Eléments clés des systèmes sous-marins et évolutions physiques majeures

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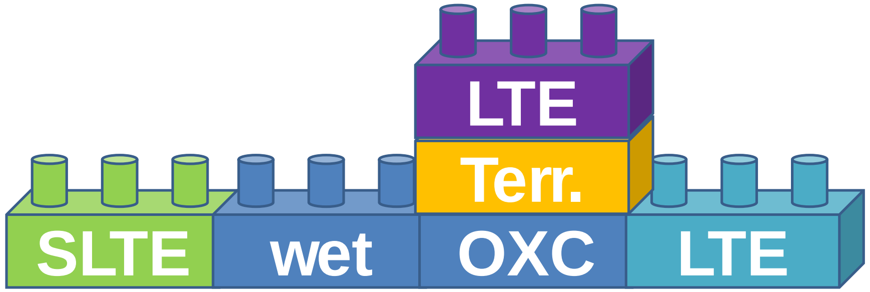
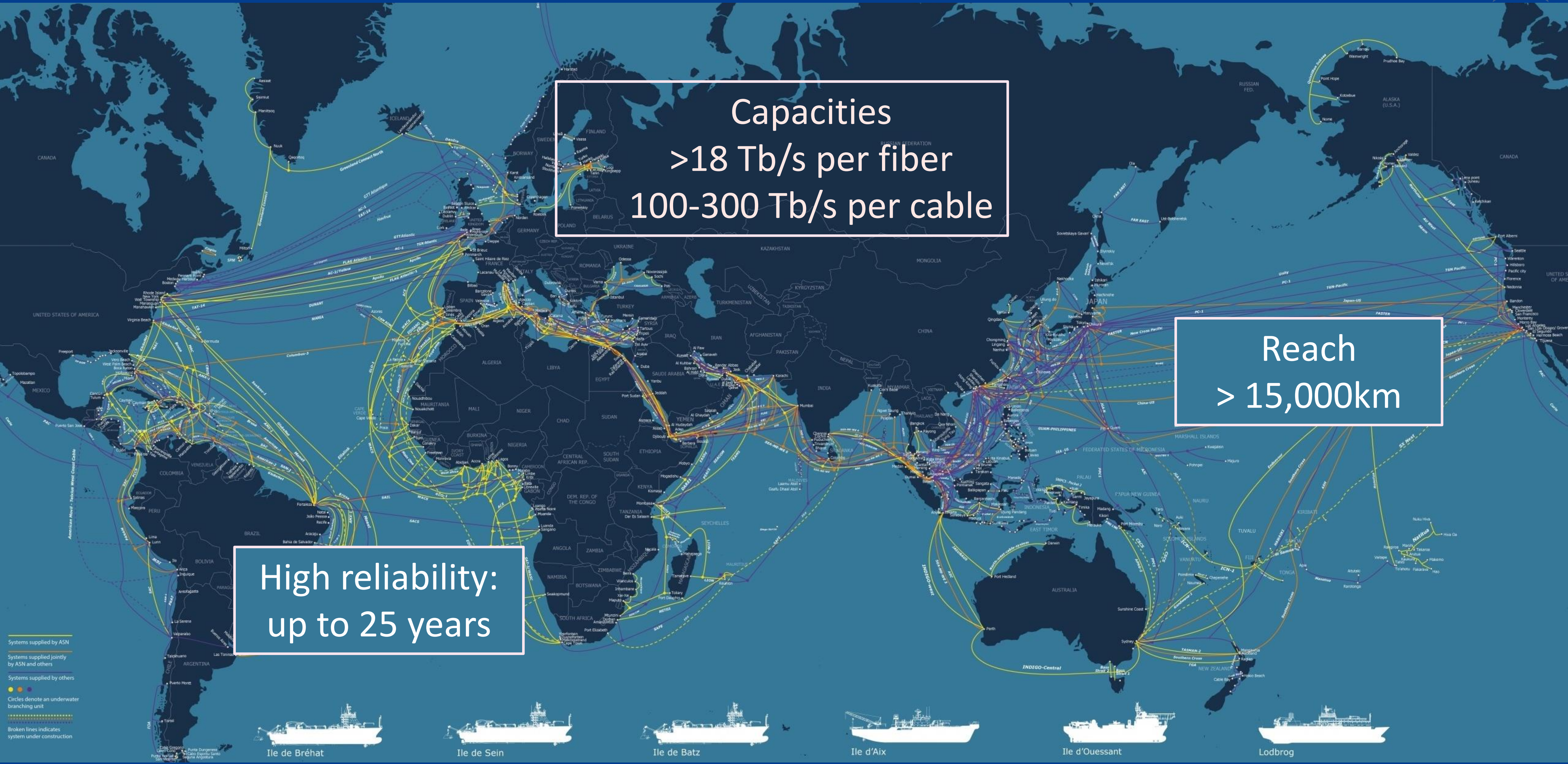
Outline of this talk

- Key building blocks of submarine networks
- Recent transformations
  - Driven by coherent technologies
  - Driven by OTT: high capacities, open cables and models
  - Approaching Shannon limits with Spatial Division Multiplexing
- More in depth lectures at www.subseaofc.com



99% of international traffic conveyed by optics. > 3 Bn km fiber laid

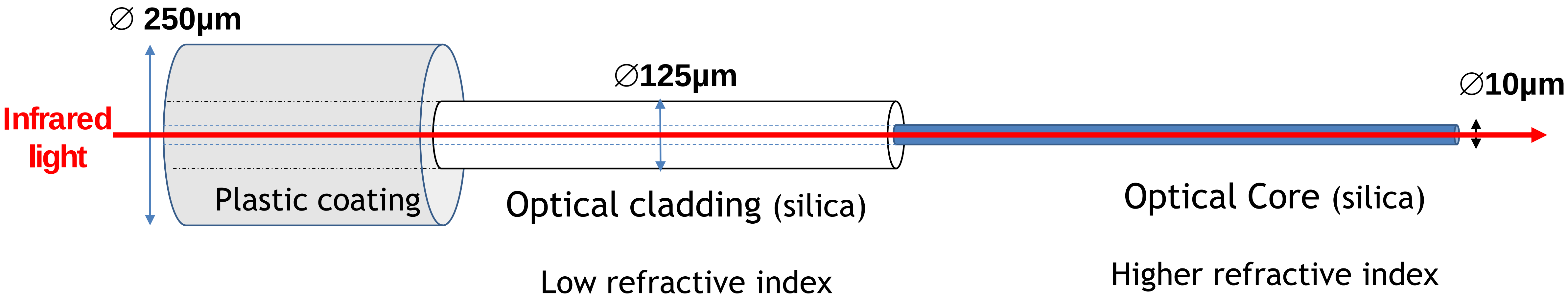


Capacities
>18 Tb/s per fiber
100-300 Tb/s per cable

Reach
> 15,000km

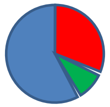
High reliability:
up to 25 years

Optical fibre = ultra-thin glass waveguide, source of signal impairments

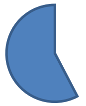


Propagation effects

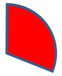
Residual impairments



- Attenuation : -50% power every 20km (@1550nm) → Optical amplifier every 50-80km → ASE noise

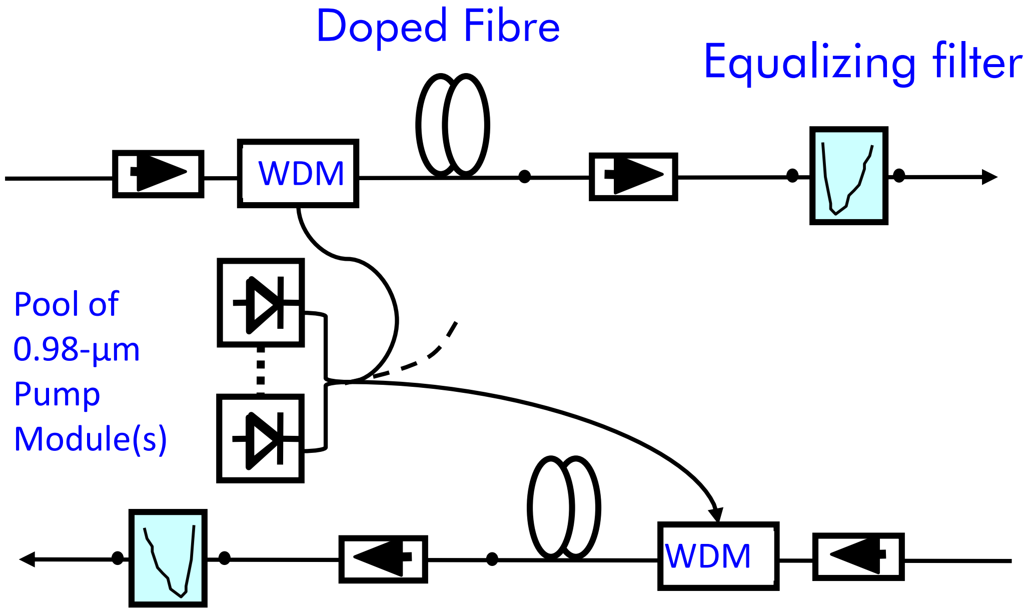


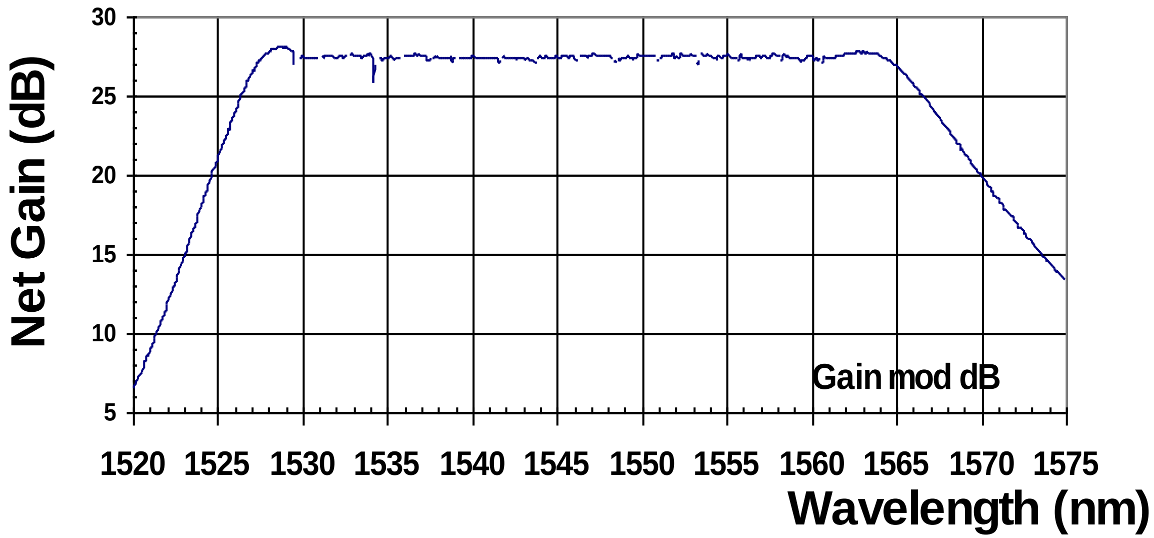
- **Chromatic Dispersion:** broadening: 1 symbol / km (70Gbaud) → Mitigation at terminals
- Power effects 1Bn W/m² → Kerr effect → Gaussian like fluctuations



- Acousto-optic effects Thermal vibrations → crosstalk → Gaussian like noise

Typical optical amplifier with optical equalization



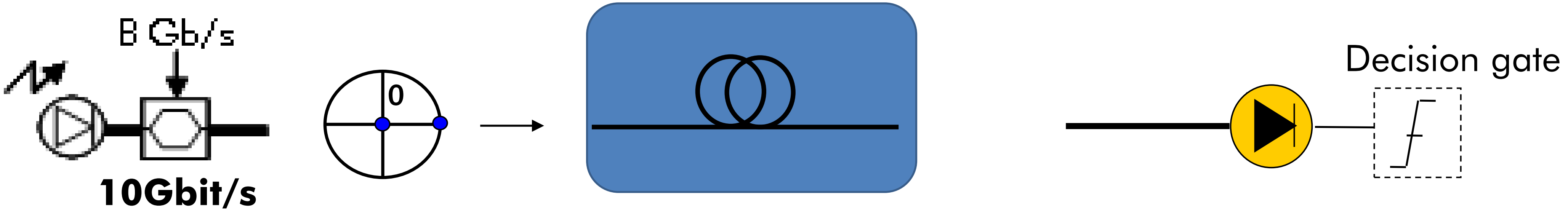


Typical features of subsea repeaters

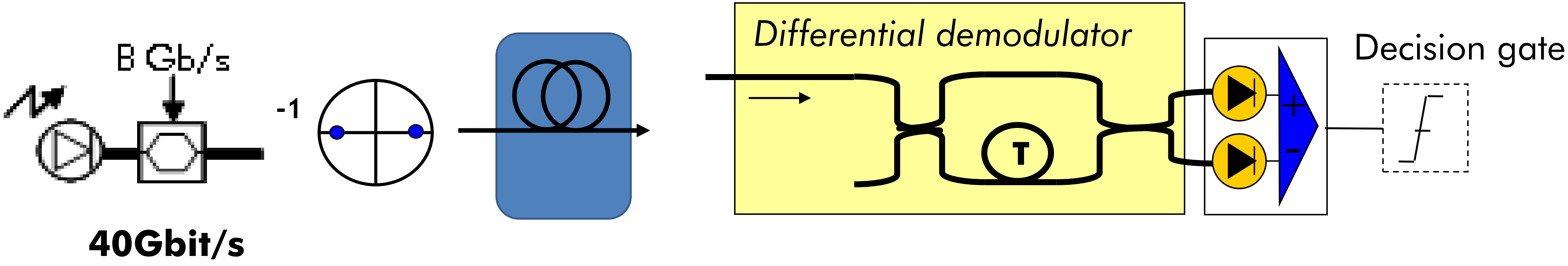
- **High performance: typ. 4.5THz bandwidth, up to 23dBm, low noise figure**
- **Customized design and equalizing filter: ± 0.1dB flatness**
- **Resilient to failures: components, pump farming, constant output power**
- **Reflectometry paths for fault localization**

Evolution of modulation technologies over ages

2000
OOK



2005
D-BPSK



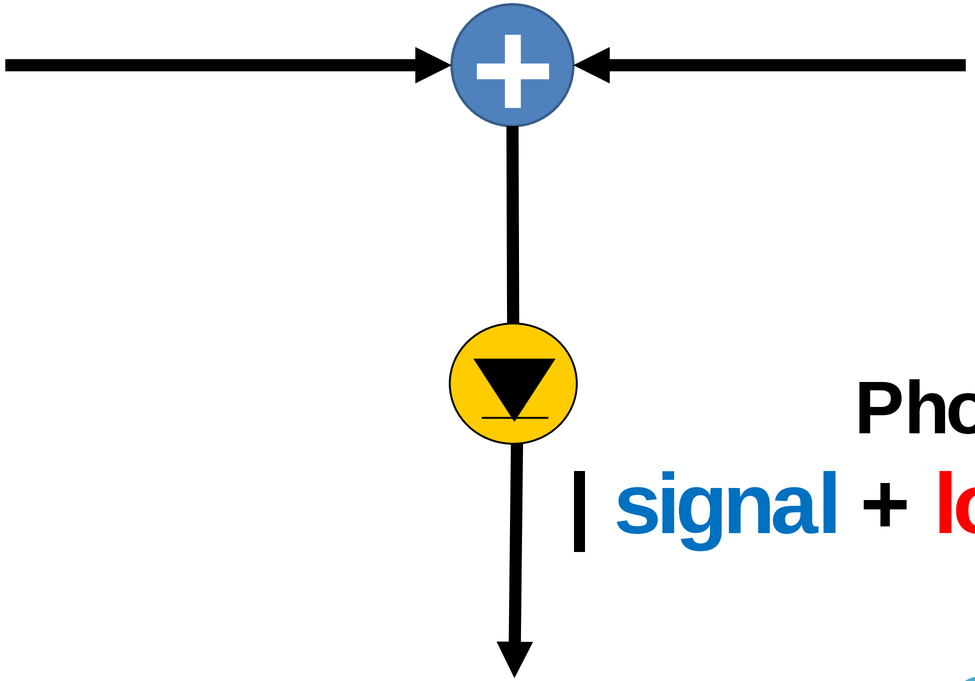
Today: Coherent detection - principle

Signal

$$s(t) = E_s(t) * e^{j\omega_s t}$$

Local oscillator

$$\mathrm{lo(t)} = E_{LO} * e^{j\omega_{LO} t}$$



Photodiode

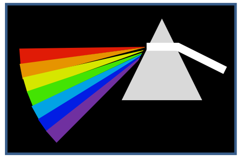
| signal + local oscillator|²

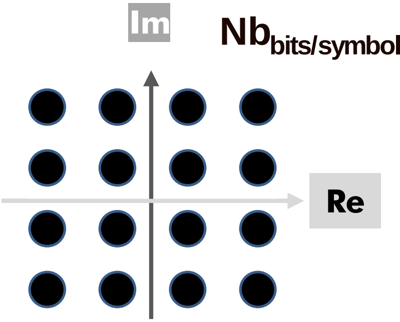
$$|s(t) + lo(t)|^2 = |E_s(t)|^2 + |E_{LO}(t)|^2 \pm 2 * Re/Im\left(E_s(t) * E_{LO}^* * e^{j(\omega_s - \omega_{lo})t}\right)$$

What we seek ($E_s(t)$)

Today's high **capacity terminals**

$Nb_{bits/symbol} = \log_2 (Nb_{symbols})$





Spectral efficiency

$$Capacity = Nb_{fiber\ pairs} * Nb_{wavelengths} * Nb_{polars} * Nb_{bit/symbol} * \frac{Symbol\ Rate}{Overhead(FEC, signaling)}$$

Up to 16

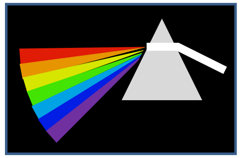
4.5THz bw
typ. 60ch

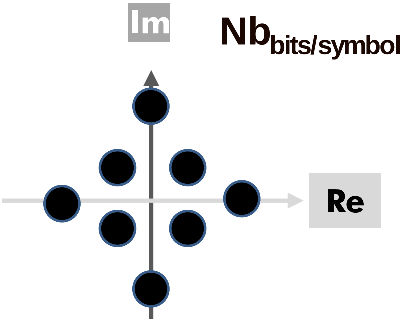
2_{polars}

1,2,3,4...

Typ. 70Gbaud (Gsymboles/s)
Net 50 Gbaud

High capacity terminals





$Nb_{bits/symbol} = \log_2 (Nb_{symbols})$

Spectral efficiency

$$Capacity = Nb_{fiber\ pairs} * Nb_{wavelengths} * Nb_{polars} * Nb_{bit/symbol} * \frac{Symbol\ Rate}{Overhead(FEC, signaling)}$$

Exemple:

16 p. fibres

4.5THz bw
60canaux

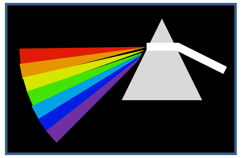
2_{polars}

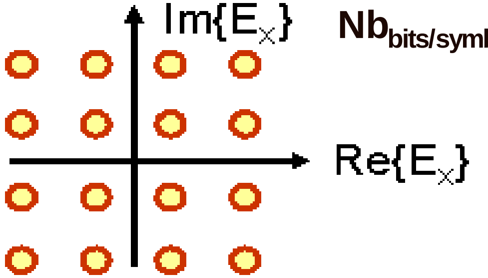
3 bits/symbole

68Gbaud (36% surdébit)
Espacement: 75GHz

$$Capacity = 16_{fiber\ pairs} * 60_{wavelengths} * 2_{polars} * 3_{bit/symbol} * \frac{68\ Gbaud}{1.36} =$$ **18Tb/s per fiber ➔ 288Tb/s**

High capacity terminals





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Spectral efficiency

$$Capacity = Nb_{fiber\ pairs} * Nb_{wavelengths} * Nb_{polars} * Nb_{bit/symbol} * \frac{Symbol\ Rate}{Overhead(FEC, signaling)}$$

- **Software-**defined "Coherent" transceivers
  - **Linear receiver assisted by high rate Digital Signal Processing enables mitigation of line impairements…**
  - **and adaptation of bit-rate to Quality of Transmission**

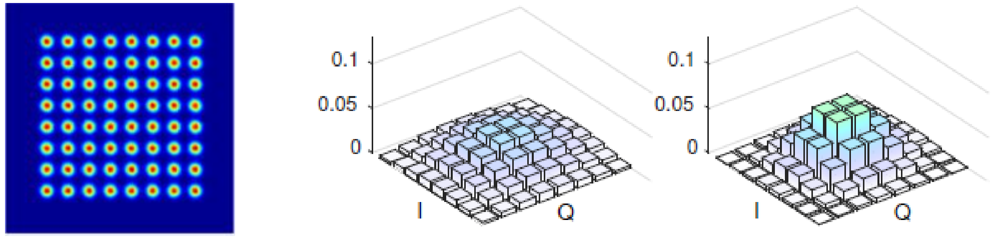
Approaching Shannon limits with terminals

- **Gaussian like-modulations**
  - ➔ Close the gap to Shannon

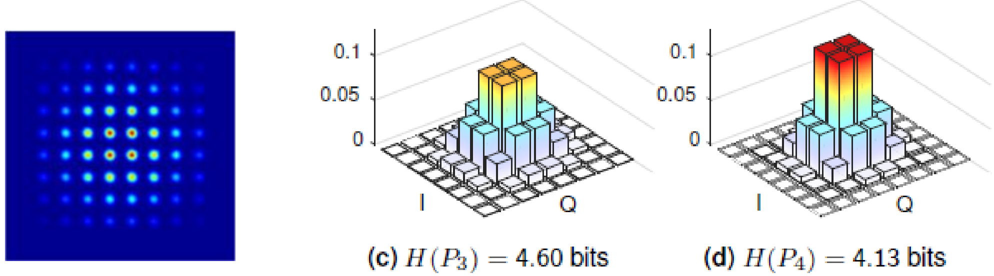
- **Maximum tuneability for any SNR**
  - Error correction rate
  - Symbol rate
  - Modulation / entropy

- **Nonlinearity mitigation techniques**

Probabilistic Constellation shaping



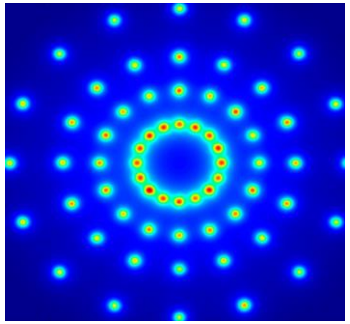
(a) $H(P_1) = 5.73$ bits (b) $H(P_2) = 5.23$ bits

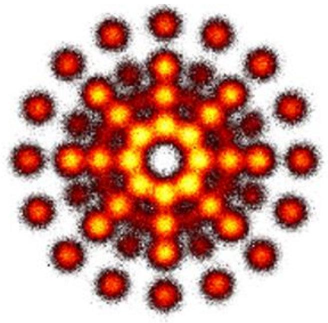


(c) $H(P_3) = 4.60$ bits (d) $H(P_4) = 4.13$ bits

Other Constellation Shapings

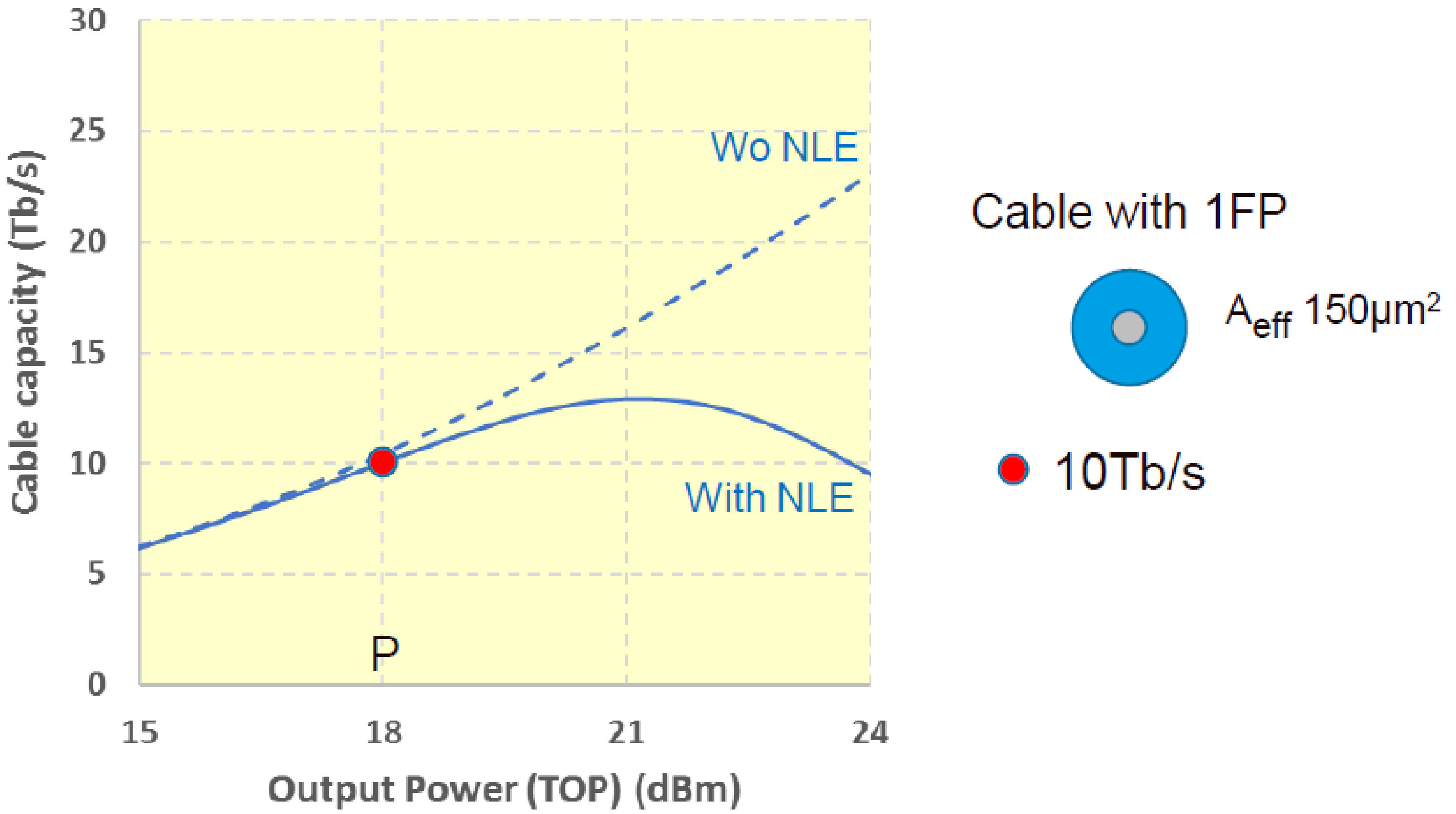
Geometric **Hybrid**





Spatial Division Multiplexing : Approaching Shannon limits in cables

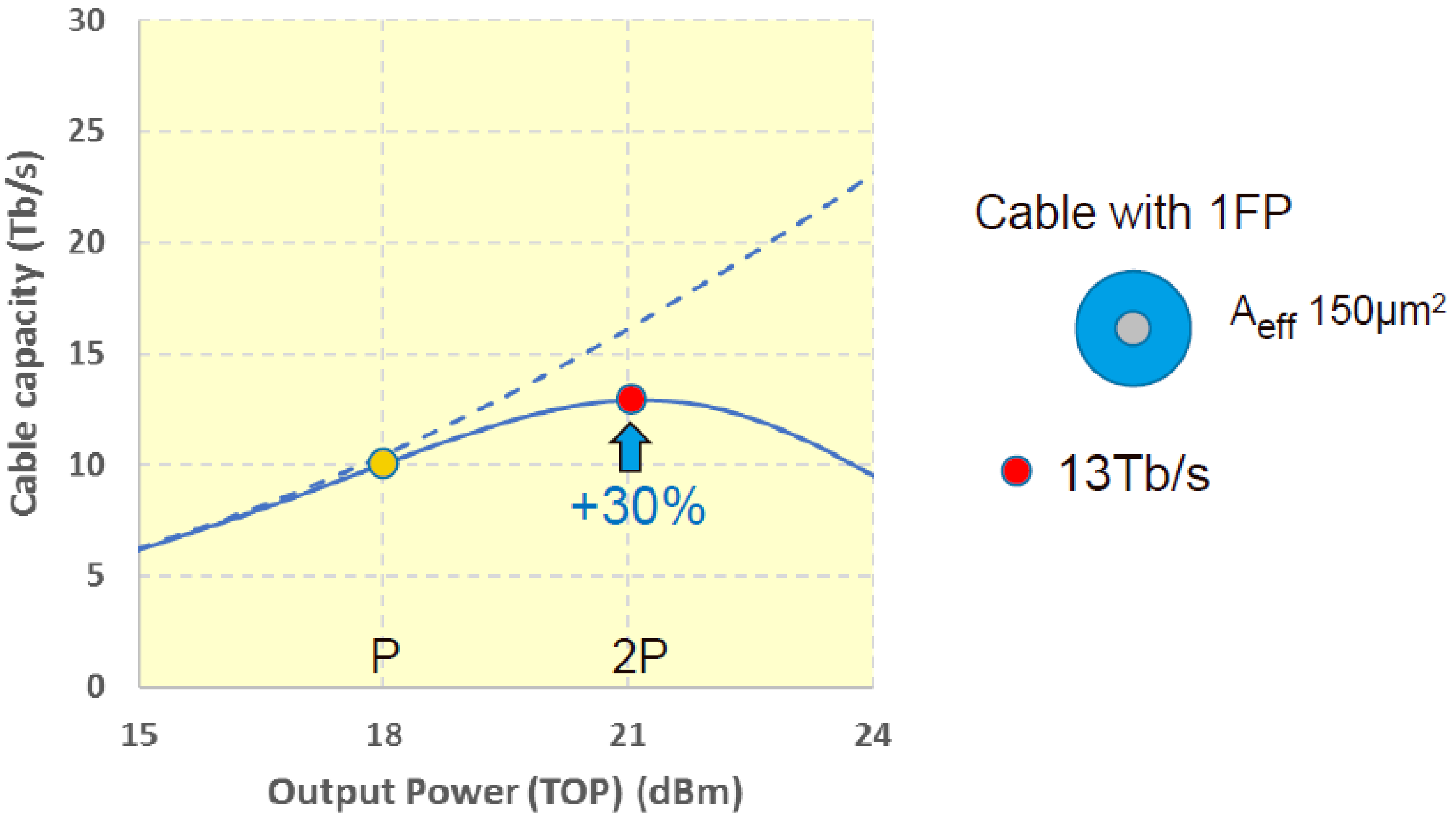
Shannon: $Capacity = N_{fibers} * 2_{polars} * Band_{EDFA} * \log_2\left(1 + \frac{SNR(Power)}{Pen}\right)$



[**Pecci**, S1D, OFC'18]

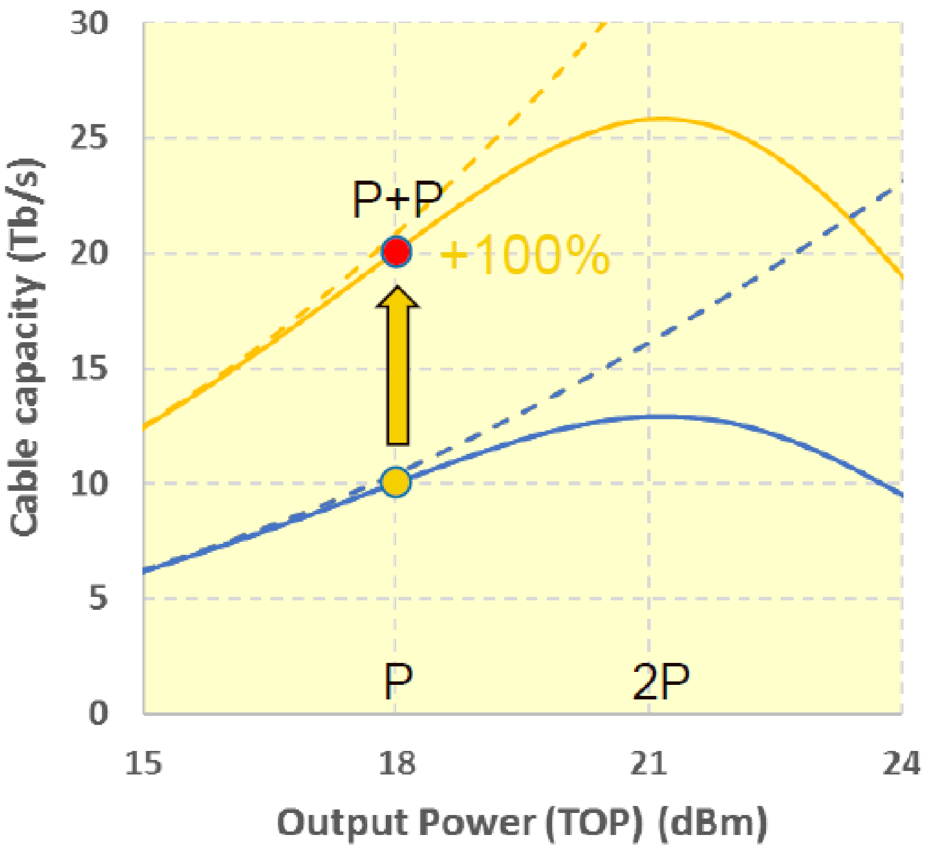
What are the options to increase capacity with a second pump?

Spatial Division Multiplexing : Approaching Shannon limits in cables



Option 1: Increase the Power (TOP, $OSNR_{ASE}$) → +30% fibre capacity (best case)

Spatial Division Multiplexing : Approaching Shannon limits in cables



Cable with 2FP

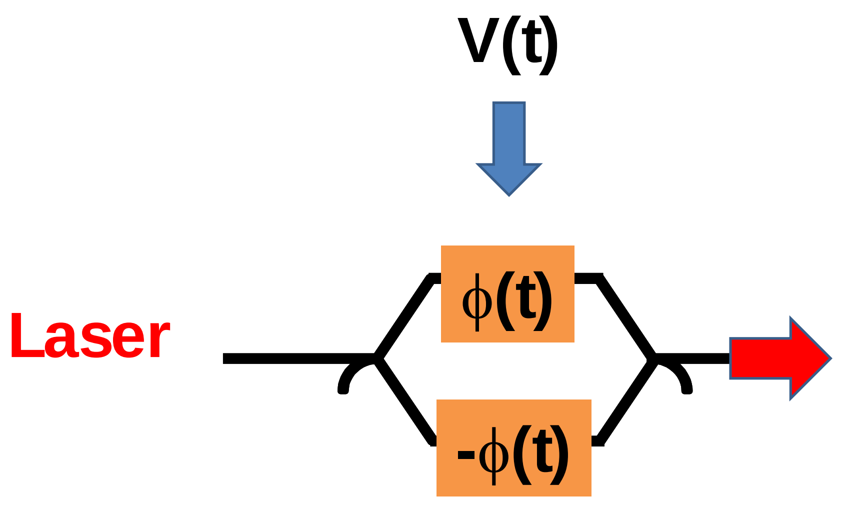
● 20Tb/s

Pump farming over multiple fibres

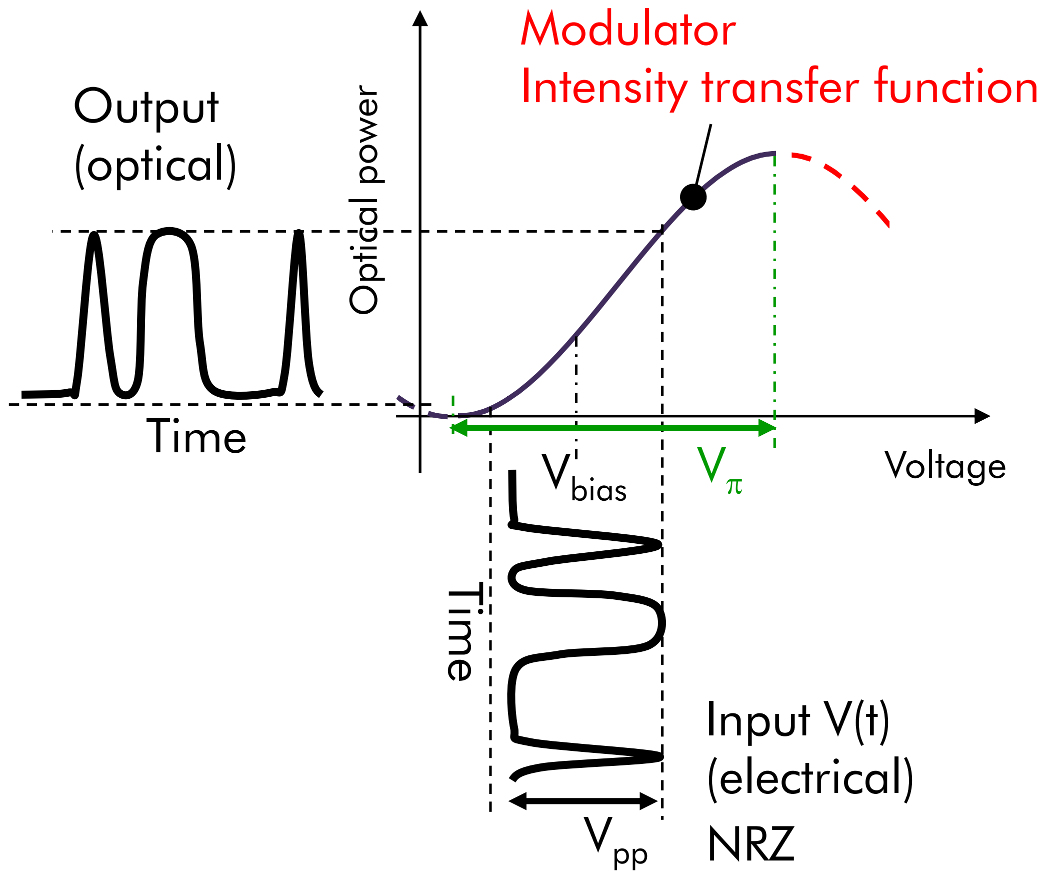
Option 2a: Add a fibre → +100% cable capacity

Back up slides

Modulation of light: key building block



Electro-optic modulator

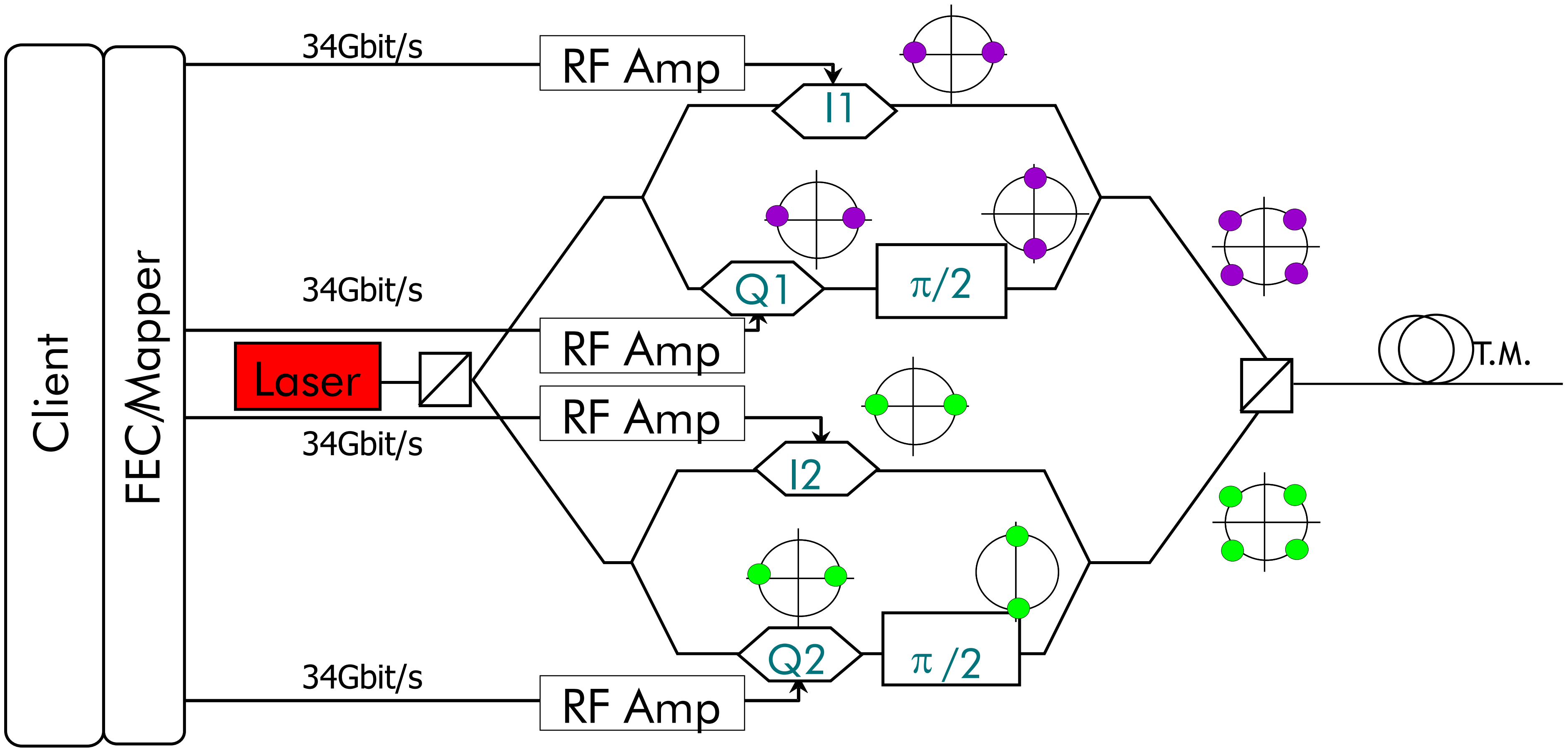


Phase modulators in push-pull configuration nested in a Mach-Zehnder interferometer

➔ Amplitude modulation

Typical 100G PDM-QPSK transmitter architecture

Courtesy S. Bigo



Modulation of in-phase and in-quadrature along two orthogonal polarizations

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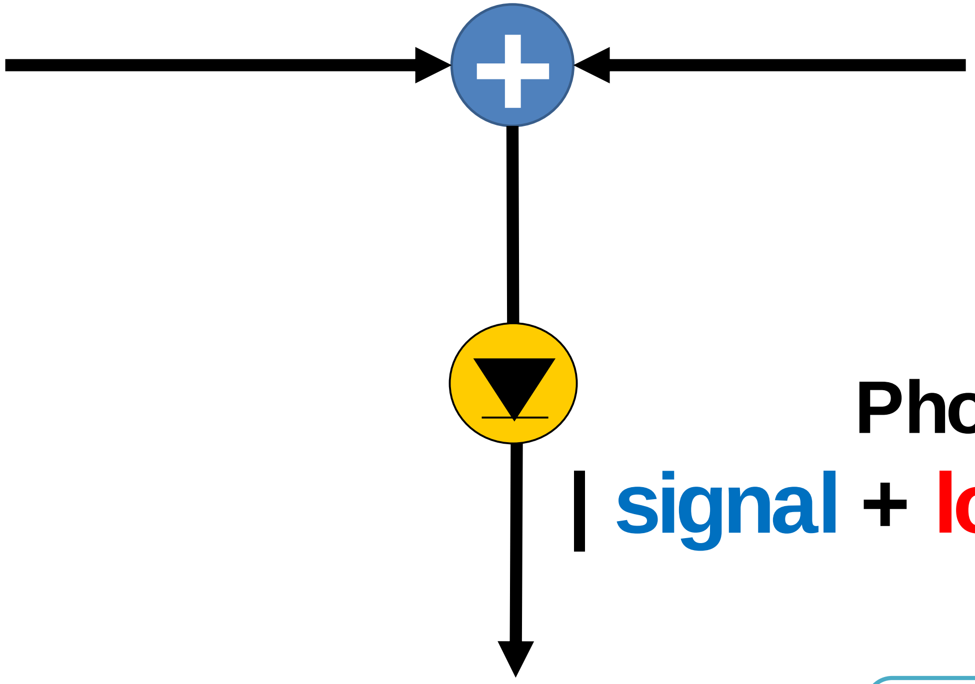

Photodiode

| signal + local oscillator|²

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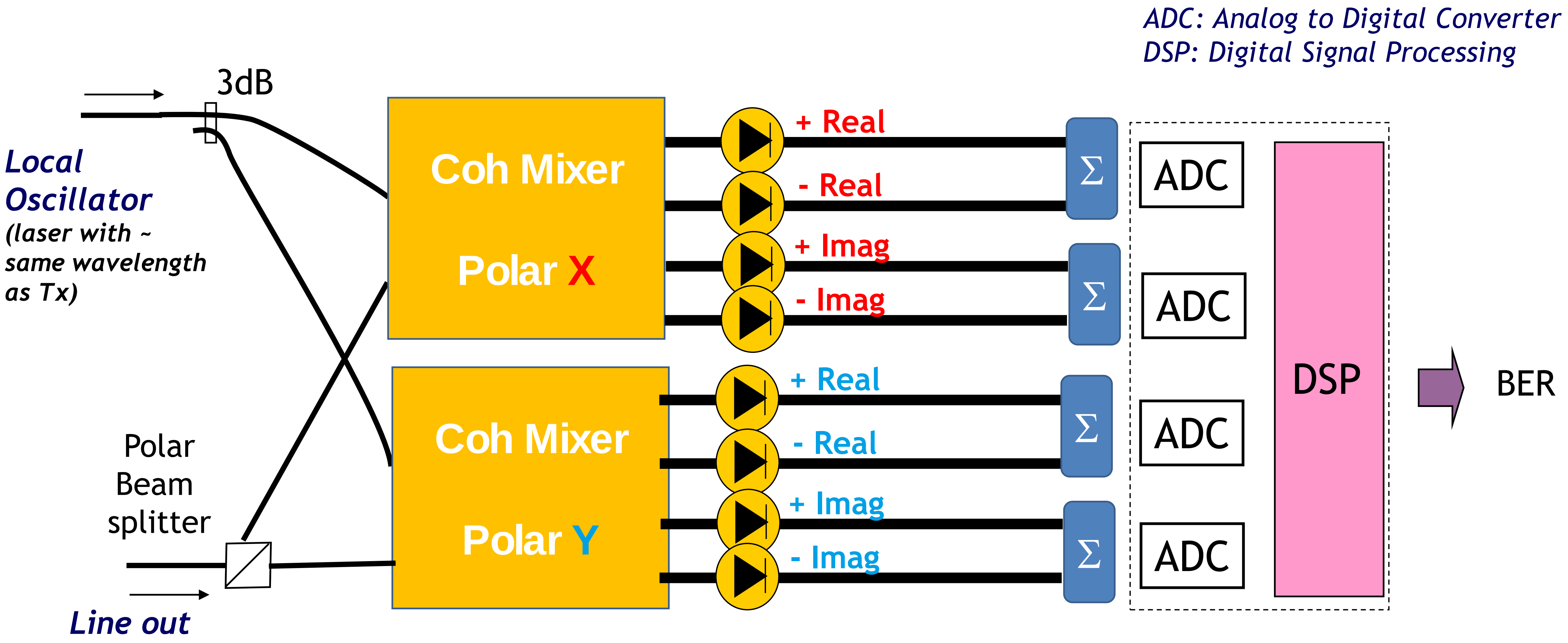
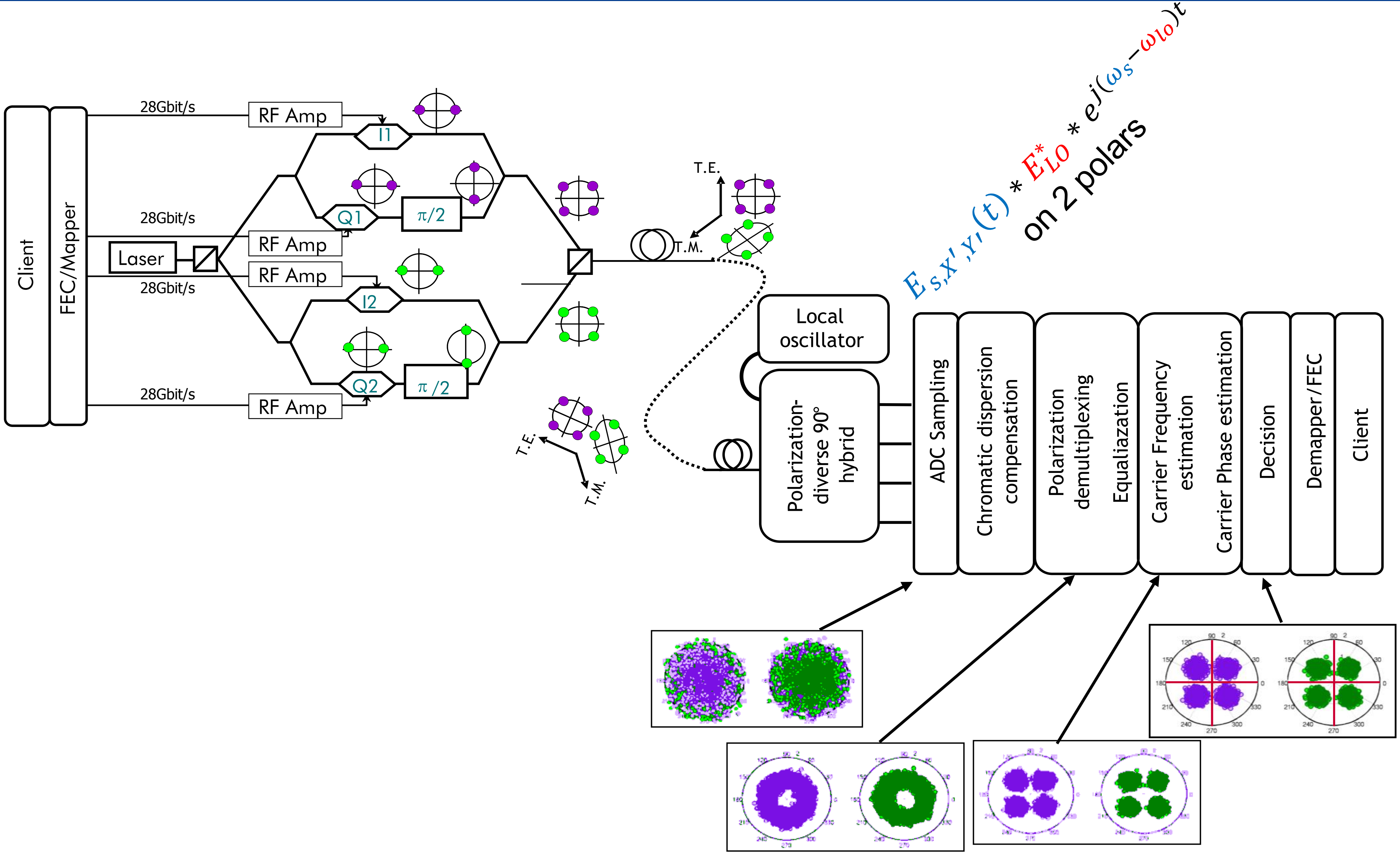
What we seek ($E_s(t)$)

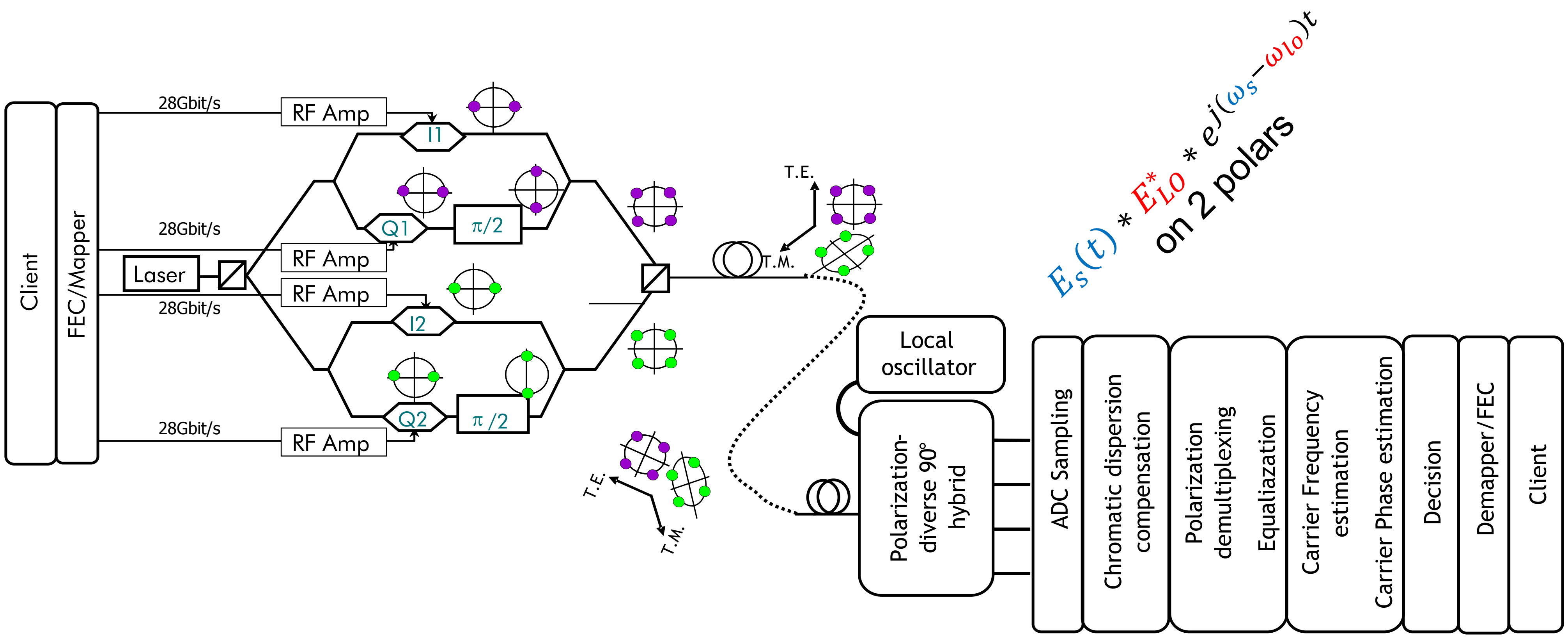
Coherent receiver (polarization independent)



100G Coherent systems architecture



100G Coherent systems architecture



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