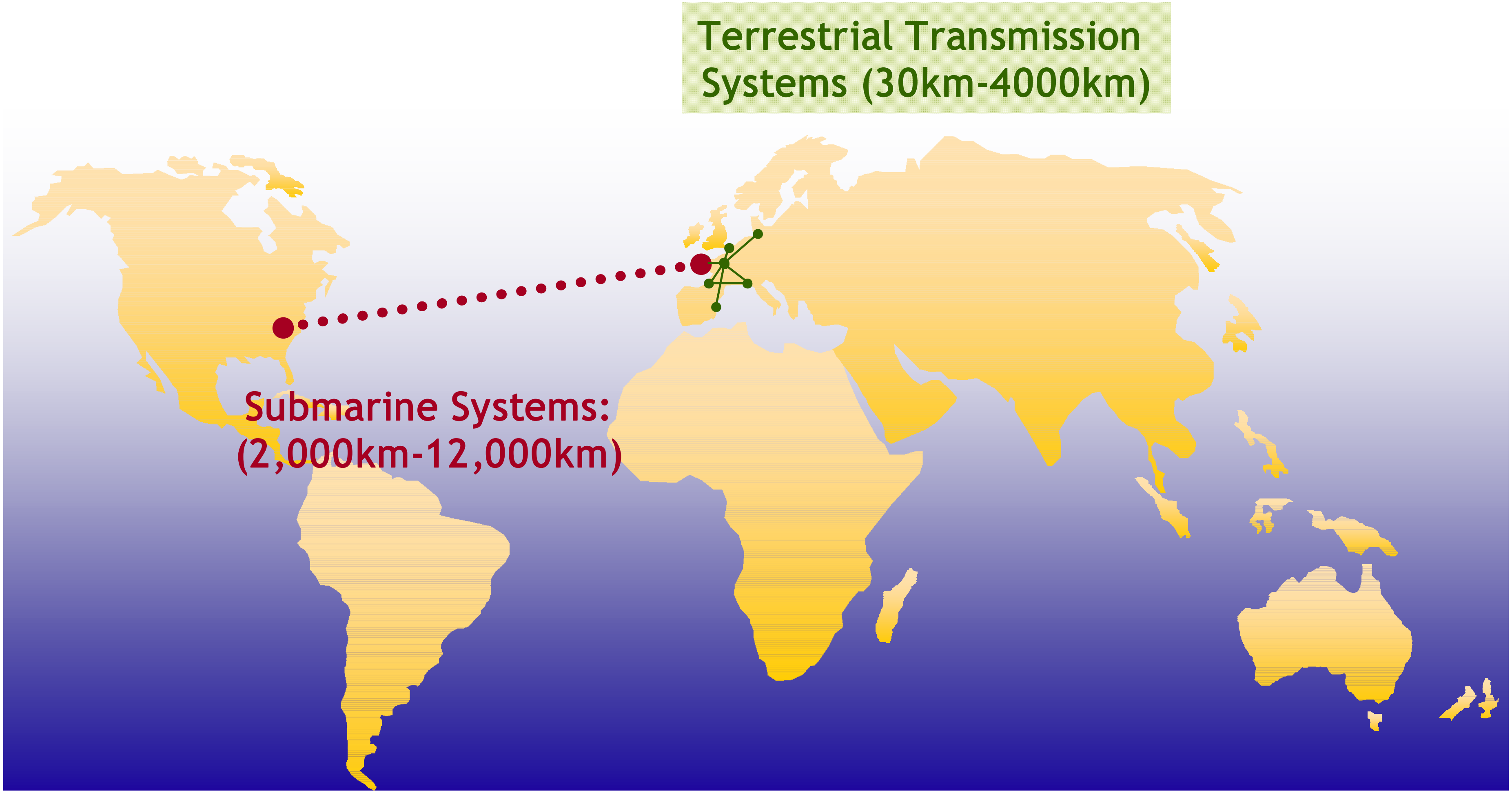
The major changes affecting the physical layer of optical networks

Sébastien Bigo
Alcatel-Lucent, Bell Labs, Centre de Villarceaux, 91620 Nozay

Seminar, February 15th, 2008
Palaiseau

Context



Alcatel·Lucent

Outline

Three major trends driving research and innovation in optical networks :

- #1 Greater *capacity*
- #2 Higher *transparency*
- #3 Full remote *reconfigurability*

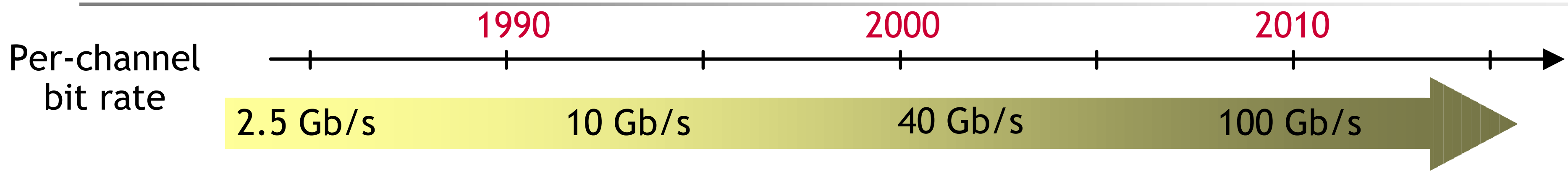
From the trends to physics

A selection of **approaches to meet the trends**

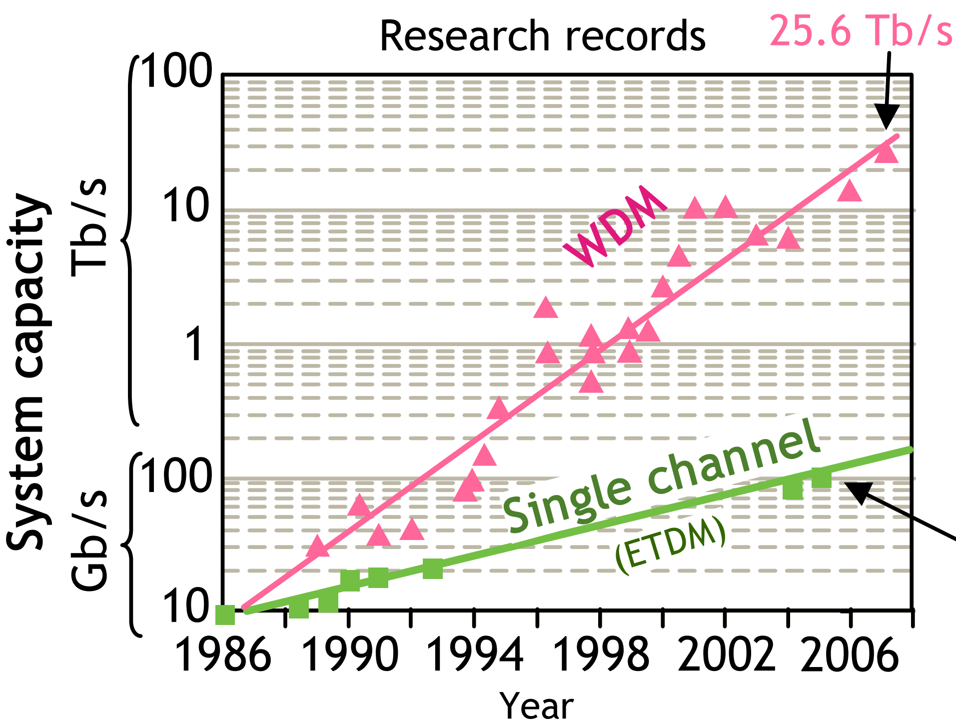
- New modulation formats
- New detection schemes
- Advanced digital signal processing technique
- Original link designs

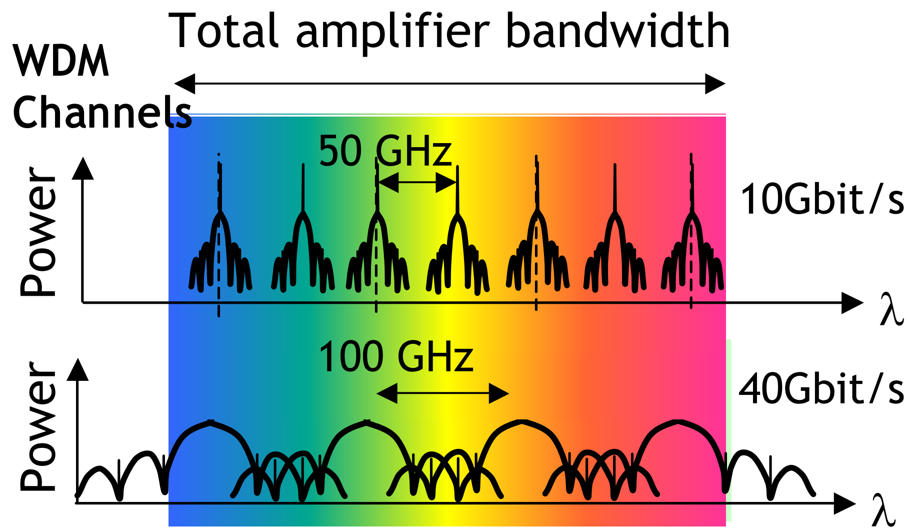
Major trends in optical networks

Greater capacity into a single fiber

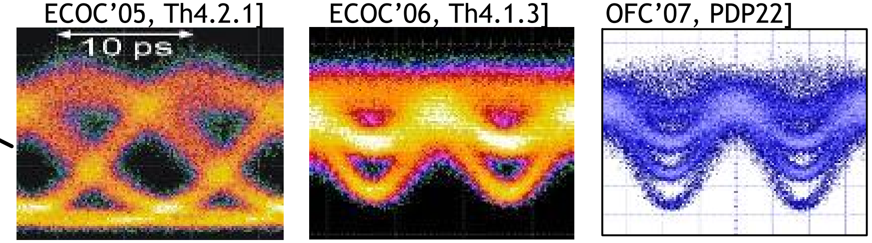


Trend #1 : greater *capacity* ➔ exponential growth, driven today by video traffic





[C. R. Doerr et al., ECOC'05, Th4.2.1]
[P. J. Winzer et al., ECOC'06, Th4.1.3]
[C. R. S. Fludger et al., OFC'07, PDP22]



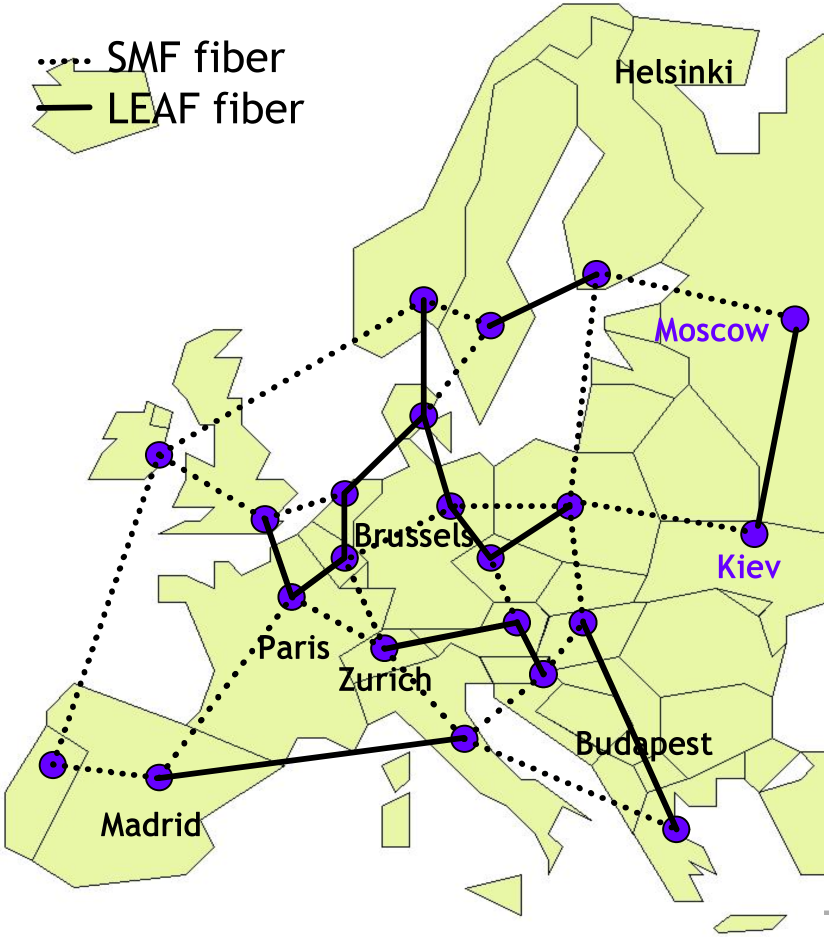
107-Gbaud OOK
53.5-Gbaud DQPSK
27.75-Gbaud PDM QPSK

Alcatel·Lucent

Towards transparent, reconfigurable mesh networks

Past (& a lot of current) networks

Electrical-Optical-Electrical (OEO) regen. at each node (mostly opaque)



Future Networks

Trend #2: *Higher transparency* ➔ photonic pass-through, avoiding OEO regeneration

➔ CAPEX reduction

Consequences (and challenges) :

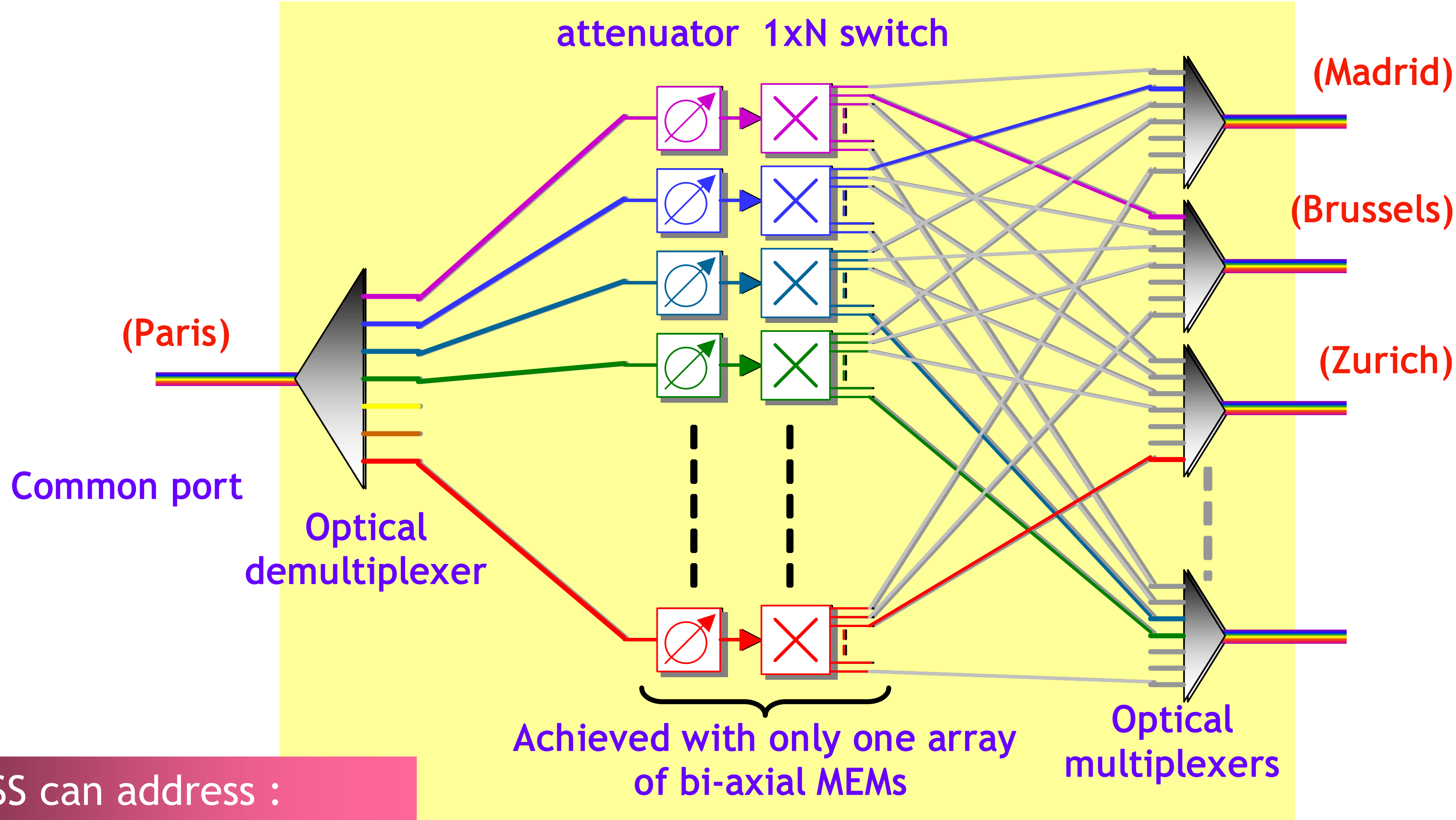
- longer distances to bridge
- several fiber types across the full fiber path
- Mix of bit-rates over the same fiber…

Trend #3: *Full remote reconfigurability* ➔ possibility to remotely configure (add/drop or pass-through) a given wavelength

➔ OPEX reduction

Application potential of this trend depends on how fast reconfiguration can be achieved.

Transparent and reconfigurable node architecture
A key technological element: Wavelength Selective Switch (WSS)



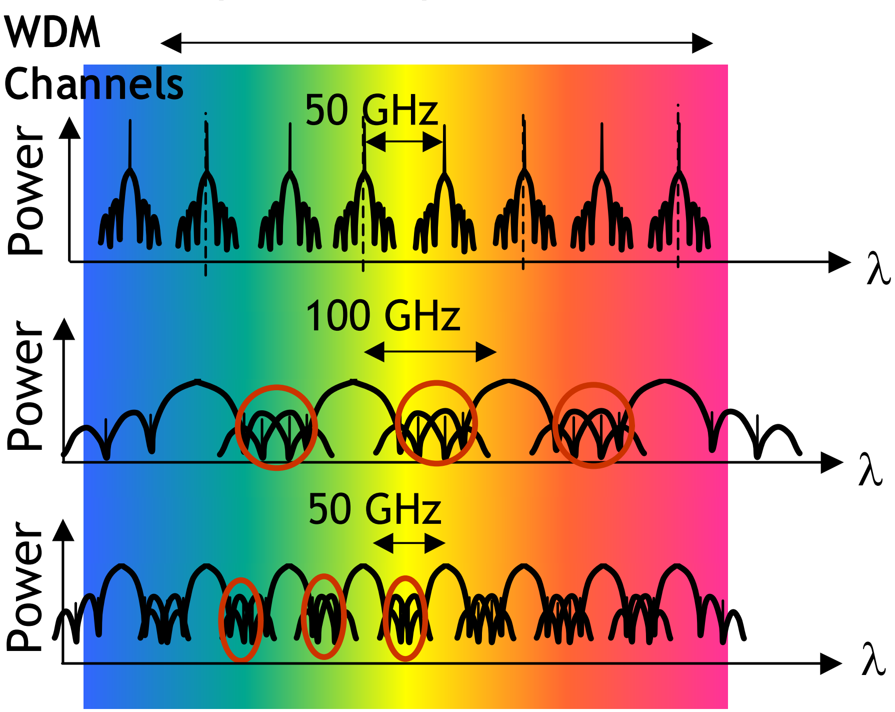
The WSS can address :
- any input channel
- to any output port
- with adjustable loss

Alcatel·Lucent

From the network trends to physics

Increasing the capacity of WDM systems
The Information Spectral Density challenge

Spectral density = bit rate / ch. spacing

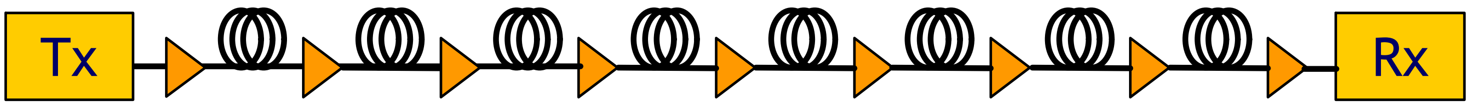


8 channels at 10 Gbit/s NRZ spaced every 50 GHz capacity = 80 Gbit/s		20%
4 channels at 40 Gbit/s DPSK spaced every 100 GHz capacity = 160 Gbit/s	*Today's best in Alcatel-Lucent portfolio*	40%
8 channels at 40 Gbit/s PSBT spaced every 50 GHz capacity = 320 Gbit/s		80%

➔When the channel bit-rate increases, the system capacity increases only if the spectral density increases.

Alcatel·Lucent

Mastering optical power levels to make an optical link viable

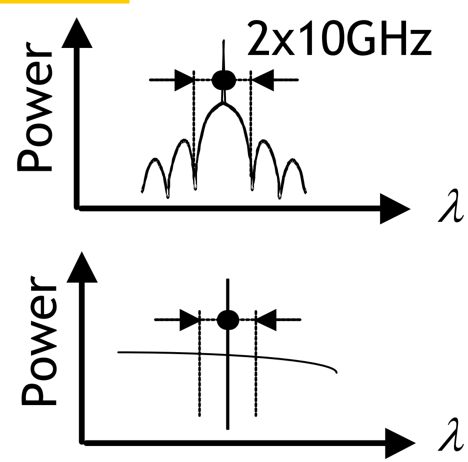


(Assuming identical power level at each optical amplifier output)

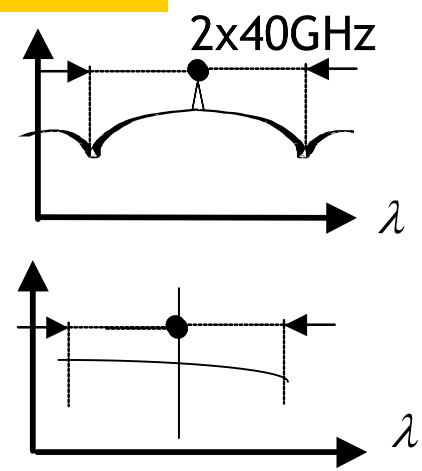
Amplifier output power level should fall between two limits :

- max power level before distortions by nonlinear effects become detrimental
- min power level before signal is drown into noise

10Gb/s



40Gb/s



$$\text{OSNR} = \frac{S}{N}$$

Signal power (S)

⊕

Amplifier Noise power (N)

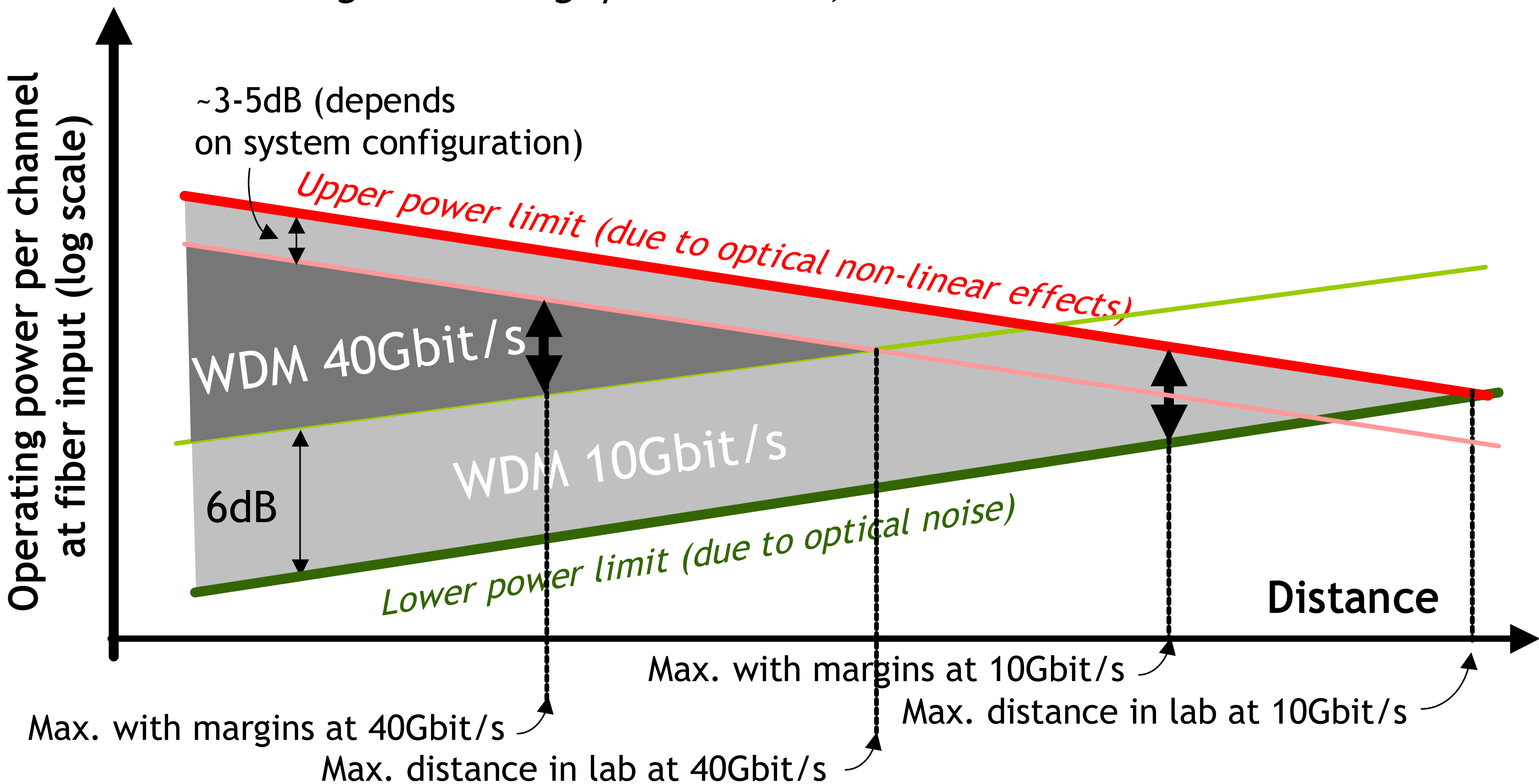
The receiver catches 4x (resp. 10x) more amplifier noise power at 40Gb/s (resp. 100Gbit/s) than at 10Gbit/s.

→ 6dB higher Optical Signal-to-Noise Ratio (OSNR) needed at 40Gbit/s than at 10Gbit/s

From 10Gbit/s to higher bit-rates

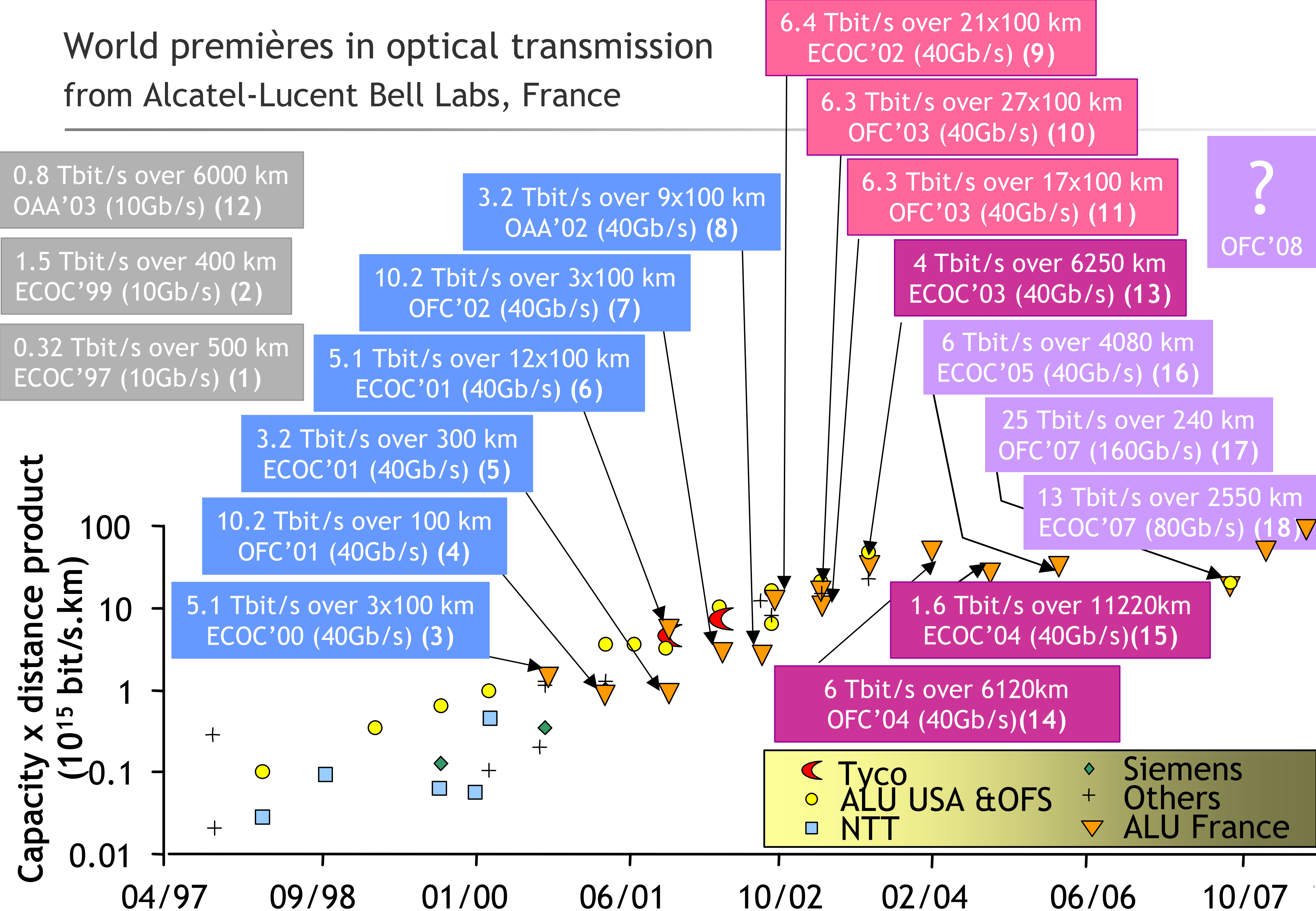
Estimation of maximum distances when based on same technologies

Estimations assuming 100km-long spans of fiber, NRZ format



➔ Reaching the same distance at a higher bit-rate is always a difficult challenge.

World premières in optical transmission
from Alcatel-Lucent Bell Labs, France



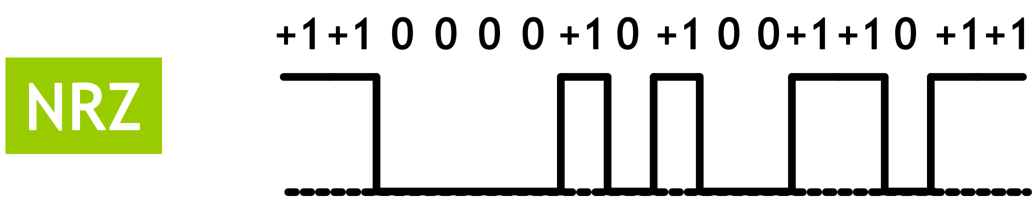
Alcatel·Lucent

A selection of approaches to meet the trends

Why departing from NRZ format when moving to 40Gbit/s ?

Modulation format = approach used to apply the incoming digital information to each of the optical carriers

At 10Gbit/s, (almost) all systems are based on ON-OFF modulation (also called Amplitude Shift Keying, **ASK**), generally with **Non-Return-to-Zero** (NRZ) format



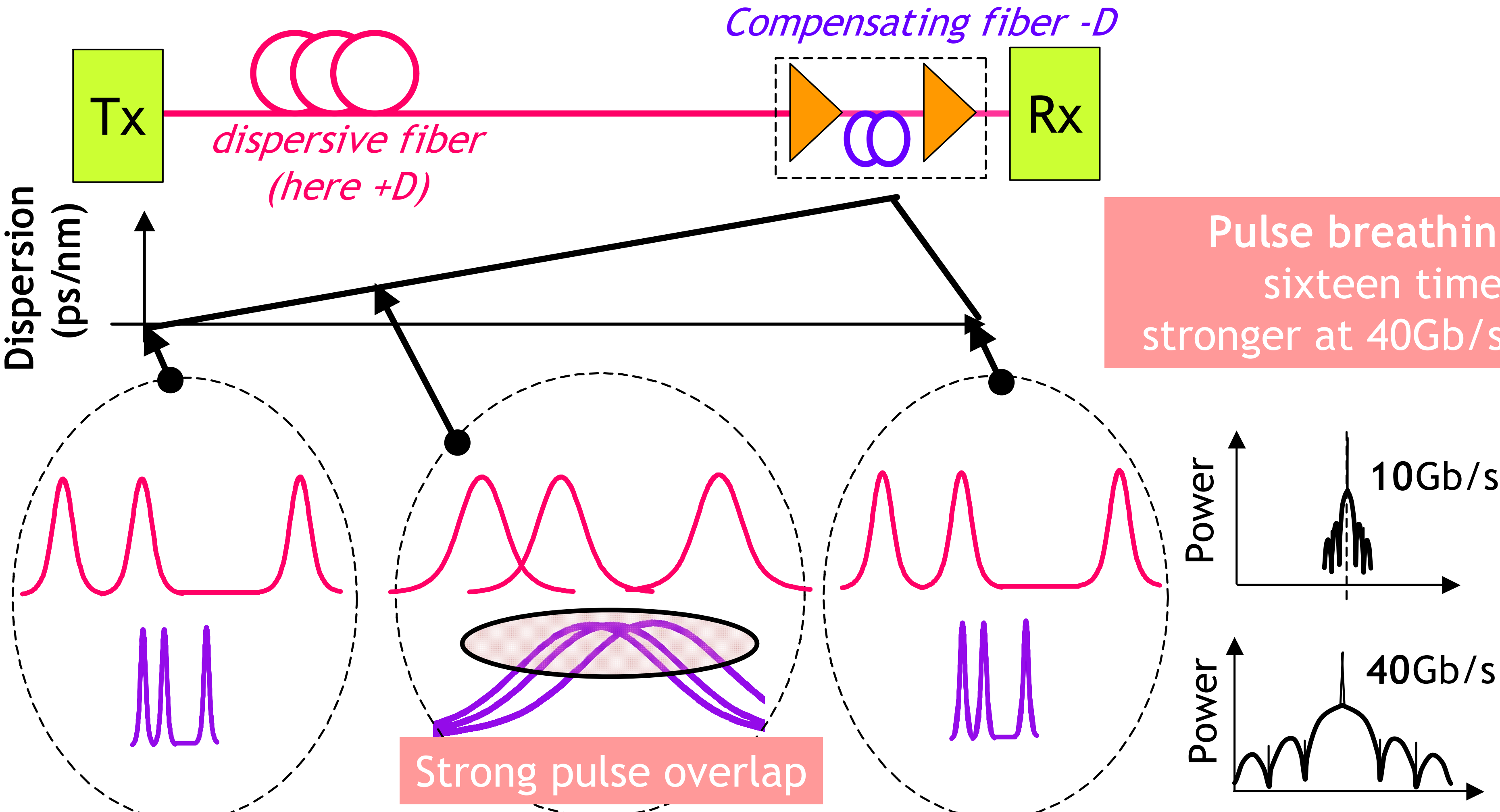
What may suggest that alternative modulation formats would bring more benefits at 40G than at 10G ?

... because the most limiting nonlinear effects have a different nature

- at 10Gbit/s, **interchannel** effects dominate
- at 40Gbit/s, **intrachannel** effects dominate

Alcatel·Lucent

Nonlinear interactions : 40Gb/s vs 10Gb/s
(intra-channel nonlinear effects)



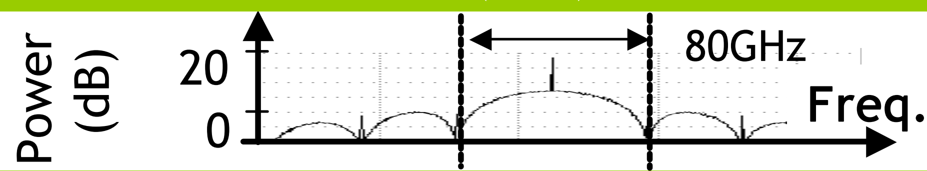
Pulse breathing sixteen times stronger at 40Gb/s!

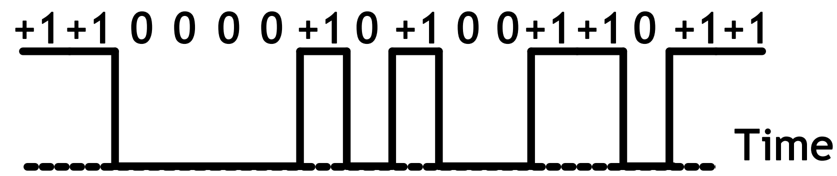
→Techniques against pulse-to-pulse interactions likely show benefits at >40Gbit/s

Alcatel·Lucent

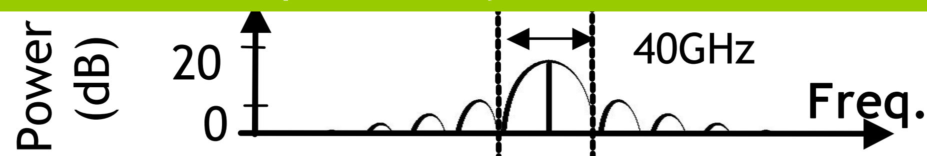
Typical data waveforms (here for 40Gbit/s systems)

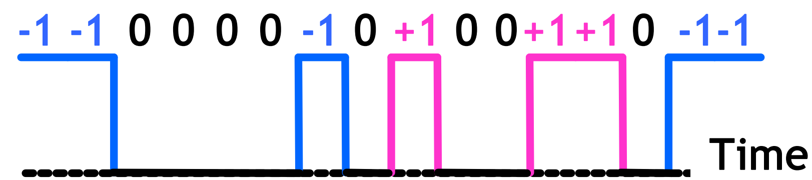
NRZ= Non Return to Zero (NRZ)



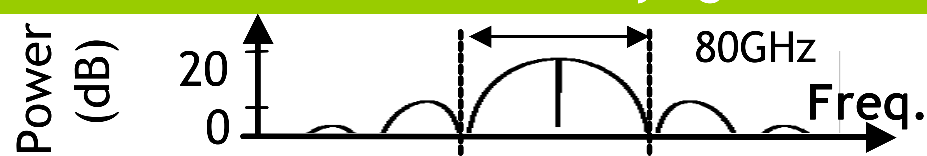


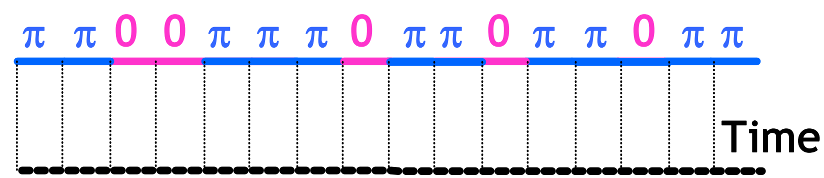
PBST= Phase-Shaped Binary Transm.



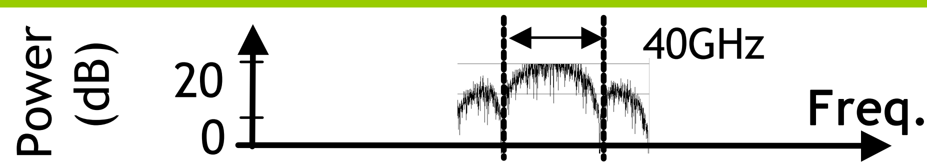


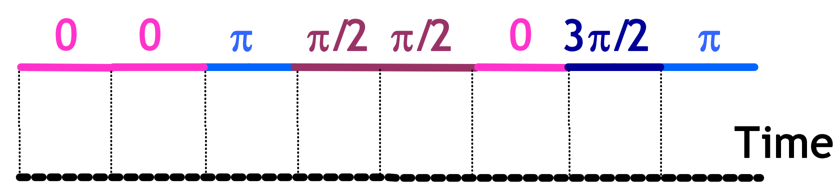
DPSK= Differential Phase Shift Keying



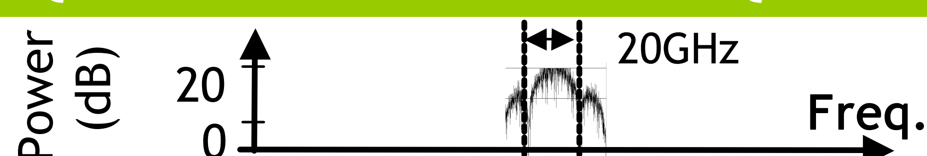


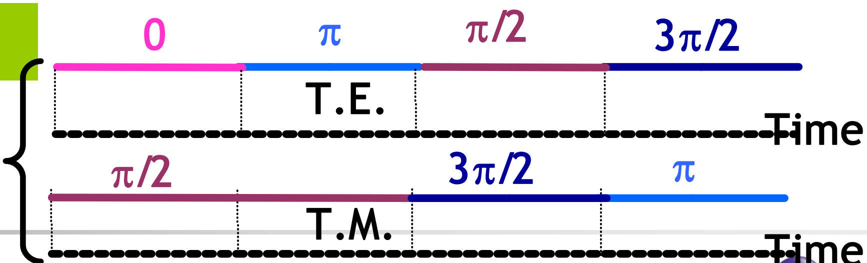
QPSK= Quadrature Phase Shift Keying





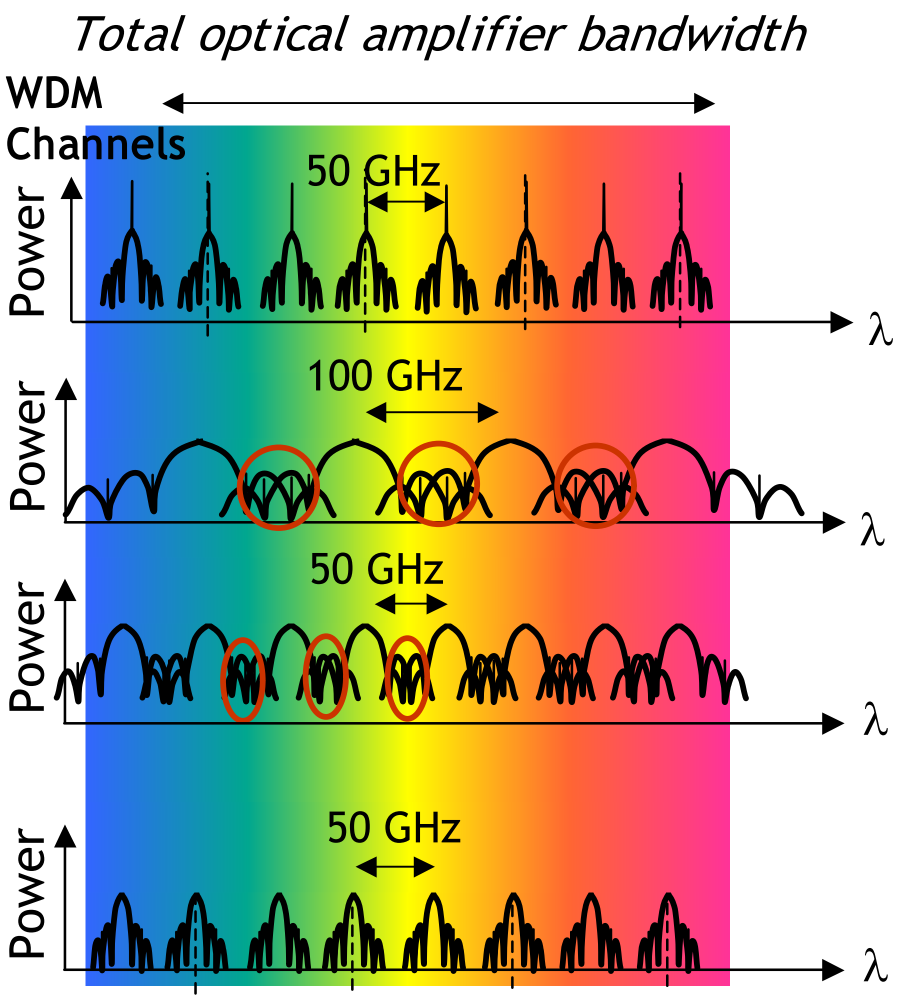
PDM-QPSK= Polarization Division Mux QPSK





Alcatel·Lucent

Increasing the capacity of WDM systems
The Information Spectral Density challenge



Spectral density =
bit rate / ch. spacing

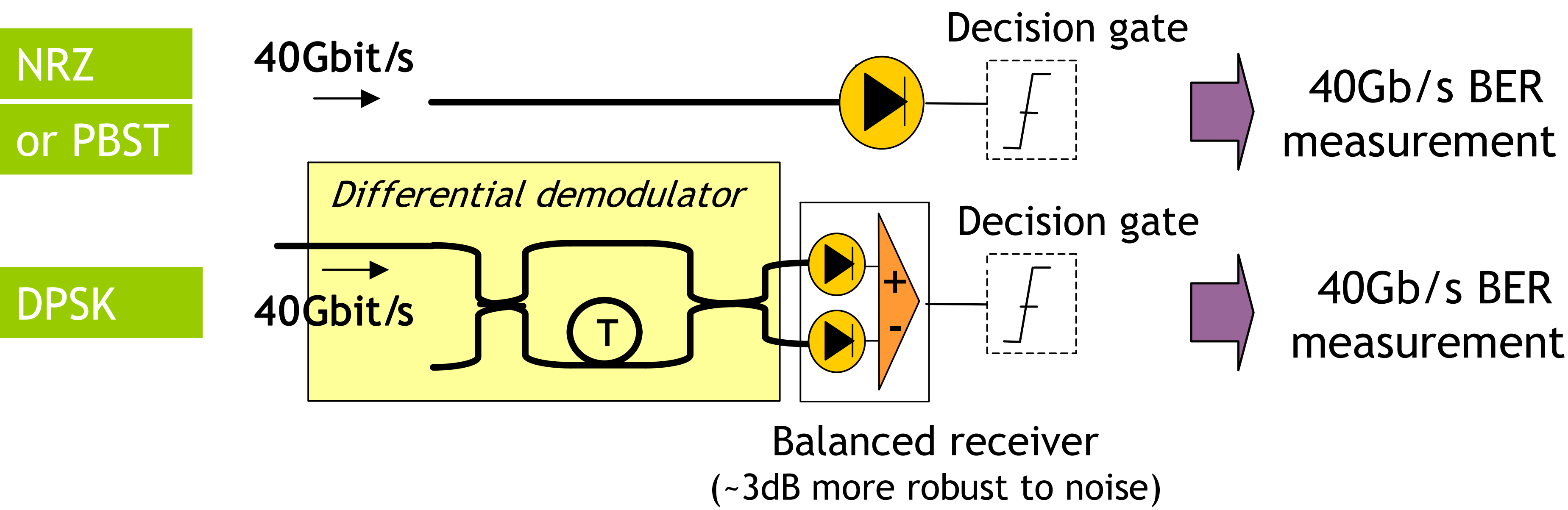
8 channels at 10 Gbit/s NRZ every 50 GHz capacity = 80 Gbit/s	20%
4 channels at 40 Gbit/s DPSK every 100 GHz capacity = 160 Gbit/s	40%
8 channels at 40 Gbit/s PSBT spaced every 50 GHz capacity = 320 Gbit/s	80%
8 channels at 40 Gbit/s PDM-QPSK spaced every 50 GHz ↘ capacity = 320 Gbit/s ↗	80% ↗↗

Today's best in Alcatel-Lucent portfolio (first three formats)

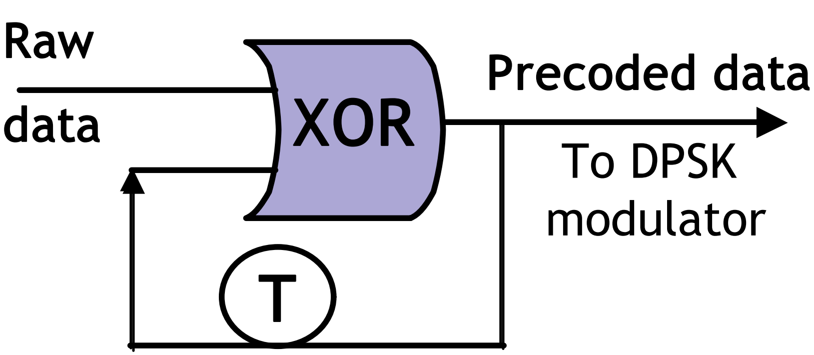
→ Multilevel modulation formats are efficient ways to increase spectral density.

Converting phase information into intensity information

Basics of differential detection



But, differential detection requires… differential precoding

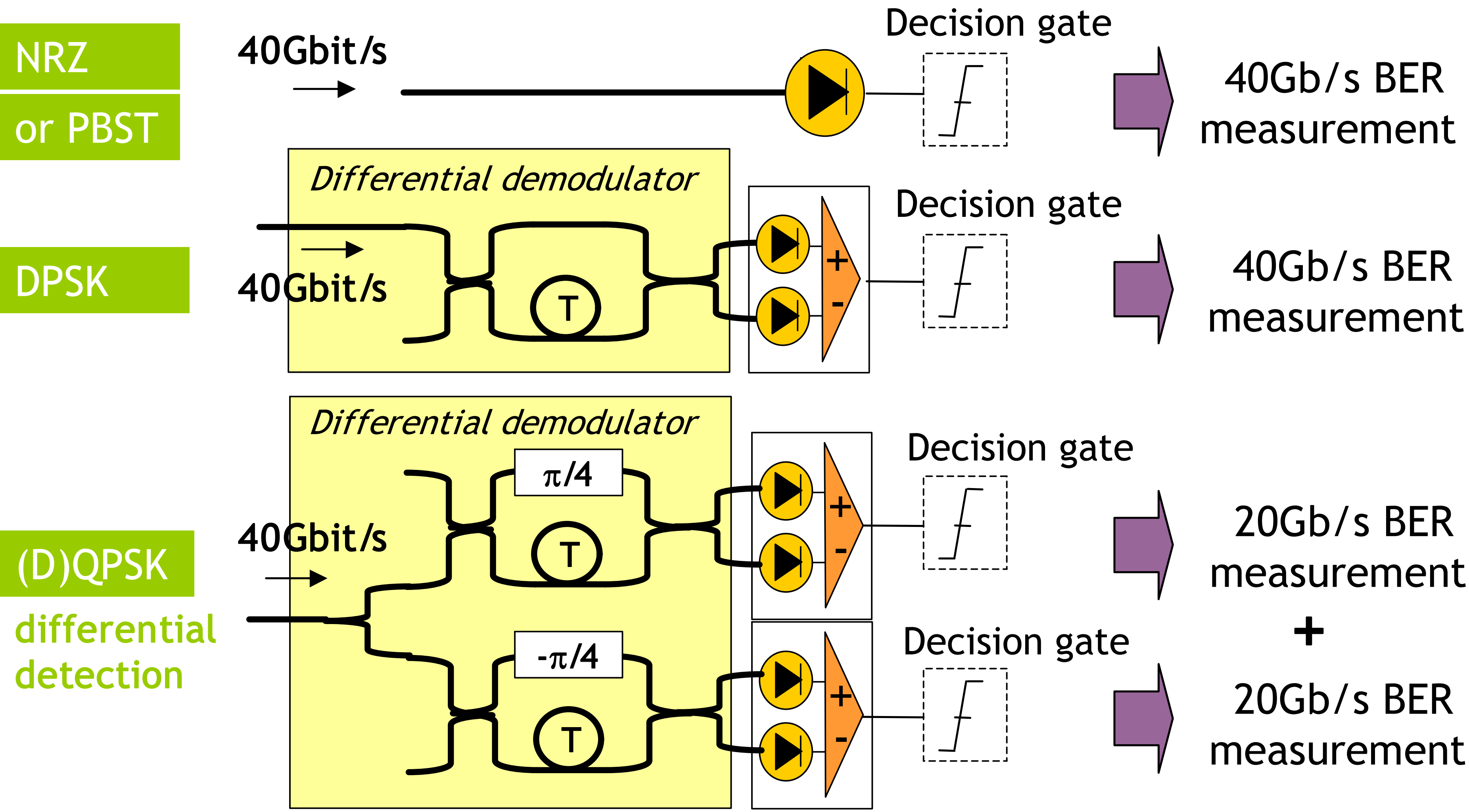


Example:

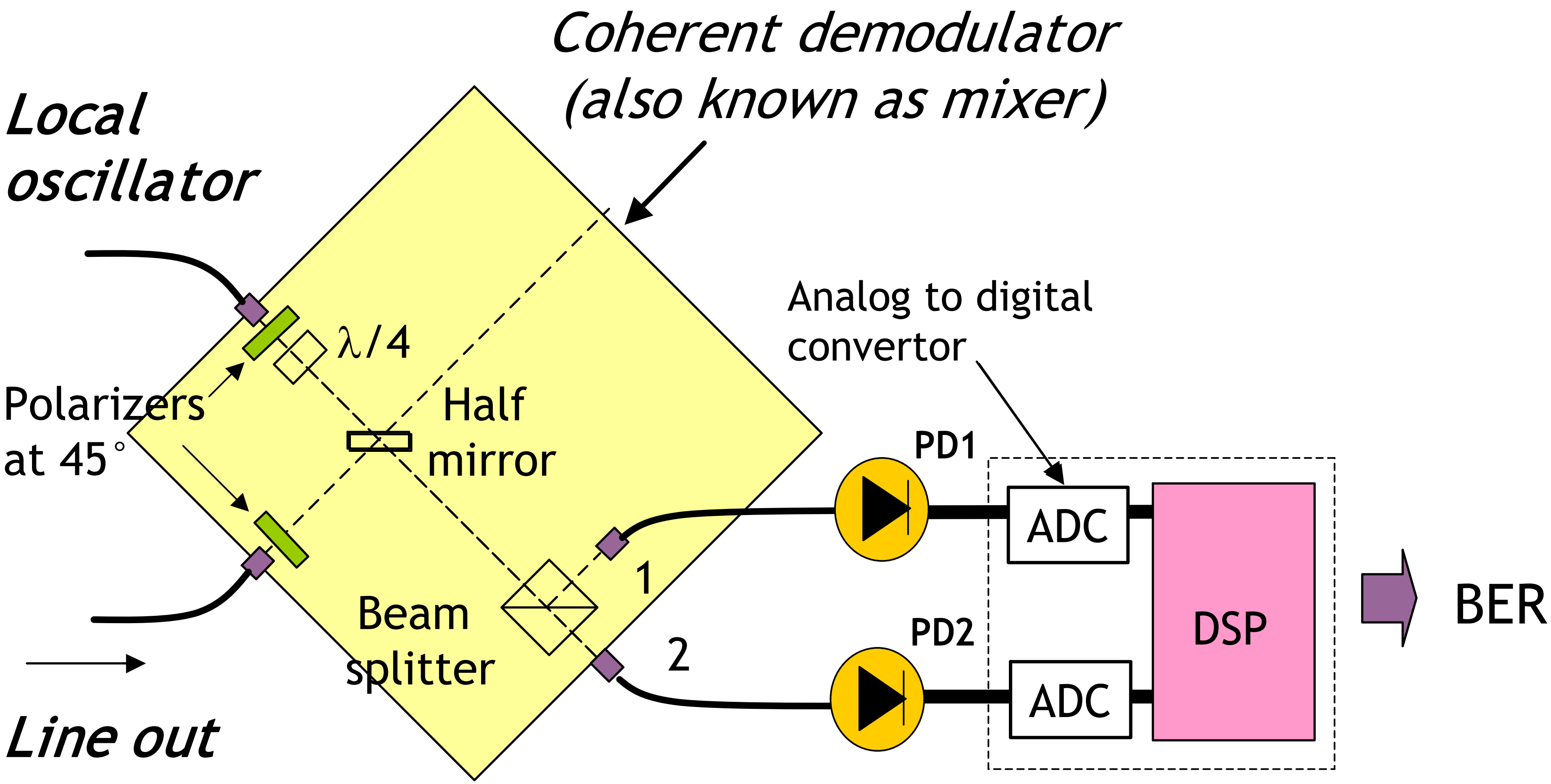
raw data: 1 0 1 0 0 1 1 0 1 1 0

Precoded data: 1 1 0 0 0 1 0 0 1 0 0

Today's possible receiver schemes at 40Gbit/s



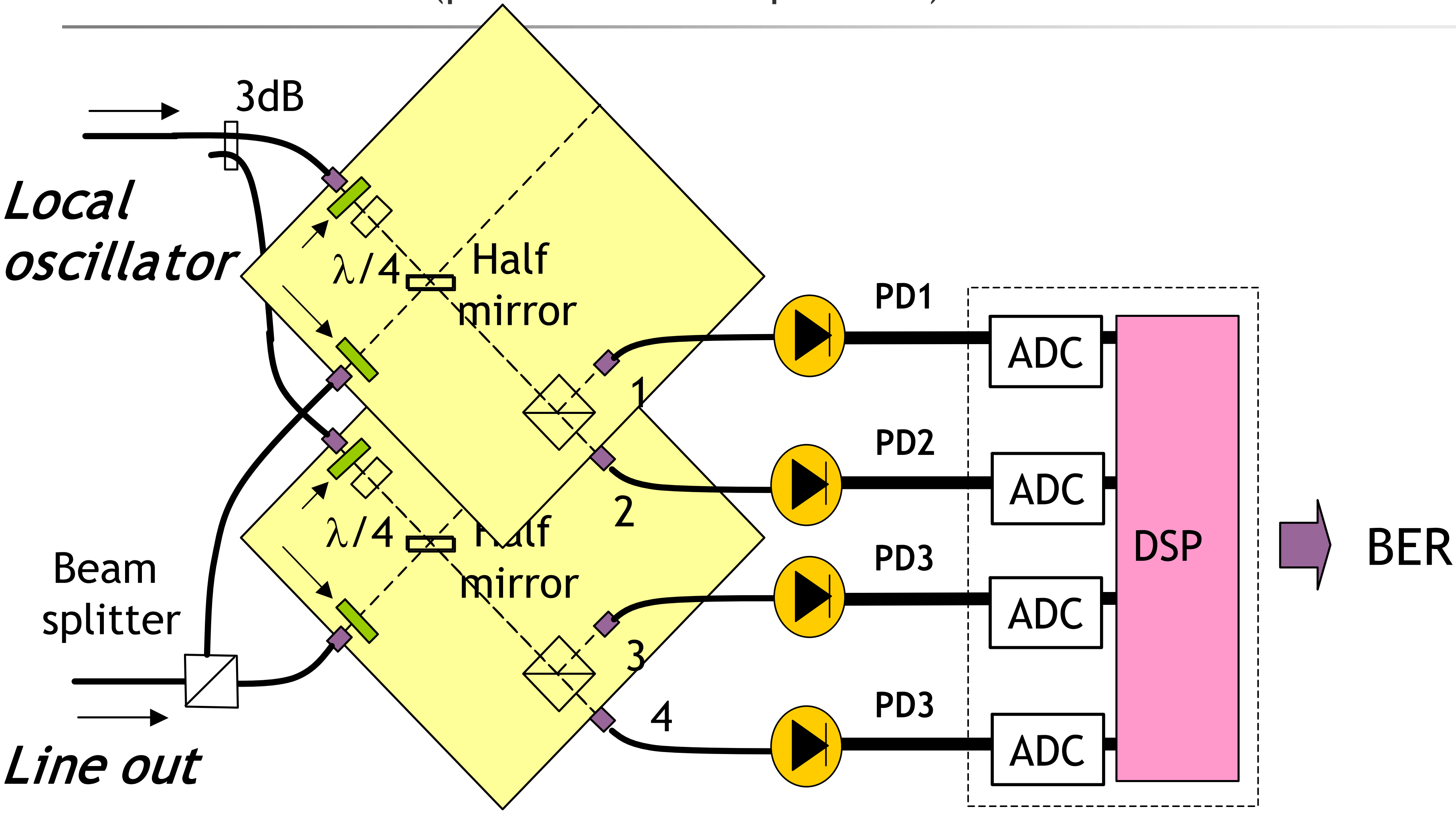
Coherent receiver (polarization dependent)



The photocurrents PD1, PD2 provide information on real and imaginary parts of the incoming signal field.

Alcatel·Lucent

Coherent receiver (polarization independent)



The photocurrents PD1, PD2, PD3 and PD4 provide full information on real and imaginary parts of signal along TE and TM polarization axes

From coherent detection to coherent systems (1)

« Coherent » is not just a type of receiver, it should be regarded as a ***fully disruptive system solution***

- Real and imaginary part of the signal are available at the expense of a more complex receiver. Some benefits of coherent detection with two-level formats (NRZ, PSBT, DPSK…) are there, but not worth the extra cost.

Cost effective coherent systems will involve multi-level (>2) modulation formats (QPSK = most promising).

- Turning a drawback into an advantage…

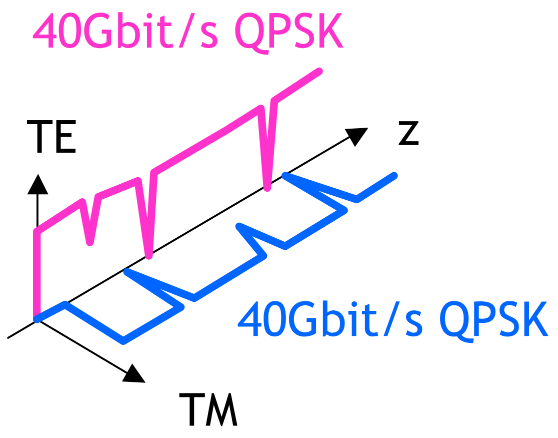
Costly polarization diversity enable polarization division multiplexing (PDM), hence doubling of system capacity without any additional hardware

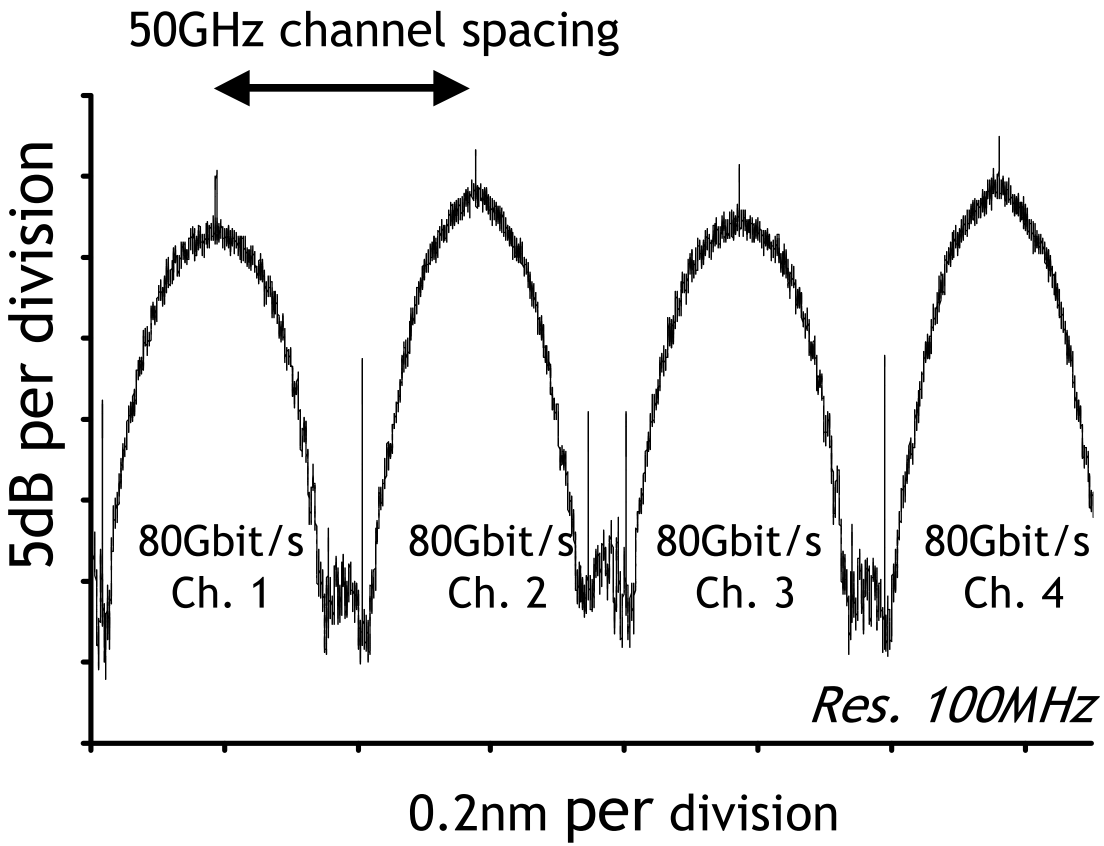
Cost effective coherent systems will involve PDM

Alcatel·Lucent

From 40Gbit/s to 80Gbit/s with PDM

Polarization-Division Multiplexing





160% information spectral density (1.6bit/s/Hz) but still a clear separation between WDM channels

Nx80Gb/s here, but upgrade to WDM at 100Gb/s seems clearly within reach.

From coherent detection to coherent systems (2)

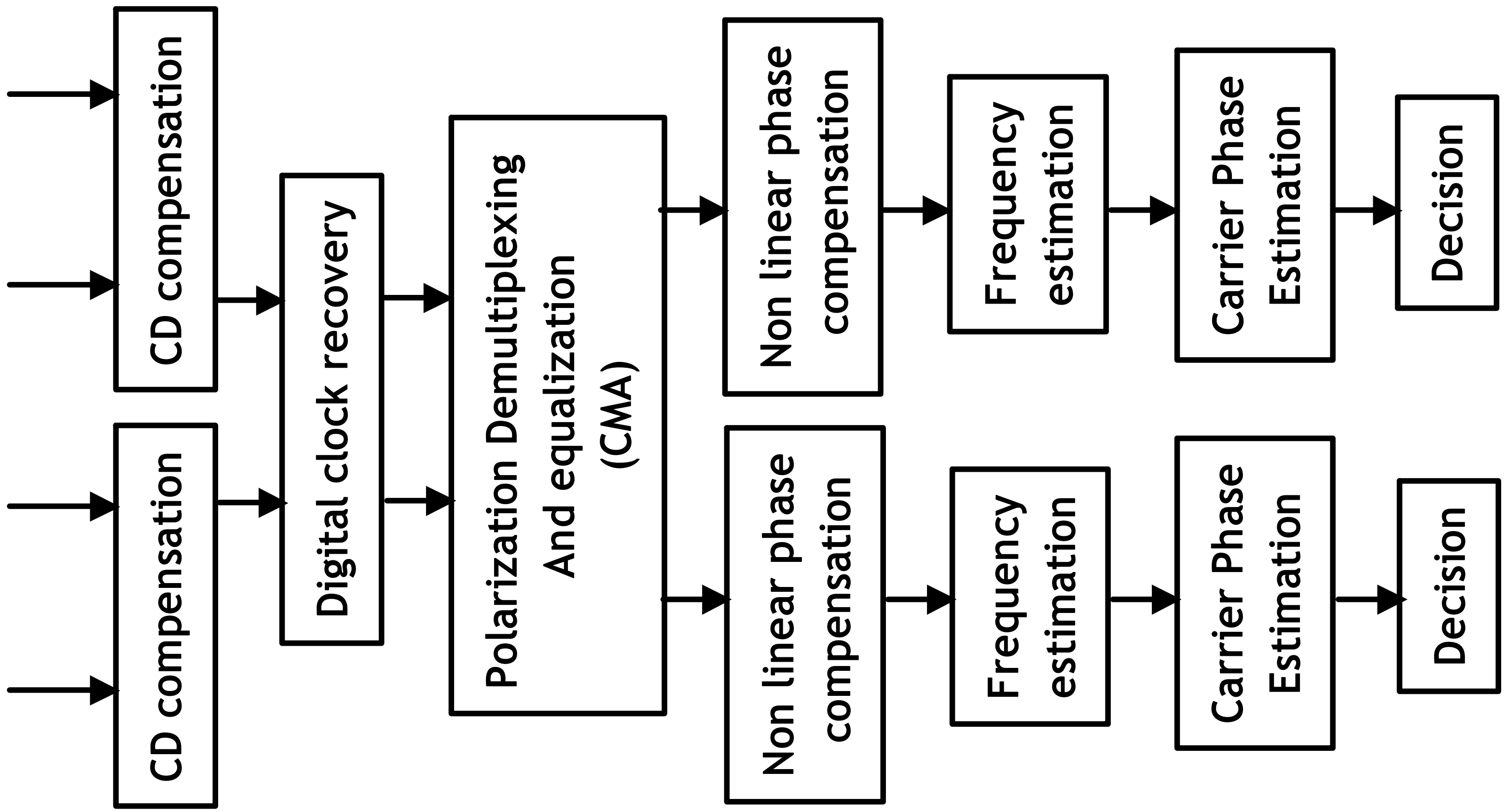
- The recovery of the real/imaginary and TE/TM signal components are not straightforward.
  - High-speed digitization is needed
    - Analog coherent detection not considered here
  - Powerful signal processing is also mandatory.

Cost-effective coherent systems will involve performance vs complexity trade-offs

What the « coherent solution » is :

1. Coherent receiver
2. Transmitter based on multi-level format
3. Polarisation division multiplexing/demultiplexing
4. High-speed sampling and high-throughput digital processor
5. Advanced algorithms for signal recovery and against fiber impairments
6. Dedicated optical system design

Coherent detection and signal processing

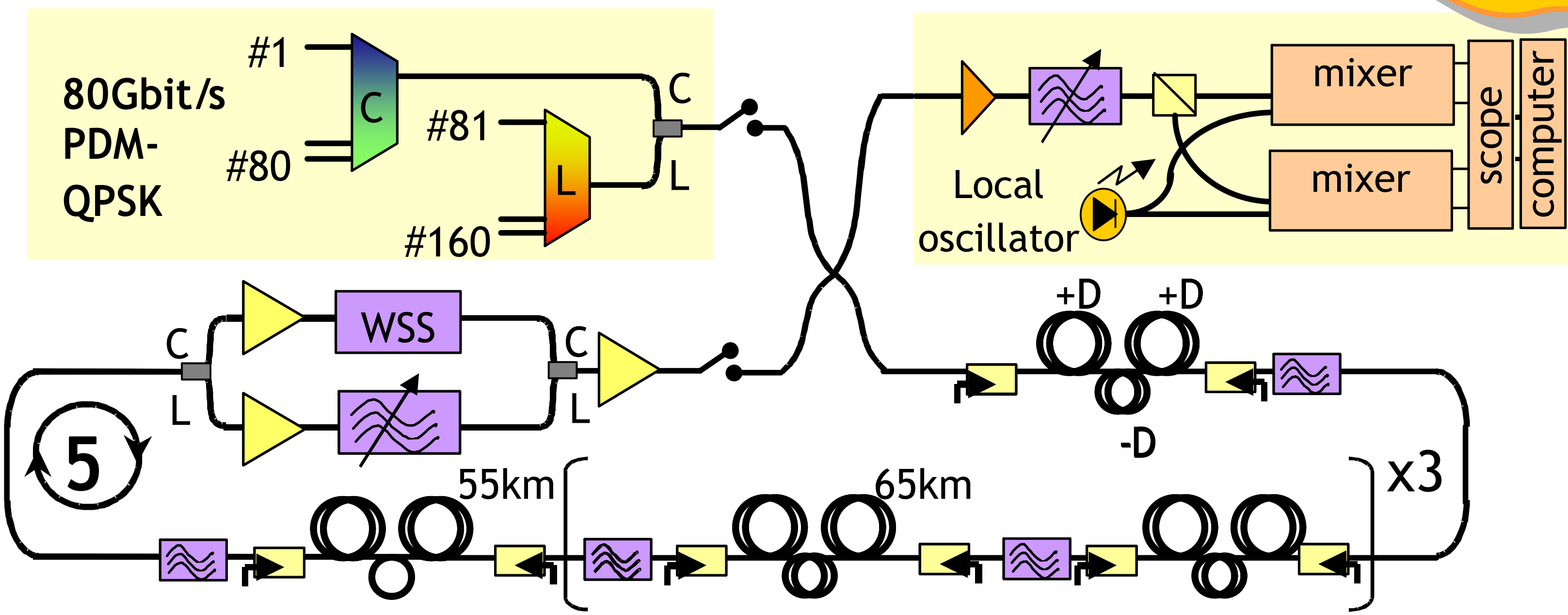


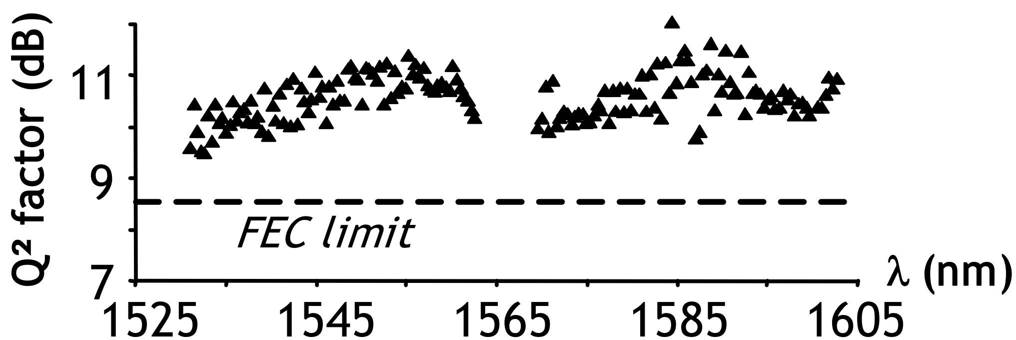
Oversampling required for CD compensation.

One sampling per symbol considered after Polarization Demultiplexing and Equalization.

160x80Gbit/s (12.8 Terabit/s) transmission over 2,550km based on coherent PDM-QPSK + digital signal processing

ECOC'07 postdeadline Sept 2007



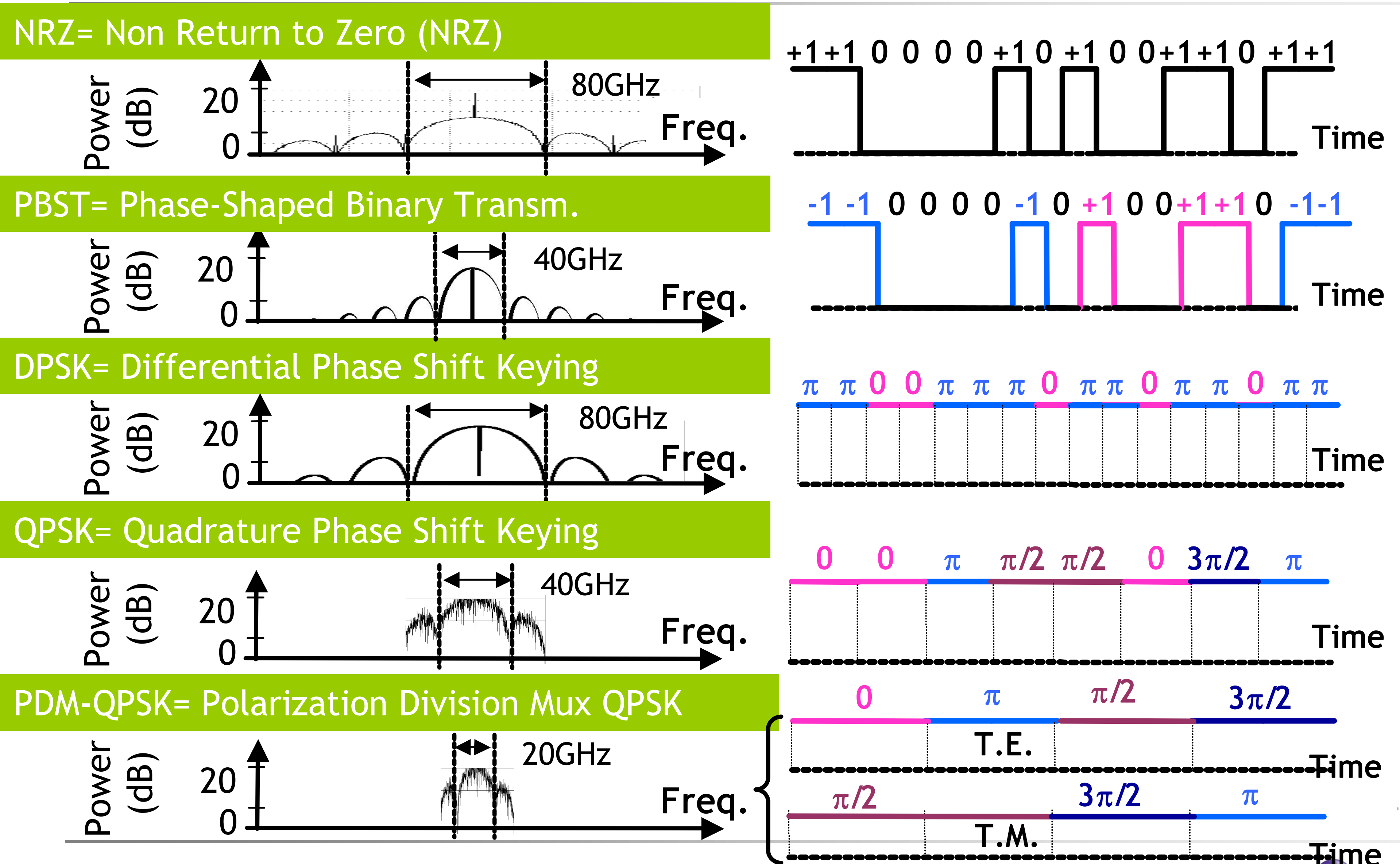


By far the longest transmission >10Tbit/s

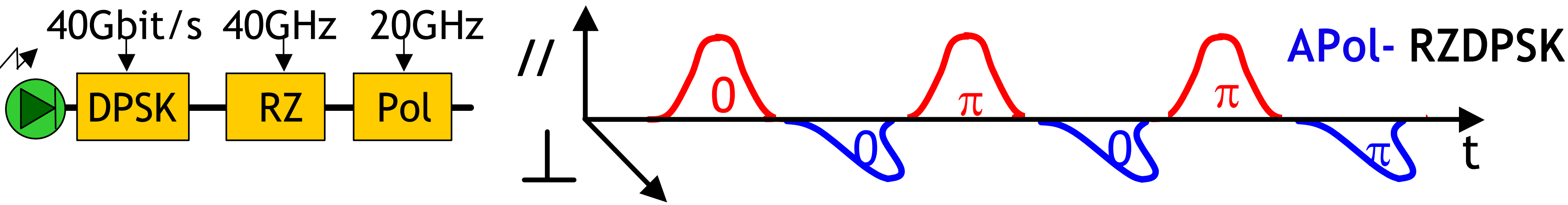
(Previous reports limited to 300km at best)

Alcatel·Lucent

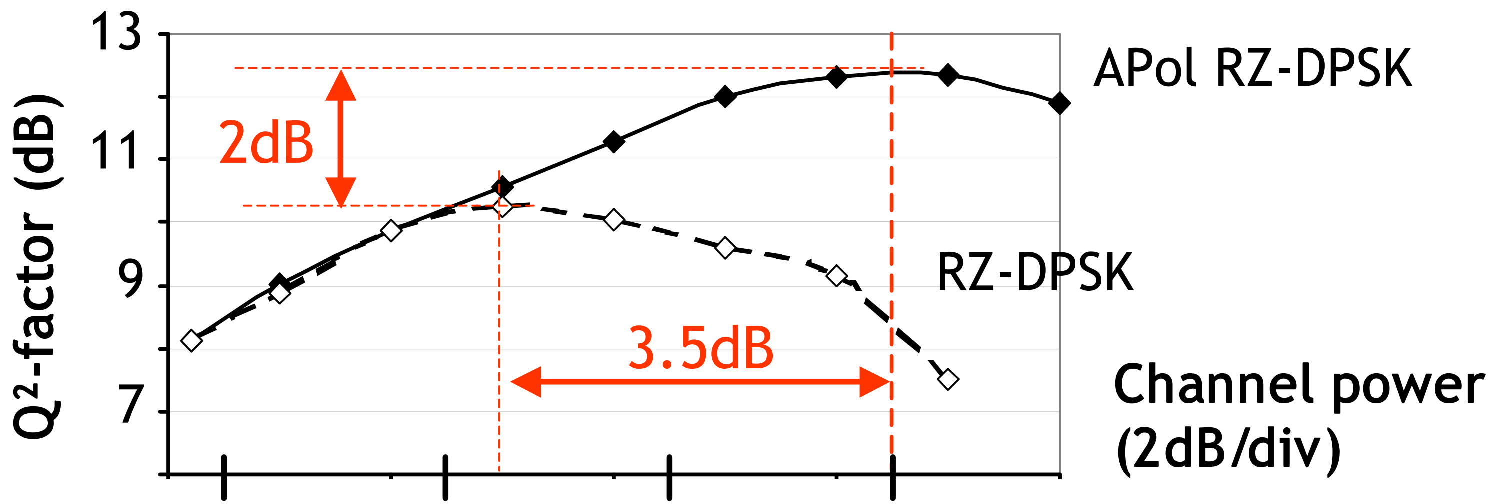
Typical data waveforms (here for 40Gbit/s systems)



Better resistance to nonlinear effects by to alternating polarization



40Gbit/s experiment in submarine configuration at 9,180km distance

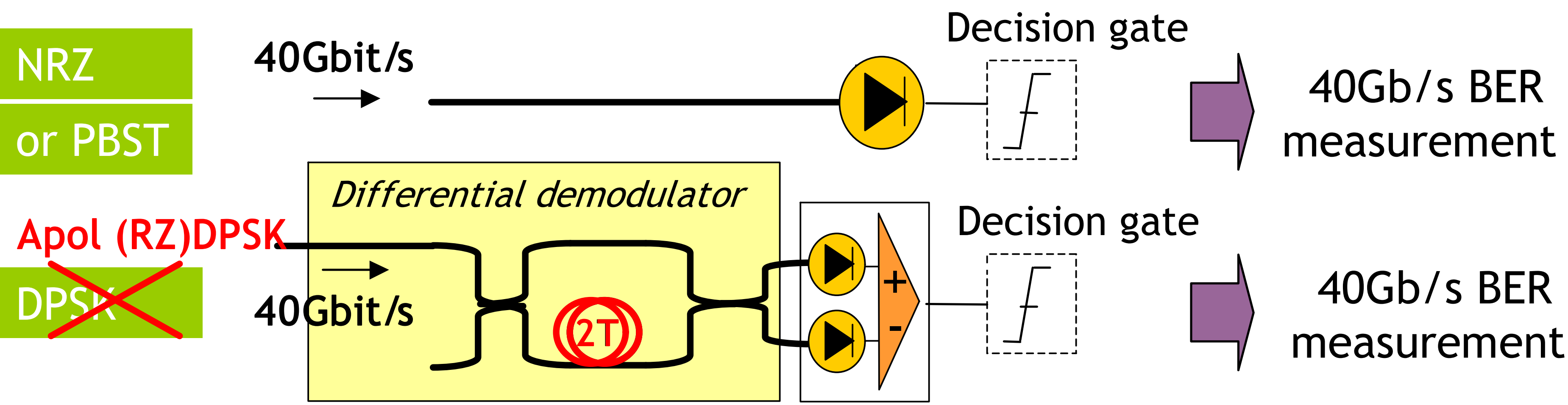


➔ Bit-to-bit polarization brings enhancement of the resistance to optical nonlinear effects in the fiber (by ~3.5dB here)

Alcatel·Lucent

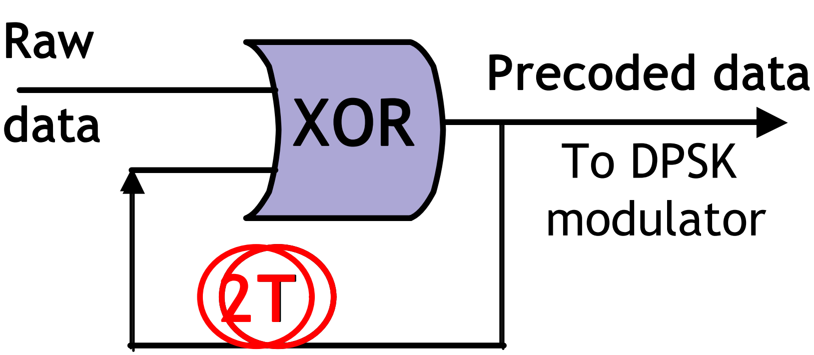
Converting phase information into intensity information

when alternating polarisation states from one bit to the next



Balanced receiver
(~3dB more robust to noise)

But, differential detection requires… differential precoding



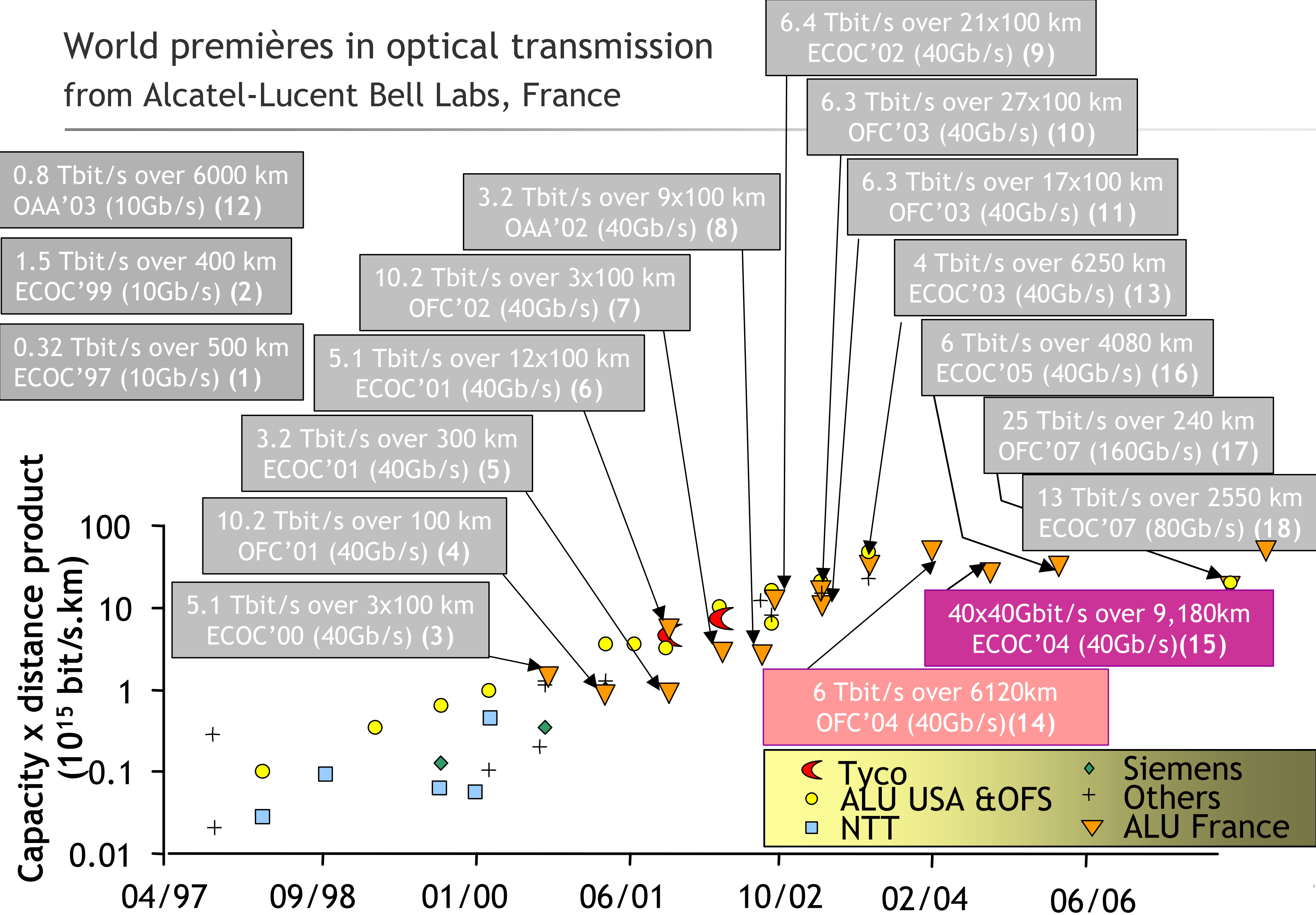
Example:

raw data: 1 0 1 0 0 1 1 0 1 1 0

Precoded data: 1 1 0 0 0 1 0 0 1 0 0

Alcatel·Lucent

World premières in optical transmission
from Alcatel-Lucent Bell Labs, France



Alcatel·Lucent

Conclusion

Optical networks are rapidly evolving along three **interworking** paths, all leading to ever more bandwidth are contained costs :

- Greater *capacity*
- Higher *transparency*
- Full remote *reconfigurability*

Research efforts are likely to continue along all three paths, but some solutions already favor one path at the expense of another.

Hence, the solutions which will ultimately prevail are those which will offer the most timely response to market needs.

Acknowledgment

Jean-Christophe Antona
Dominique Bayart
Jean-Luc Beylat
Gabriel Charlet
Jean-Pierre Hamaide
Jérémie Renaudier
Massimiliano Salsi

Alcatel·Lucent

www.alcatel-lucent.com