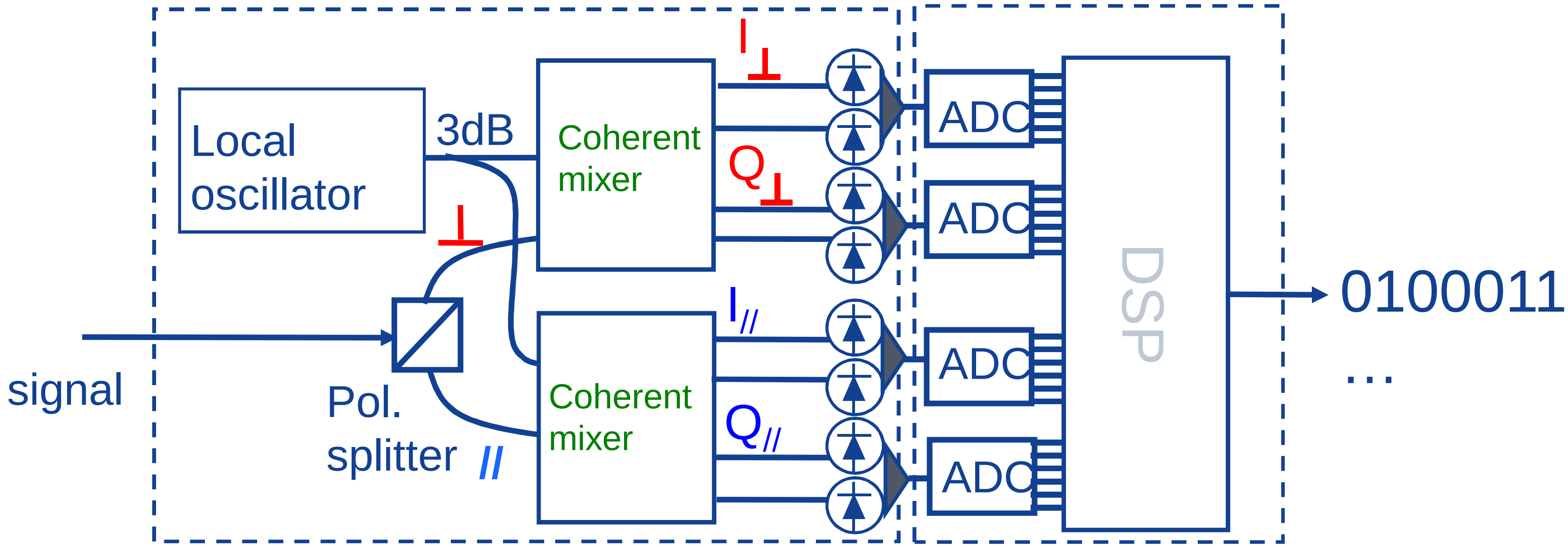
$$PD_2 = (E_s - E_{lo}).(E_s - E_{lo})^* = |A_s|^2 + |A_{ol}|^2 - 2A_sA_{ol}\cos[(\omega_s - \omega_{ol})t + \varphi(t)]$$

$$I_1(t) = 4A_sA_{lo}\cos[(\omega_s - \omega_{lo})t + \varphi(t)]$$ In phase “I”

$$I_2(t) = 4A_sA_{lo}\sin[(\omega_s - \omega_{lo})t + \varphi(t)]$$ Quadrature “Q”

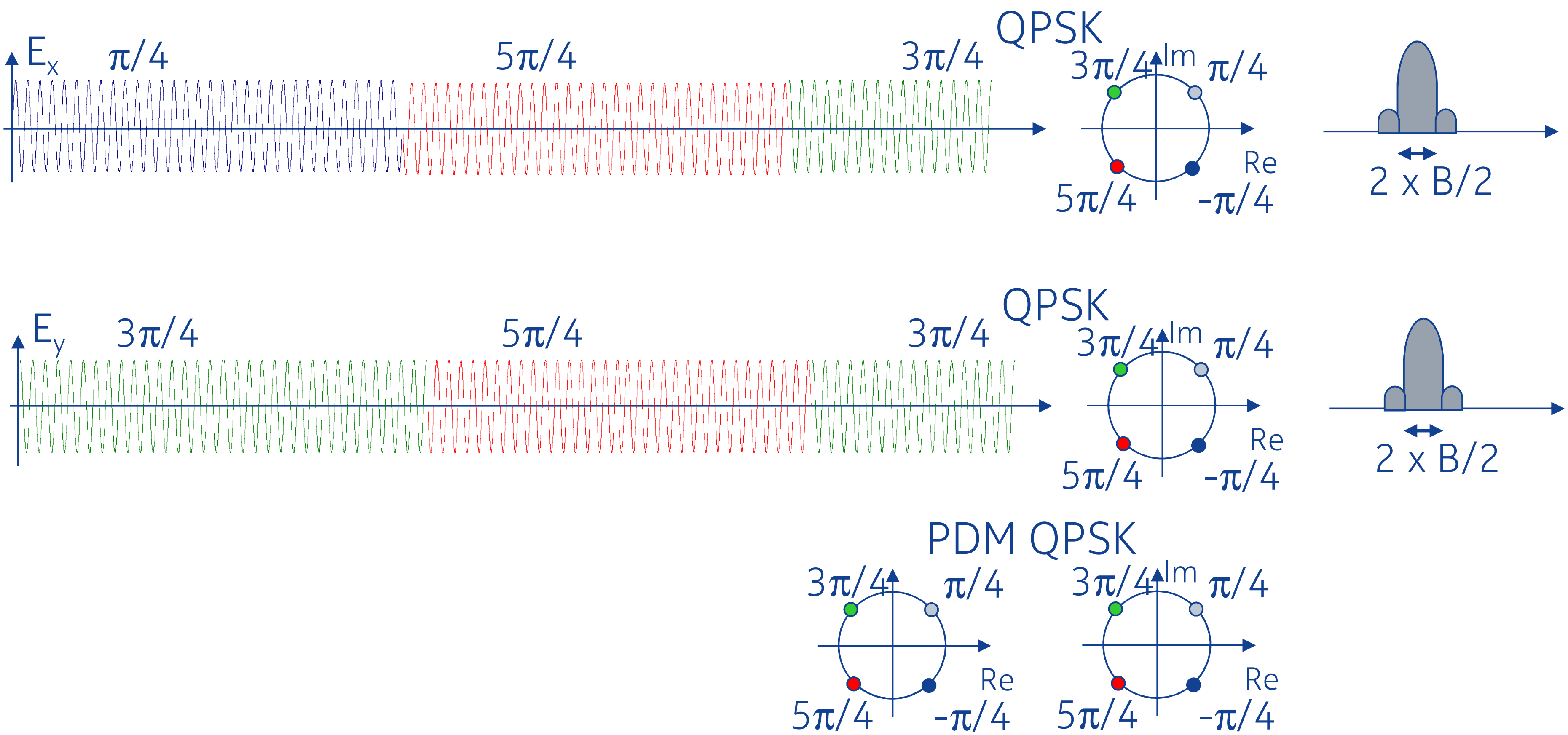
Polarization diversity receiver

signal polarization fluctuate over time => polarization diversity RX required



Polarization division multiplexing: PDM

Double the bit rate transported



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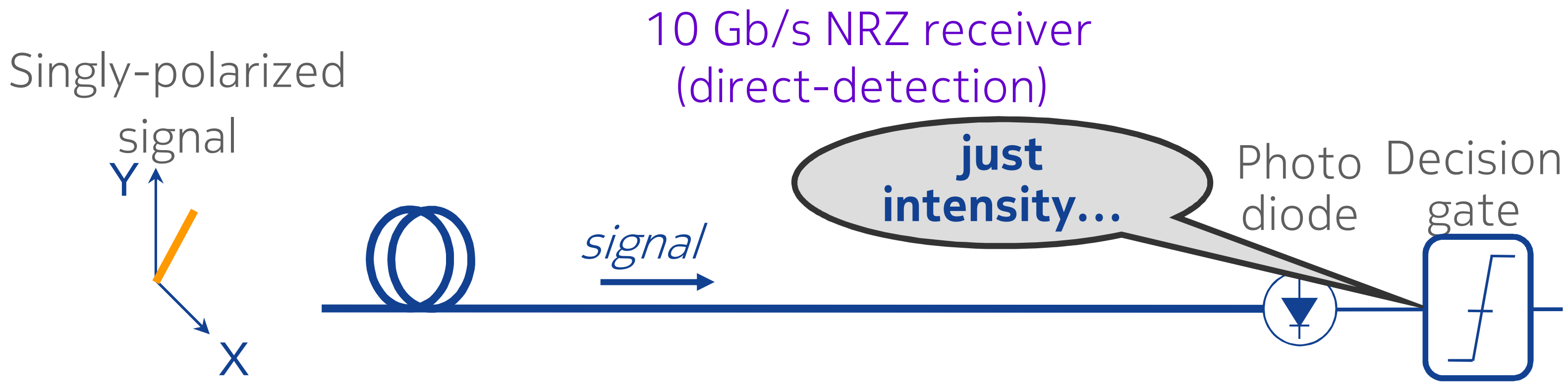
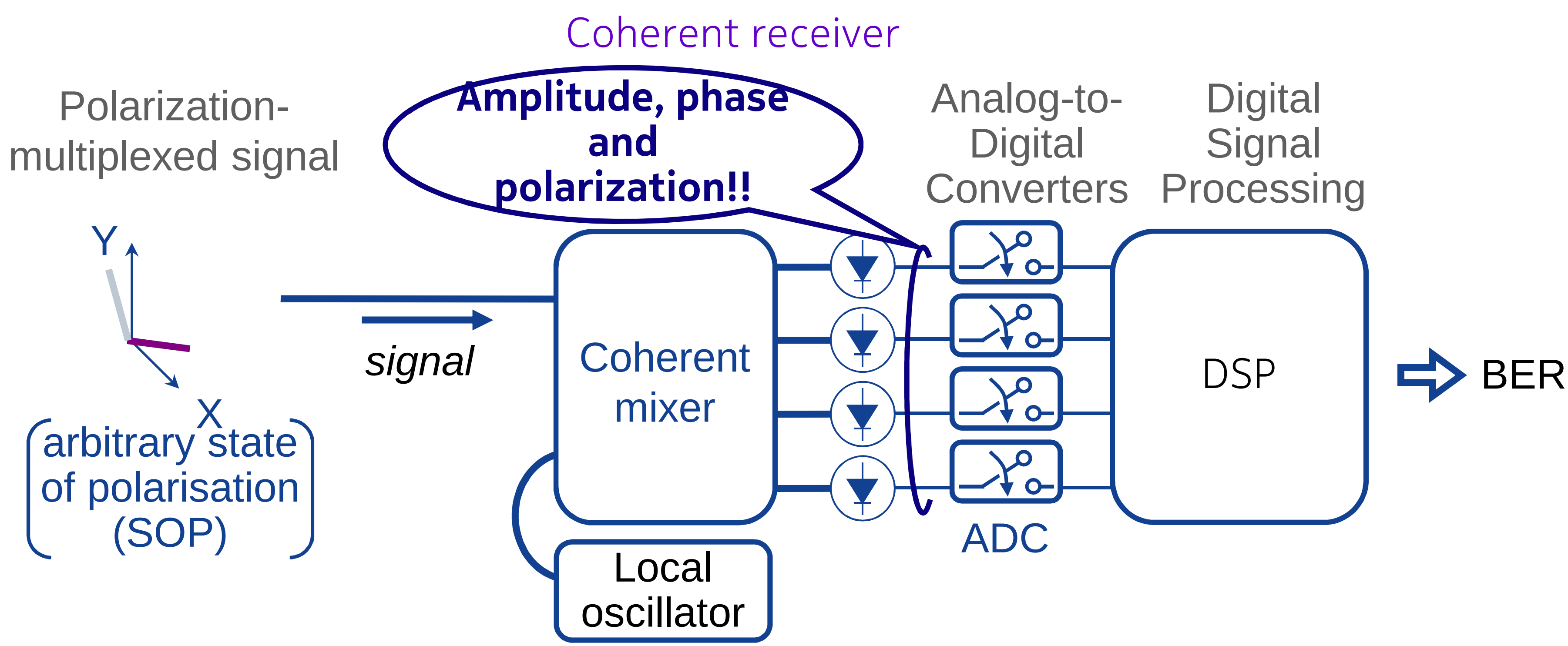
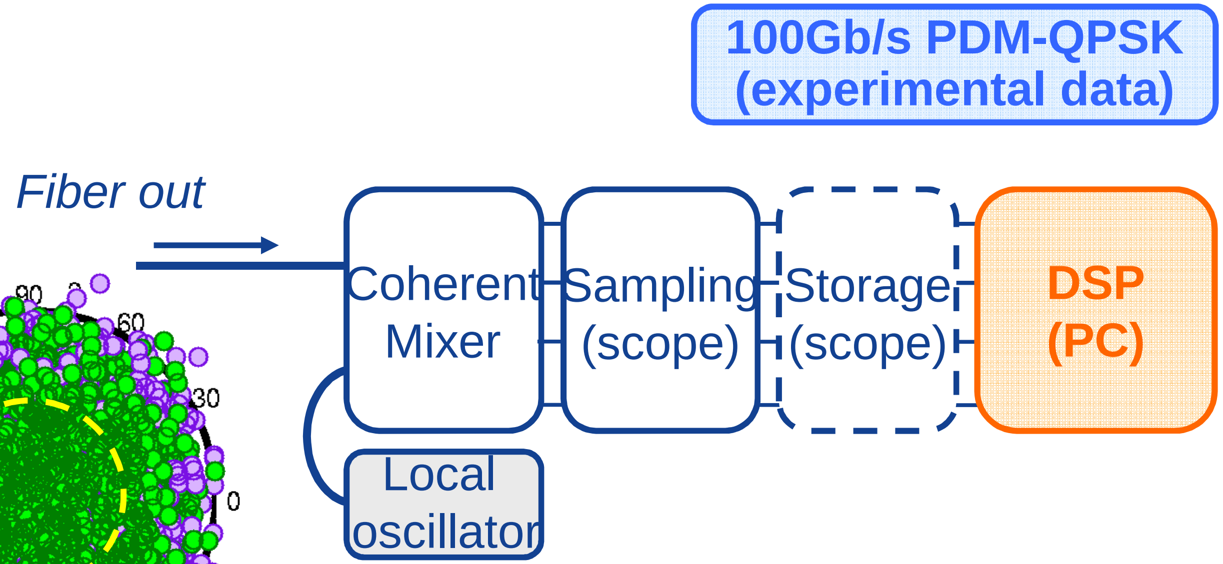
Digital coherent receiver versus direct-detected systems…

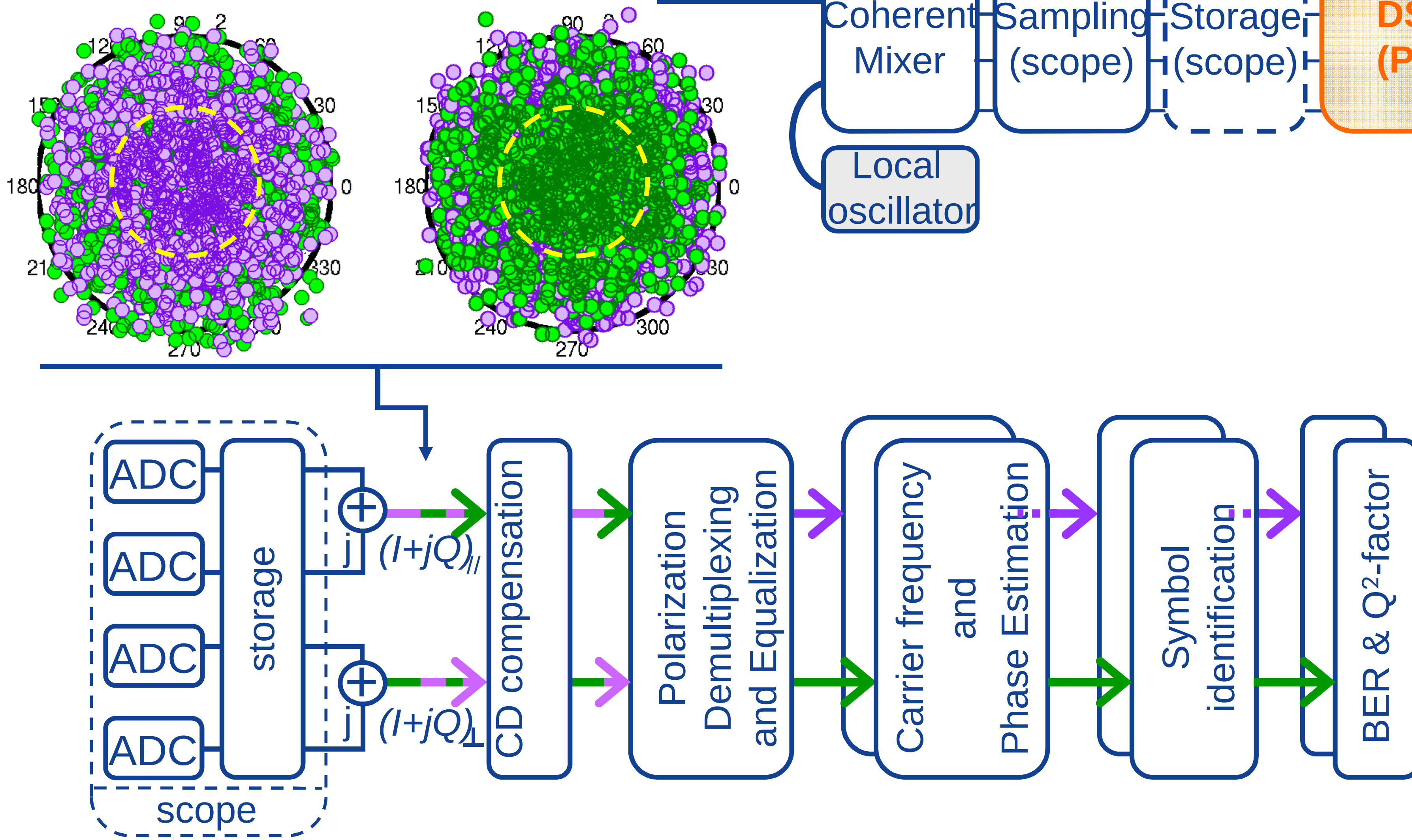




Coherent receiver

Digital signal processing





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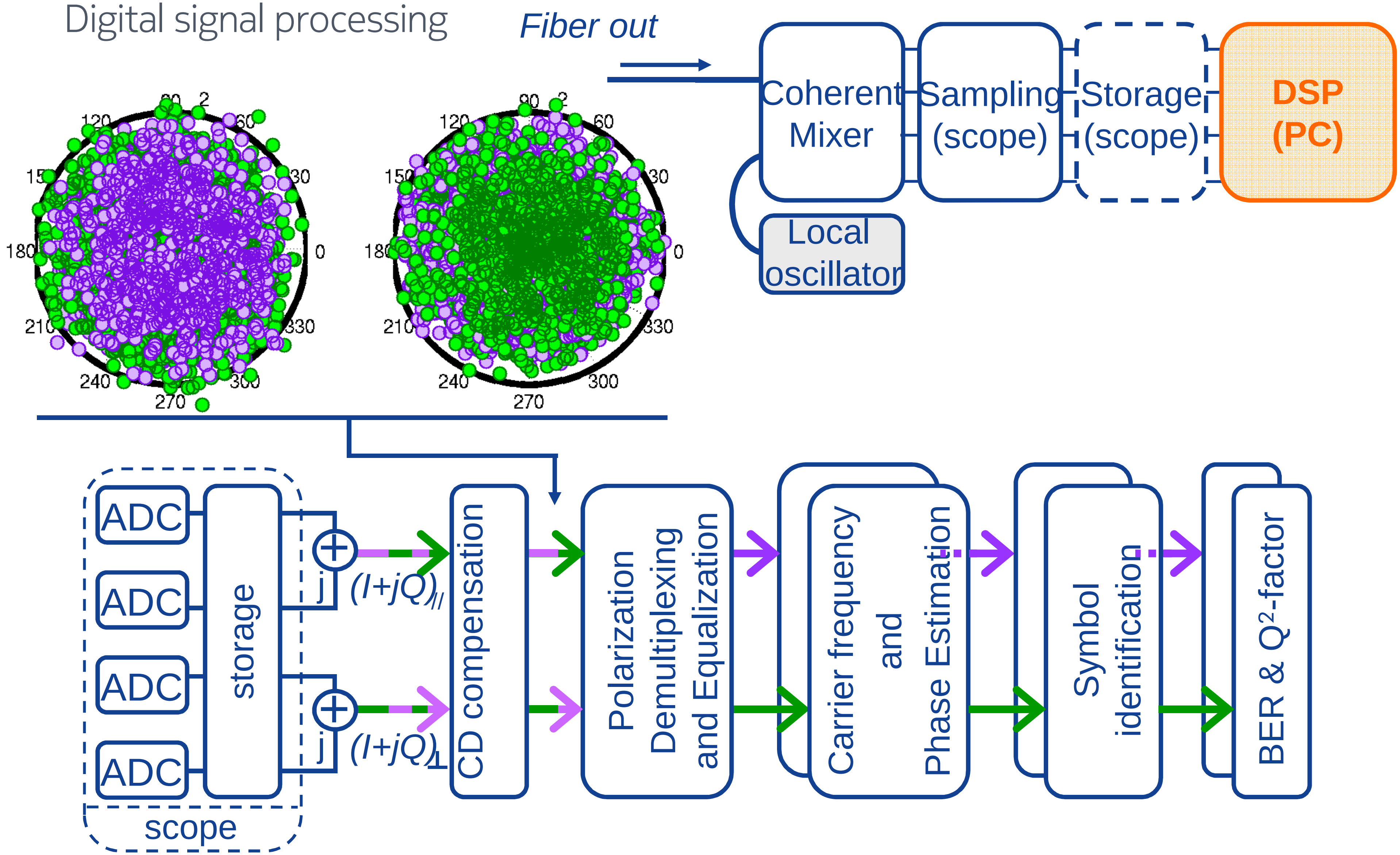
100Gb/s PDM-QPSK (experimental data)

Coherent receiver

Digital signal processing



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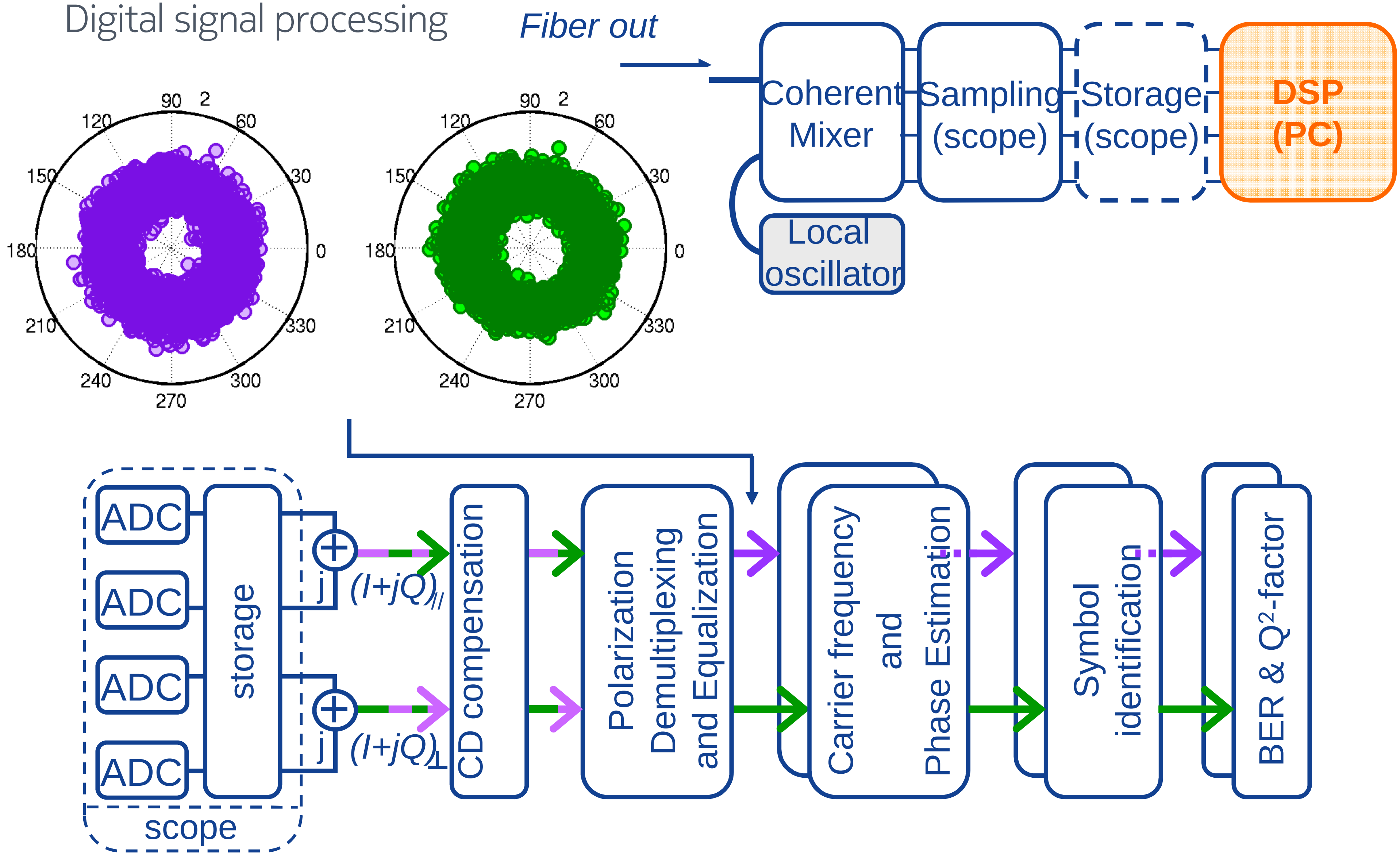
Coherent receiver

Digital signal processing

100Gb/s PDM-QPSK (experimental data)



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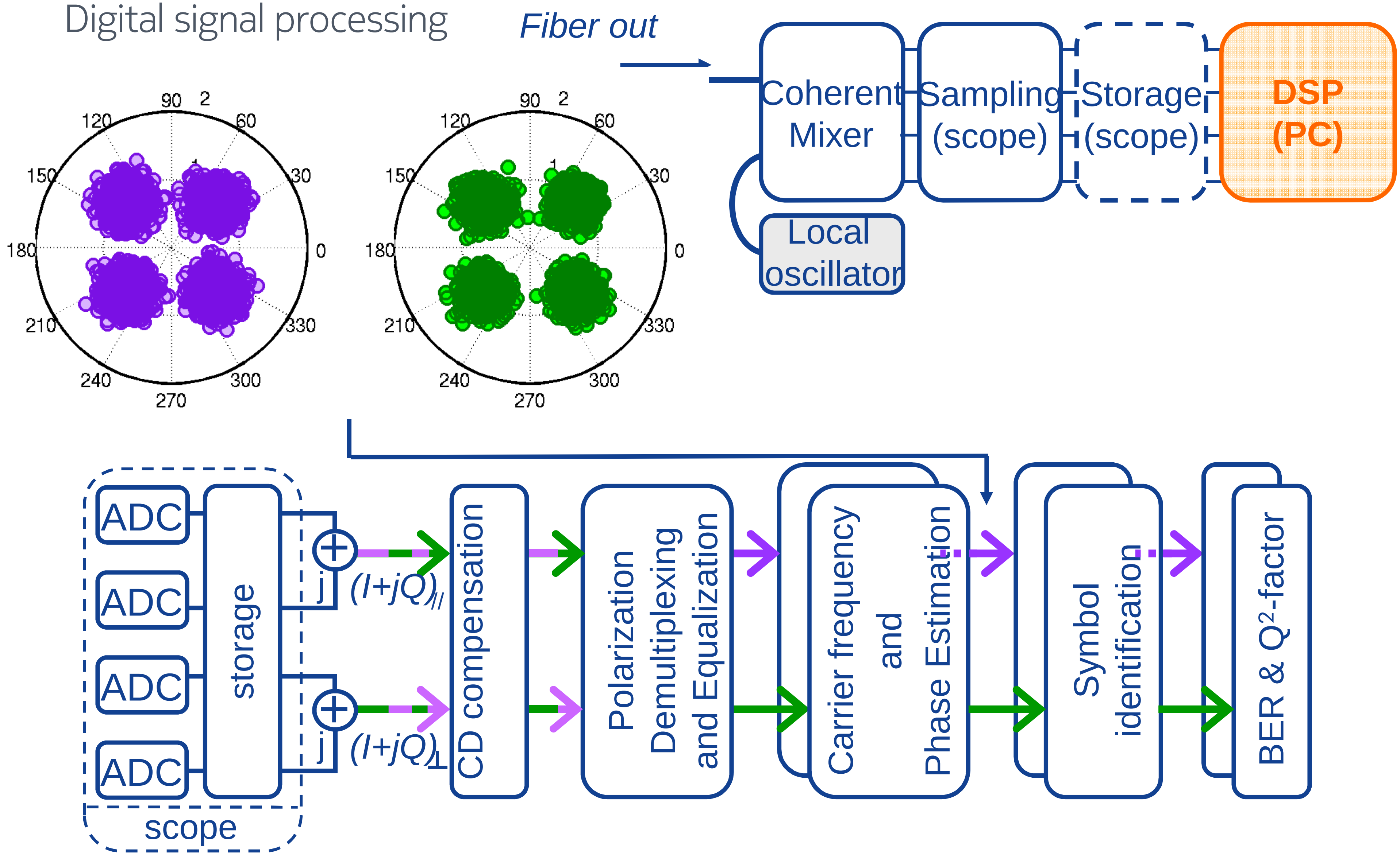
100Gb/s PDM-QPSK (experimental data)

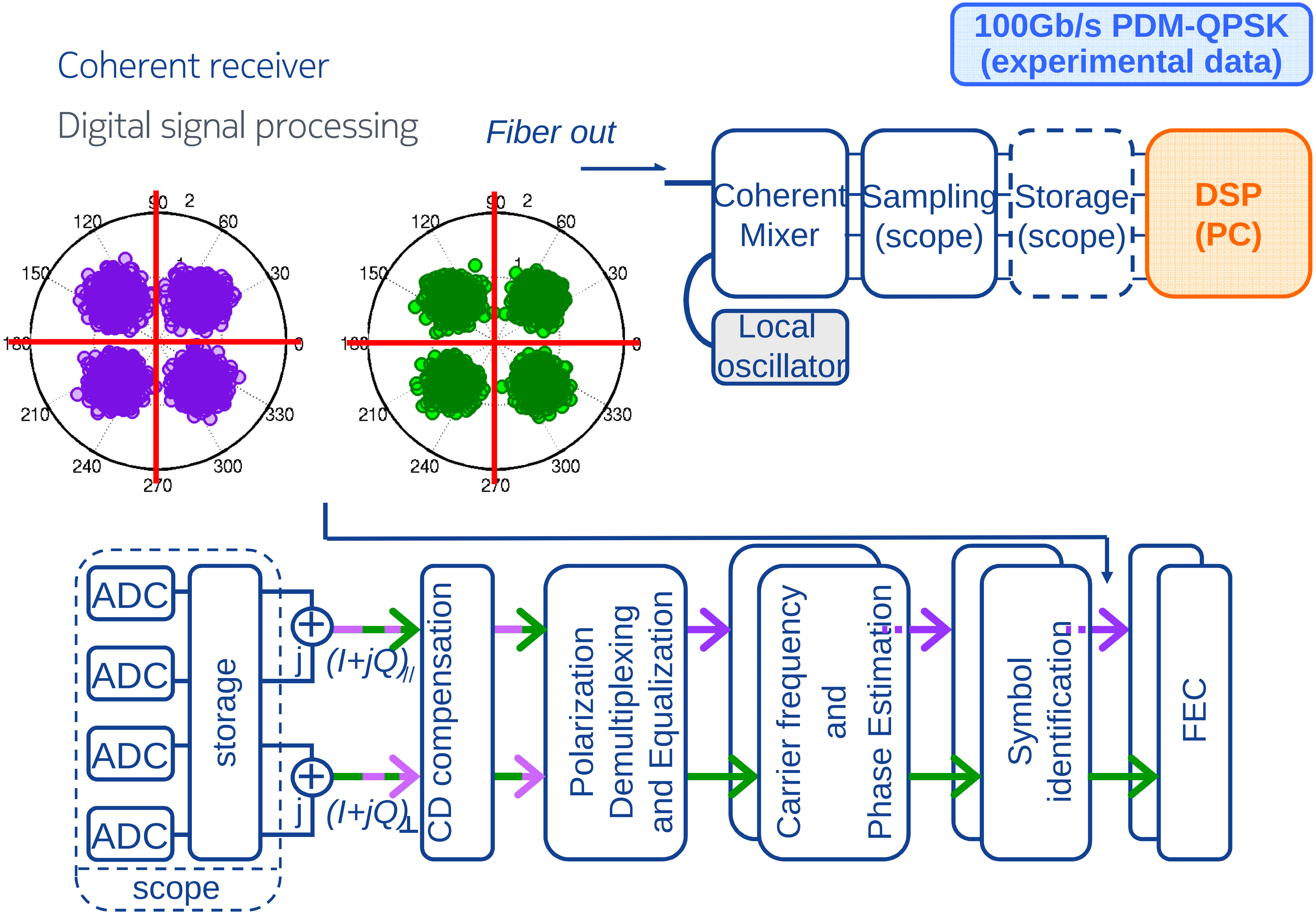
Coherent receiver

Digital signal processing



Coherent receiver

Digital signal processing



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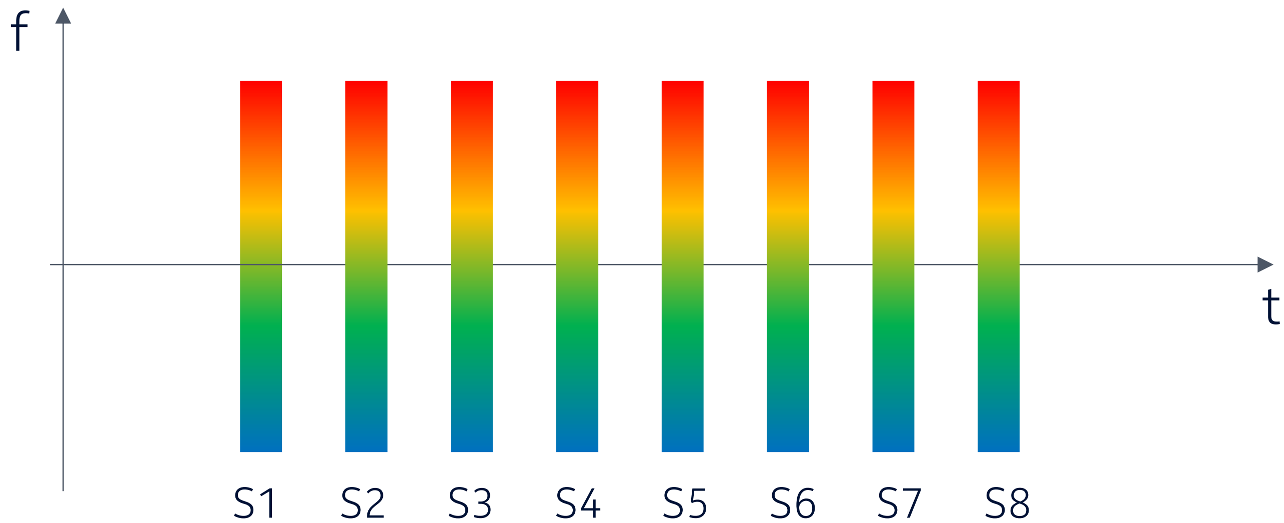
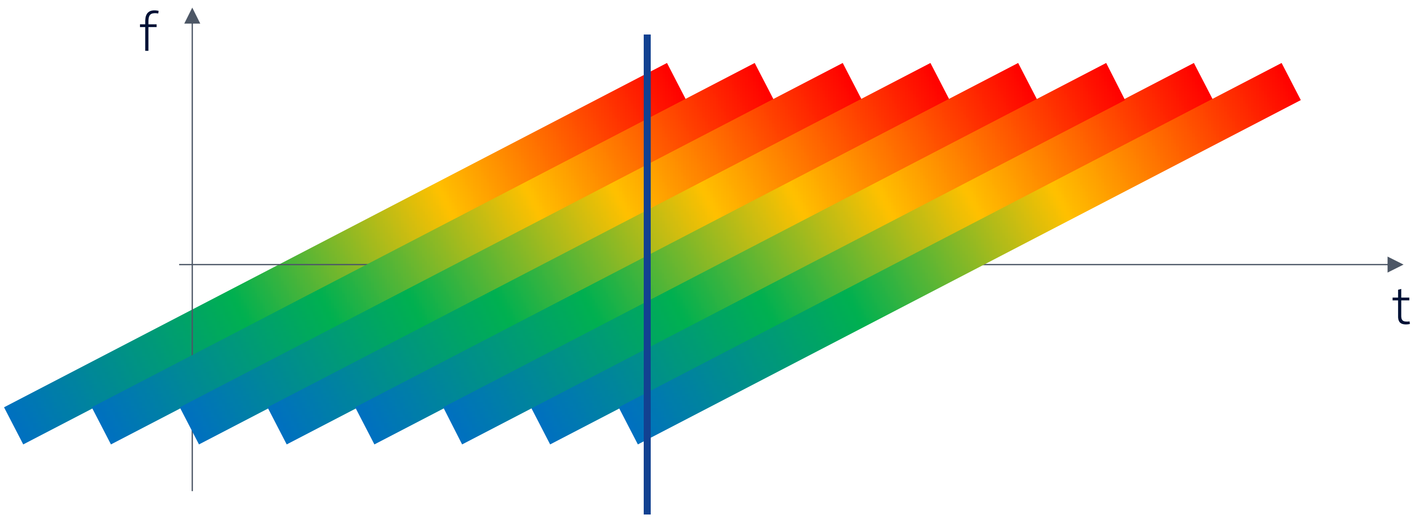
Chromatic dispersion compensation block



- Each symbol has a given spectral extension (~Baudrate).

Chromatic dispersion compensation block



- Each symbol has a given spectral extension.
- After transmission and chromatic dispersion impact, symbols overlap each others

- Frequency domain implementation to delay some frequencies and resynchronize all frequency components from transmitter symbol.

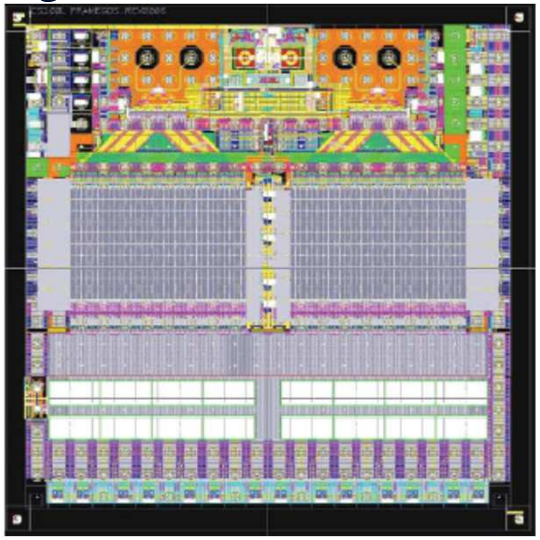
- Each symbol can overlap > 1000 symbols for transoceanic links.

ADC and DSP in a single CMOS chip

- 2010: first apparition of high speed CMOS ADC
- 56GS/s sampling rate, 8 bit resolution and ~15GHz analog bandwidth

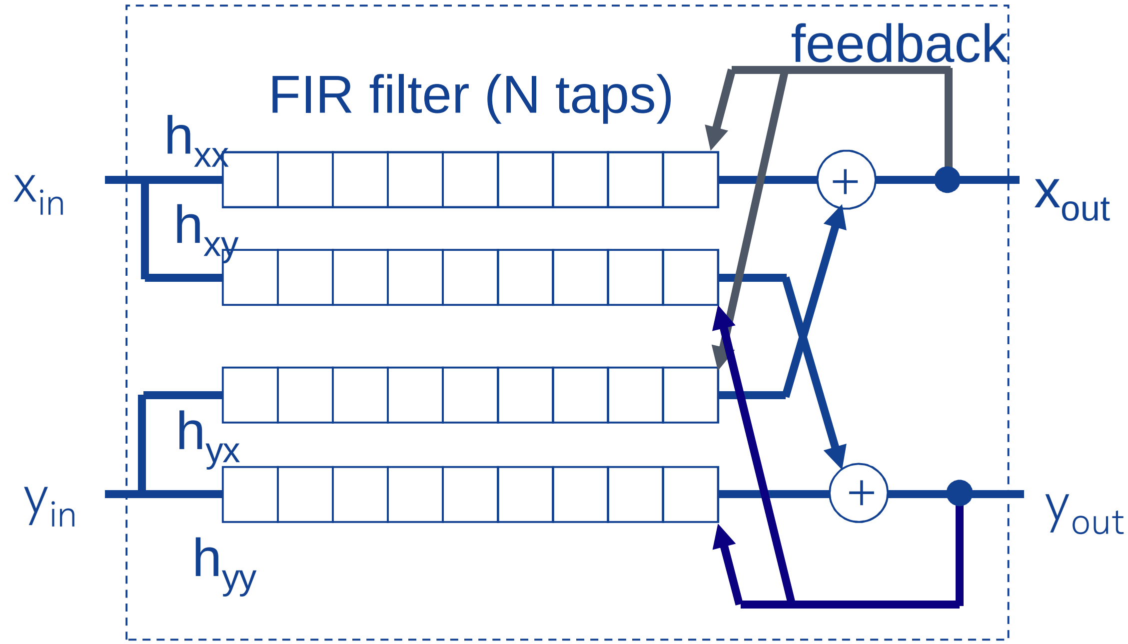
- Total amount of data to be processed for 100Gb/s PDM-QPSK: **4x56x8= 1.8Tb/s**!
- Unpractical to exchange 1.8Tb/s between 2 separate chips => single chip required for ADC and DSP. CMOS required for low power DSP.

- In 2010, first ADC-DSP chip with 65nm CMOS technology including
- 4 ADCs (56GS/s, 8bits)
- CD compensation (~2000km)
- Clock recovery
- MIMO 2x2 (polarization deMux, equalization)
- Optical carrier frequency estimation
- Optical carrier phase estimation
- FEC (product code BCHxBCH)



MIMO processing (polarization demultiplex. & equalization)

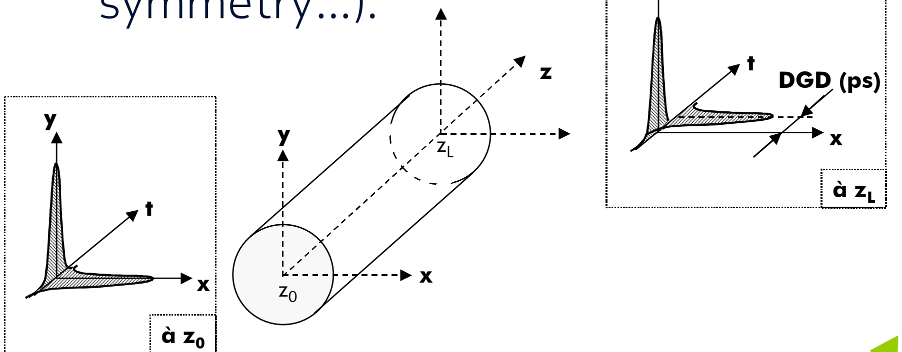
- Equalization is NOT done thanks to channel estimation (through training sequence or pilot), NOR by using decision on the symbol after full DSP processing.
- Blind equalization using only the intensity information (before phase processing). => no overhead associated with training sequence or pilot.

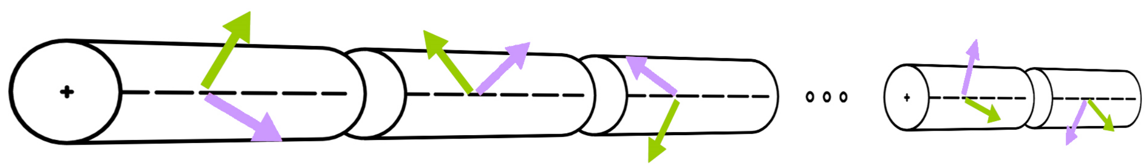


Butterfly structure

Polarization Mode Dispersion (PMD) and coherent detection

- PMD caused by fiber optics imperfections (stress, non perfect circular symmetry…).





- PMD is a stochastic effect. Differential group delay (DGD) can be ~3 times larger than average DGD value.
- PMD has been a major limitation for the deployment of 40Gb/s systems.

- But entirely solved with MIMO equalizer of coherent receiver !

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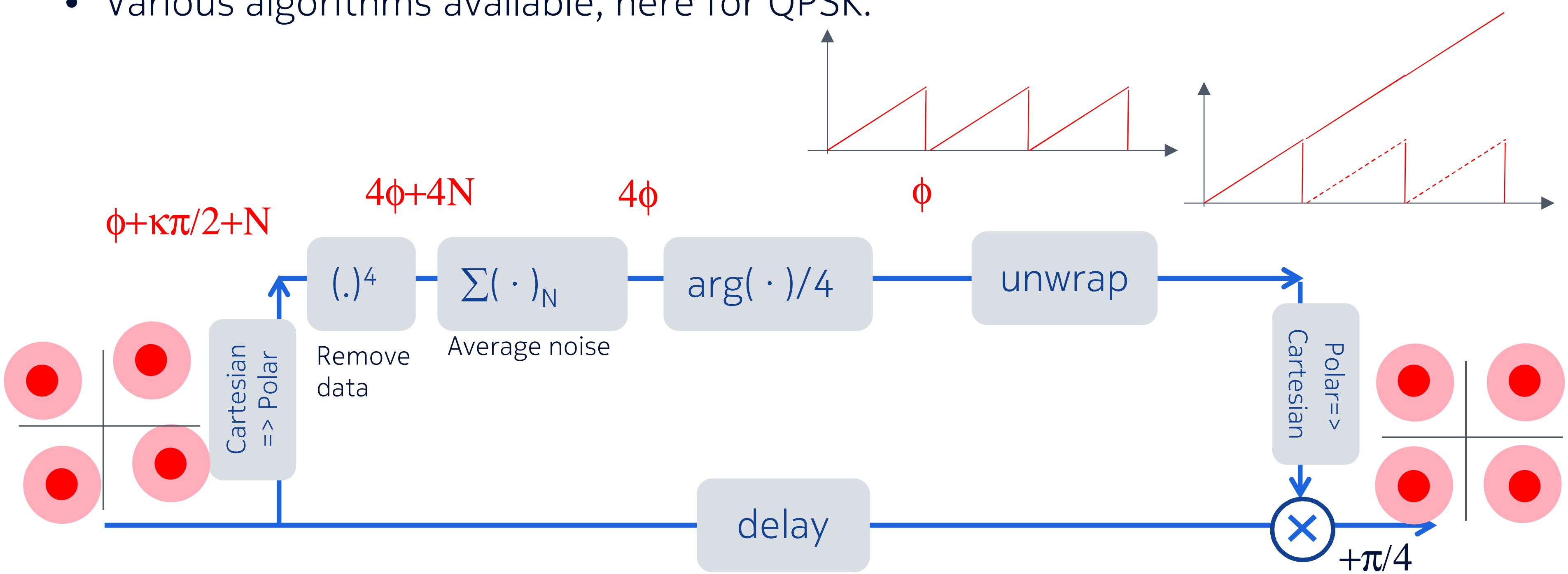
Carrier phase estimation (CPE)

Required because intradyne detection is used

- Phase estimation is a key part allowing to avoid the use of « optical phase locked laser » of the 1980's.
- Preceded by coarse frequency estimation to allow for several GHz of frequency offset between TX and RX laser.
- Various algorithms available, here for QPSK.



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Bit error rate and forward error correction (FEC)

- Optical communication requested BER is 10^{-13} (or even 10^{-16}).
- Maximization of transmission reach and/or capacity is obtained through the use of forward error correction similarly to any other digital systems.
- But processing of up to 500Gb/s in a single chip !

Code rate

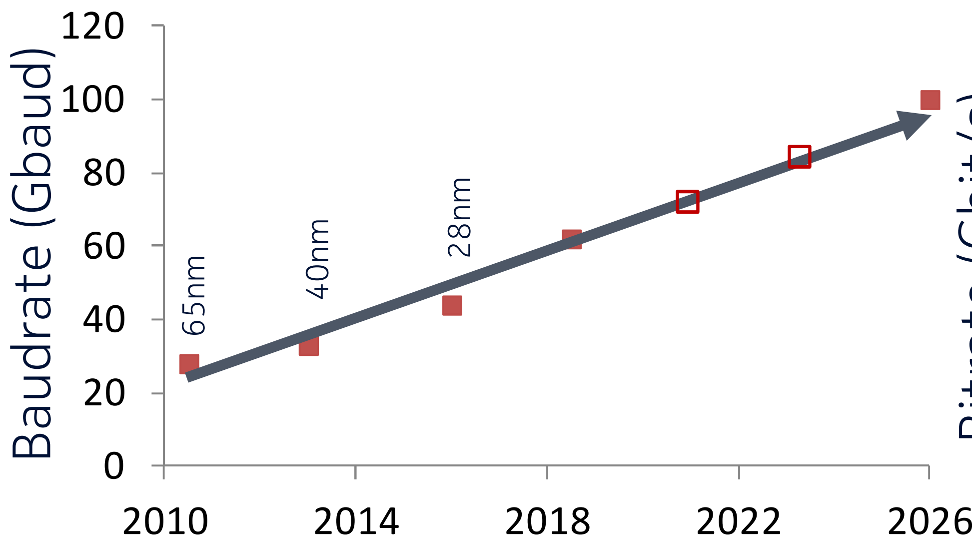
$$r = K / N$$

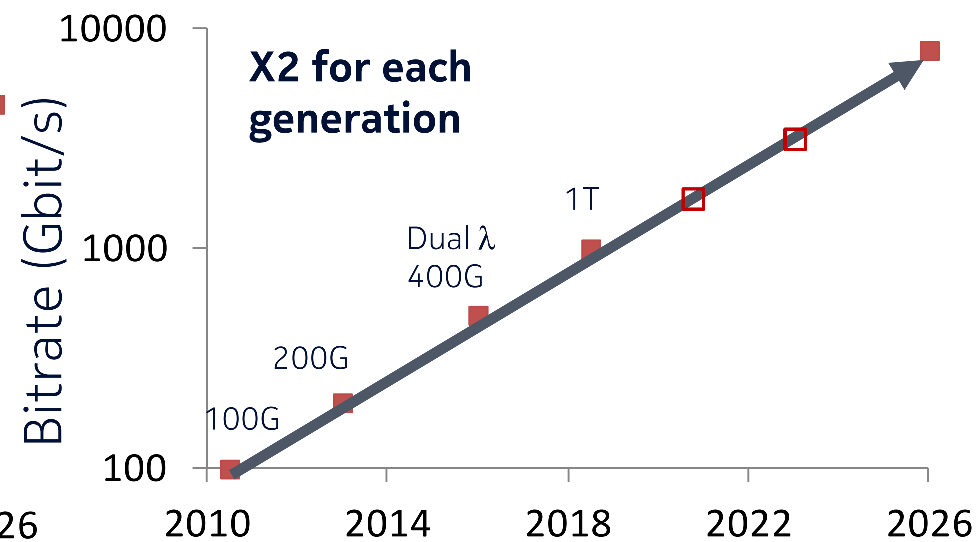
- Code rate (r) vs overhead (OH): $OH = (1/r - 1)$
- Code rate r=0.8 => overhead 25%
- Code rate r=0.5 => overhead 100%

- 2000: 7% overhead and code RS 255-239: FEC threshold 10^{-4} **(Q~11.5dB)**
- 2003: 7% overhead and code BCHxBCH: FEC threshold 4 10^{-3} **(Q~8.5dB)**
- 2012: 25% overhead and "soft decision" LDPC (low density parity check): FEC threshold ~2 10^{-2} **(Q~5.5dB)**

Maximizing bit rate per device to minimize cost per bit

Maximizing baudrate, format level & carrier count per ASIC





Tremendous progress of high speed optical coherent interfaces

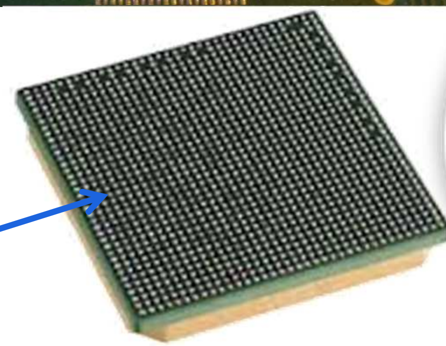
Opto-electronic components

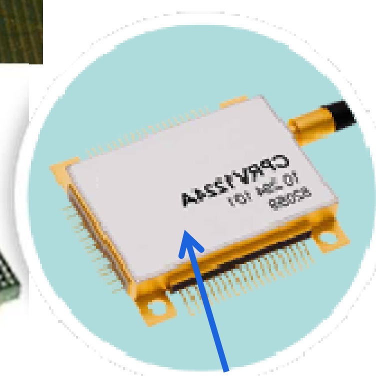
PDM I/Q modulator (LiNbO3, InP, siPho)

Tunable laser (InP)

Quad driver
(InP, GaAs)

ADC, DSP, DAC
(CMOS)





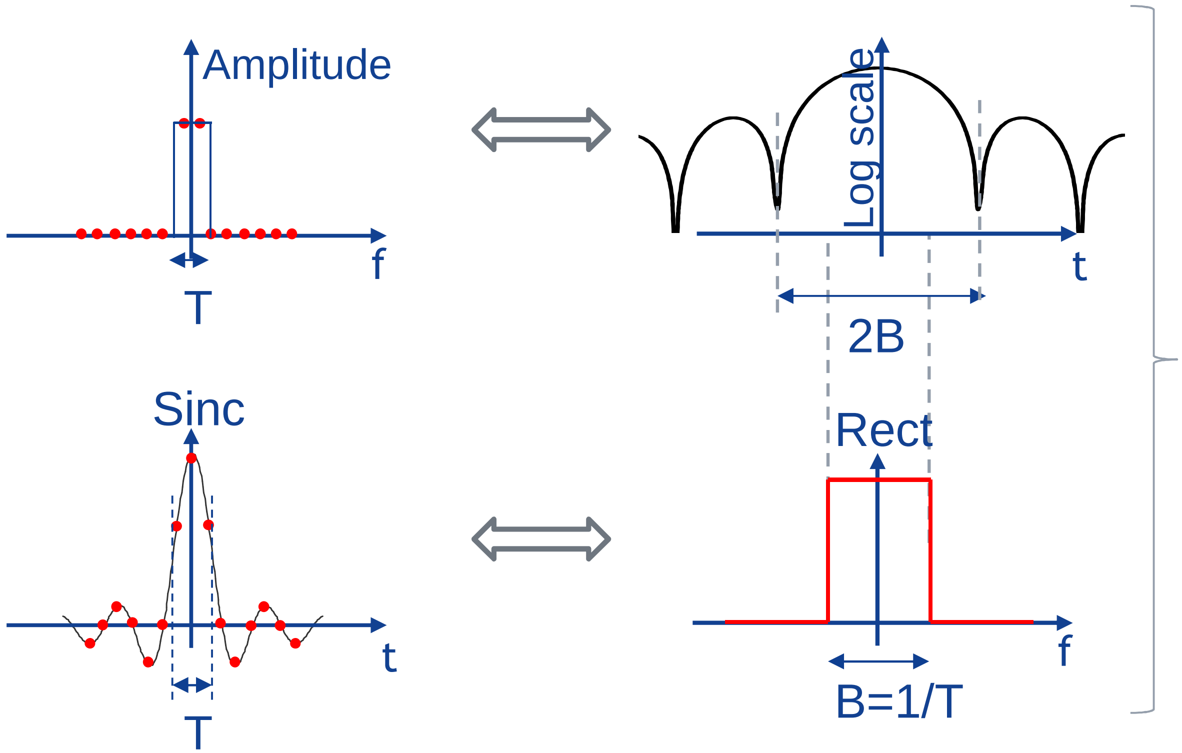
Coherent receiver (InP, SiPho, free space…)

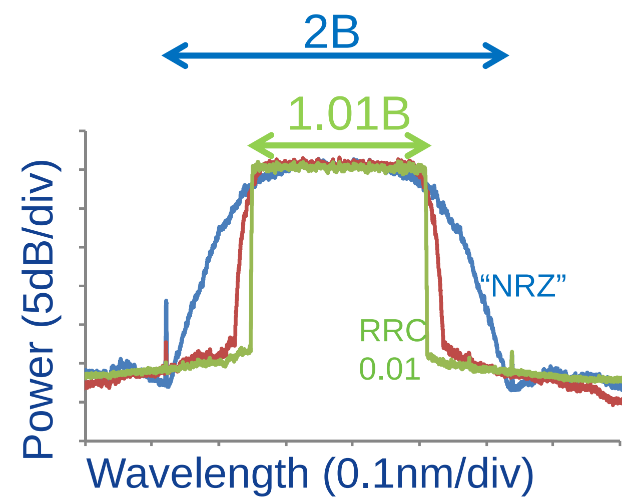
<u>multi-channel photonic integration:</u>

- Dual PDM I/Q modulator
- dual tunable laser
- dual coherent receiver
- dual ADC/DSP/DAC chip…

Spectrum shaping thanks to DAC (Digital to Analog Convertor) at TX

Time domain (impulse response) | Frequency domain (spectrum)





Spectrum shaping thanks to digital filter in transmitter to reduce spectrum occupancy and increase spectrum efficiency

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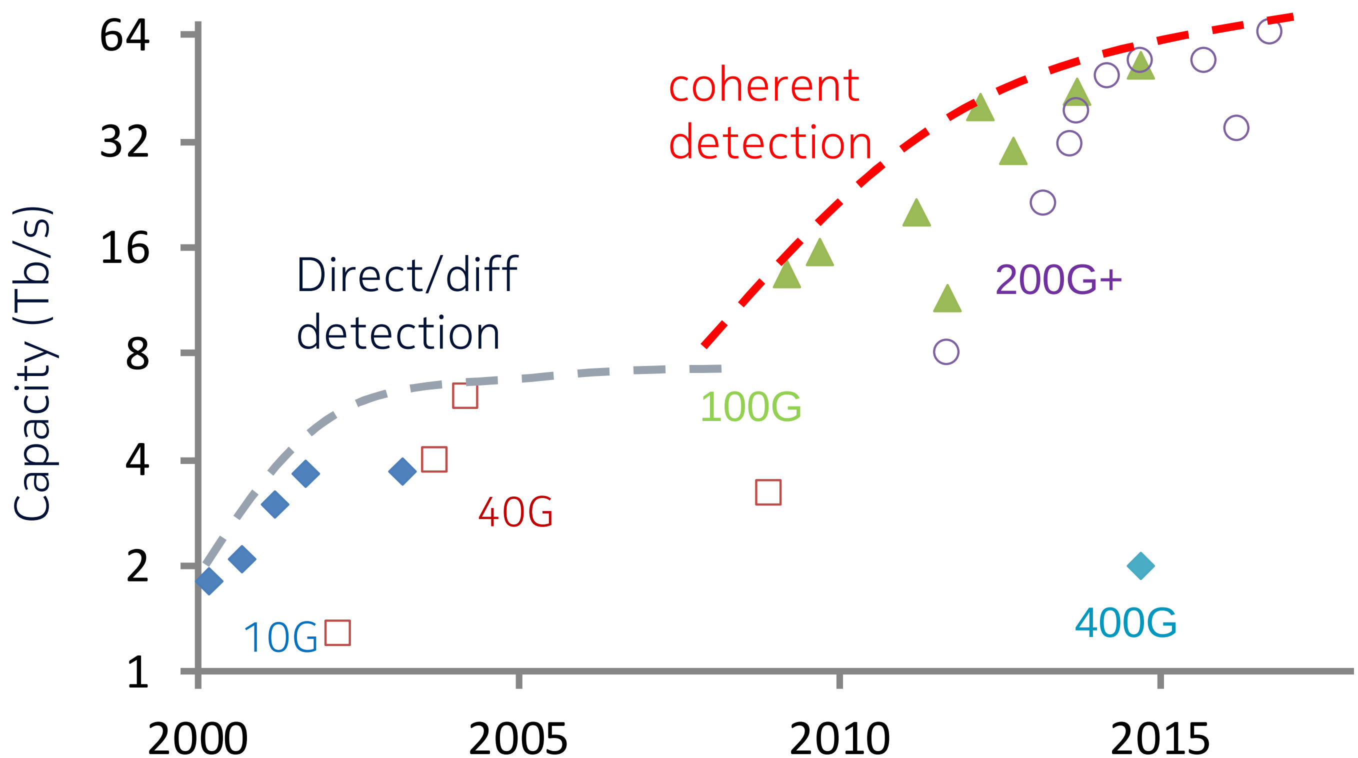
Progress in submarine capacity per fiber

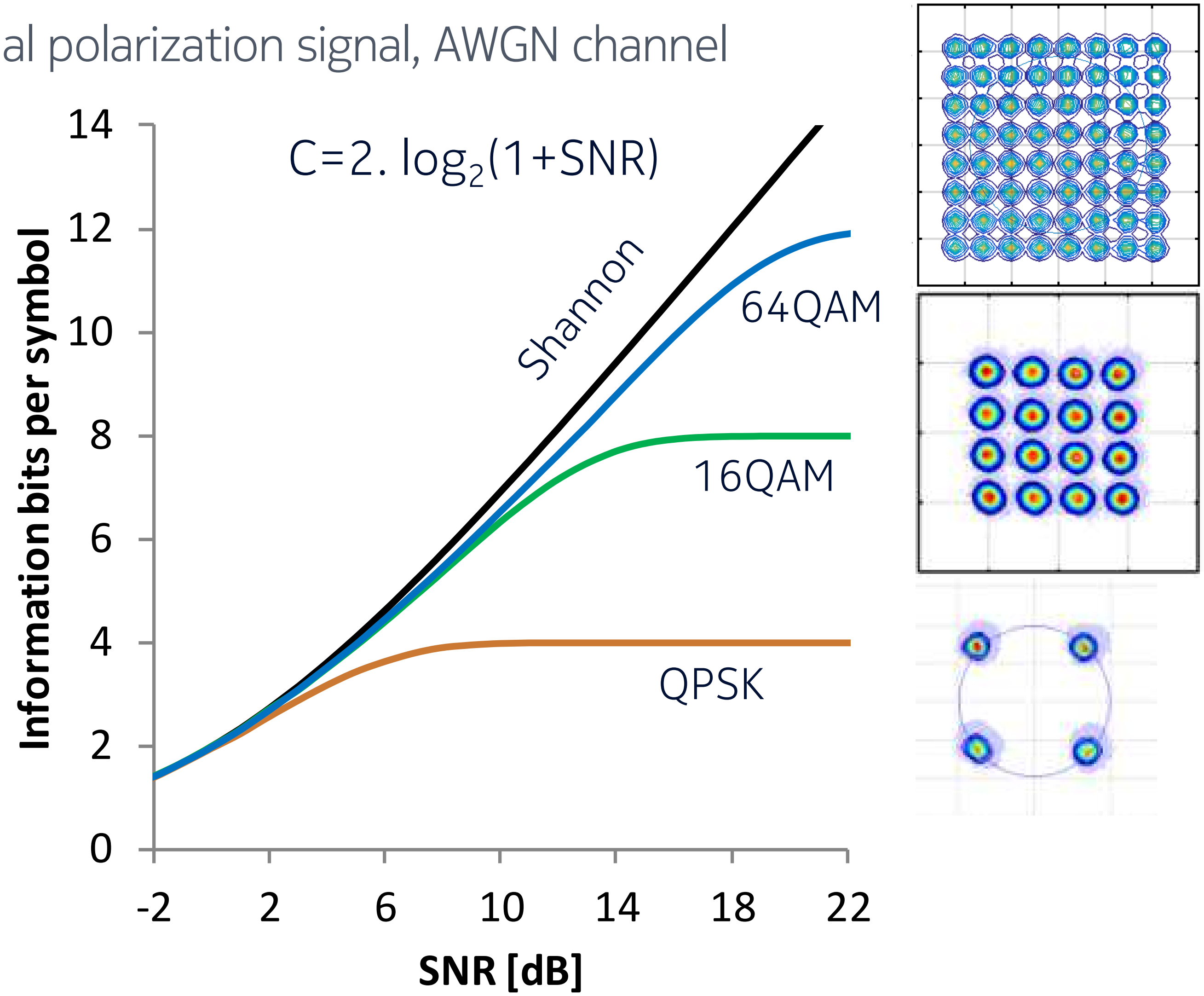
(transmission distance > 6000km)



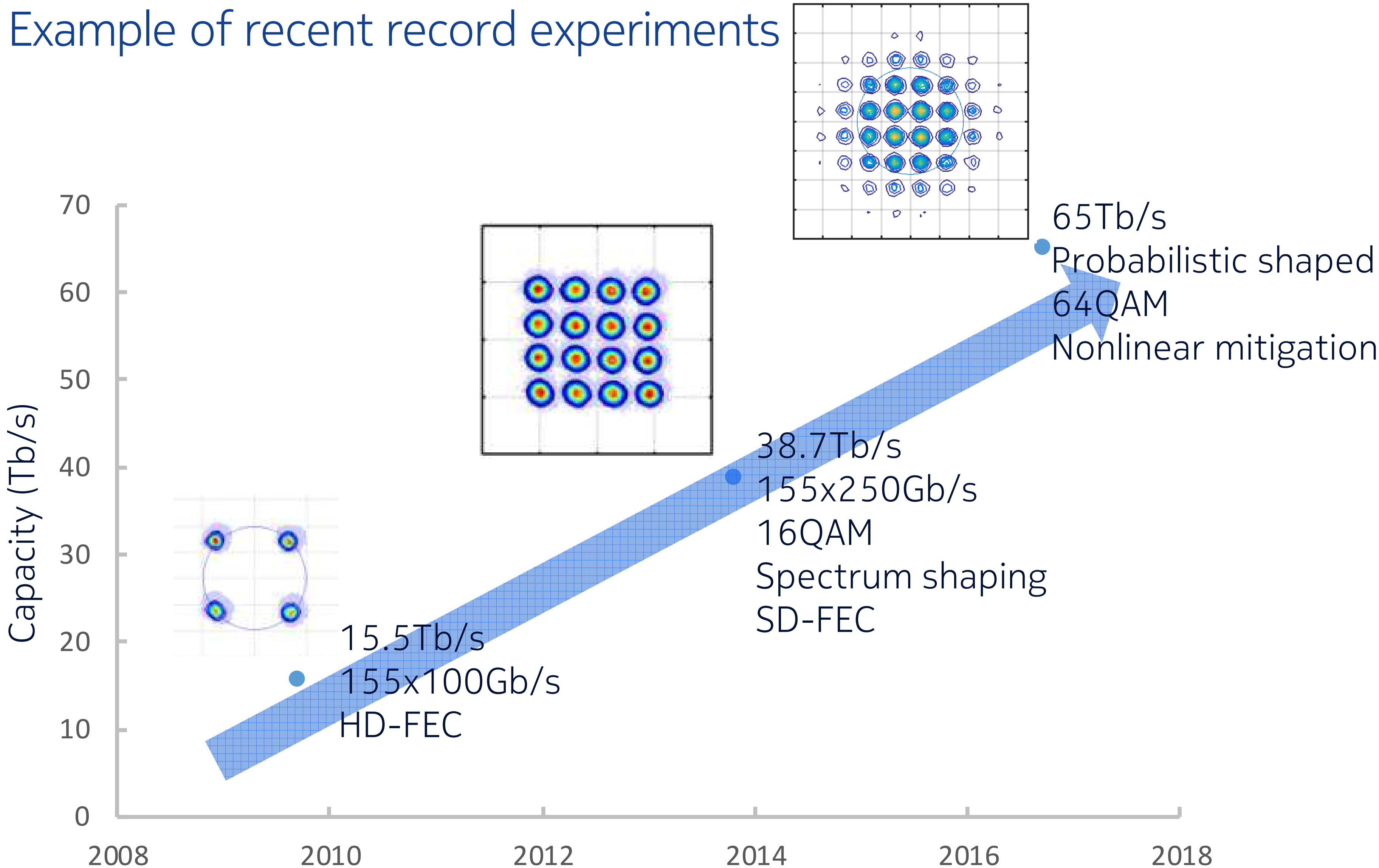
Strong capacity increase thanks to coherent detection

Shannon limit

For dual polarization signal, AWGN channel



Example of recent record experiments



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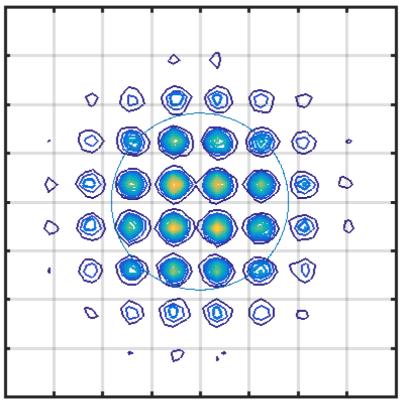
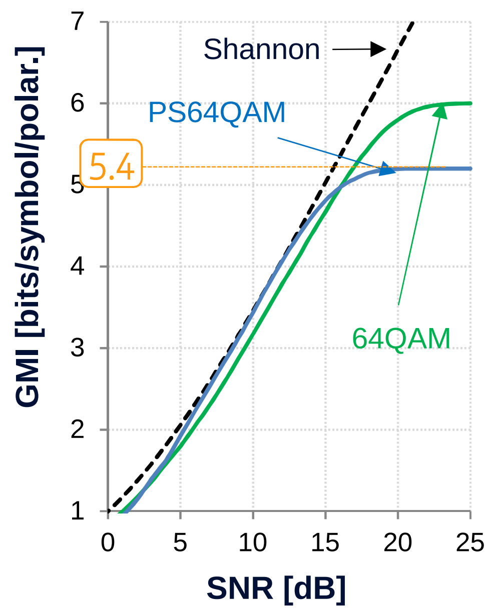
65Tb/s transmission over 6,600km

Thanks to Probabilistic Constellation Shaping and NL mitigation



Probabilistic constellation shaping: **PCS 64QAM**



- Highest capacity over submarine distance.
  - Probabilistic constellation shaping
  - Nonlinear mitigation
  - Adaptive rate FEC

Highest capacity, close to expected limits

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Nonlinear mitigation

- Optical channel is not an arbitratry white Gaussian noise (AWGN) channel.
- Kerr nonlinearities because of propagation through optical fiber.

$$i\frac{\partial A}{\partial z}+\underbrace{\frac{i}{2}\alpha . A}_{\text{Attenuation}}-\underbrace{\frac{\beta_2}{2}\frac{\partial^2 A}{\partial T^2}-\frac{i}{6}\beta_3\frac{\partial^3 A}{\partial T^3}}_{\text{Dispersion}}+\underbrace{\gamma|A|^2 A}_{\text{Kerr nonlinearities}}=0$$

Attenuation

Dispersion

Kerr nonlinearities

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Nonlinear mitigation

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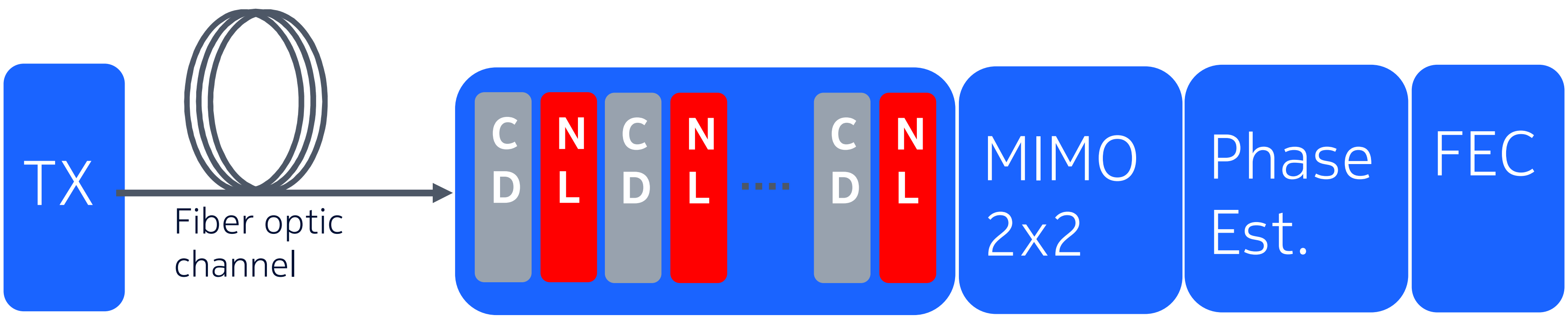
- Kerr nonlinearities because of propagation through optical fiber.

$$i\frac{\partial A}{\partial z}+\frac{i}{2}\alpha .A-\frac{\beta_2}{2}\frac{\partial^2 A}{\partial T^2}-\frac{i}{6}\beta_3\frac{\partial^3 A}{\partial T^3}+\gamma |A|^2 A=0$$

Attenuation — Dispersion — Kerr nonlinearities



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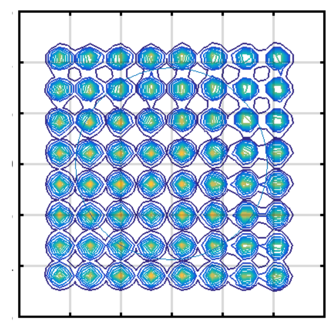
Conclusion

- Coherent detection has revolutionized the world of optical communication.
  - Removed the need for optical dispersion compensation
  - Solved the PMD issue
  - Practical way to use the 2 polarization of the light
  - Drastically Increased the spectral efficiency



400Gb/s on a single wavelength !

- We are now approaching the spectral efficiency limits of fiber optics…

NOKIA