COMBATING THE COMING CAPACITY CRUNCH

Andrew R. Chraplyvy

Bell Labs

Tel Aviv 11-21-11

Special Thanks

S. Chandrasekhar

C. Doerr

R-J. Essiambre

G. Foschini

A. Gnauck

X. Liu

S. Randel

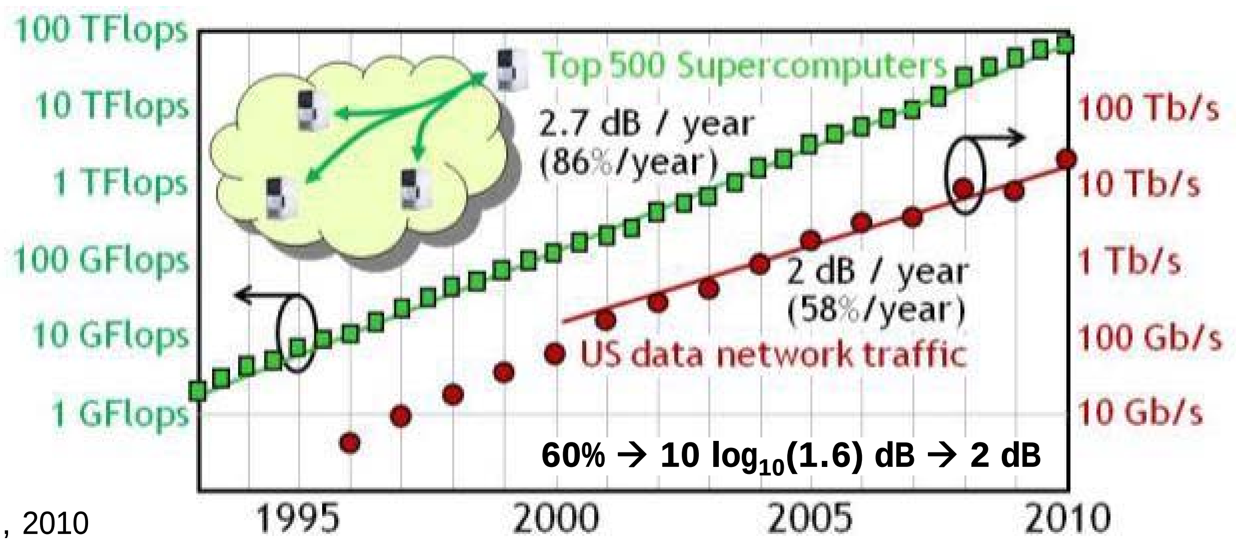
R. Ryf

R. Tkach

P. Winzer

All Rights Reserved © Alcatel-Lucent 2009

NETWORK TRAFFIC IS GROWING EXPONENTIALLY



R.W.Tkach, BLTJ, 2010

Exponential network traffic growth is driven by high-bandwidth digital applications

Video-on-demand, telepresence, wireless backhaul, cloud computing & services

Courtesy P. Winzer

All Rights Reserved © Alcatel-Lucent 2009

Alcatel·Lucent

The Spectral Efficiency Imperative

- Optical amplifier bandwidths are fully occupied
- Traffic growing at ~ 2 dB/year

  Doing nothing means doubling the number of systems (lit fibers) every 18 months
  - 1 additional system in 18 mo for every existing system at exhaust
  - 2 additional systems in 36 mo
  - 4 additional systems in 54 mo
  - 8 additional systems in 6 years
  - Etc

  Serious problem for carriers with limited numbers of fiber pairs

  This strategy does not reduce the cost per bit nor energy consumption per bit
- Advanced modulation formats

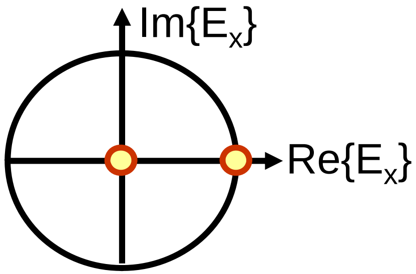
  Enable higher spectral efficiency

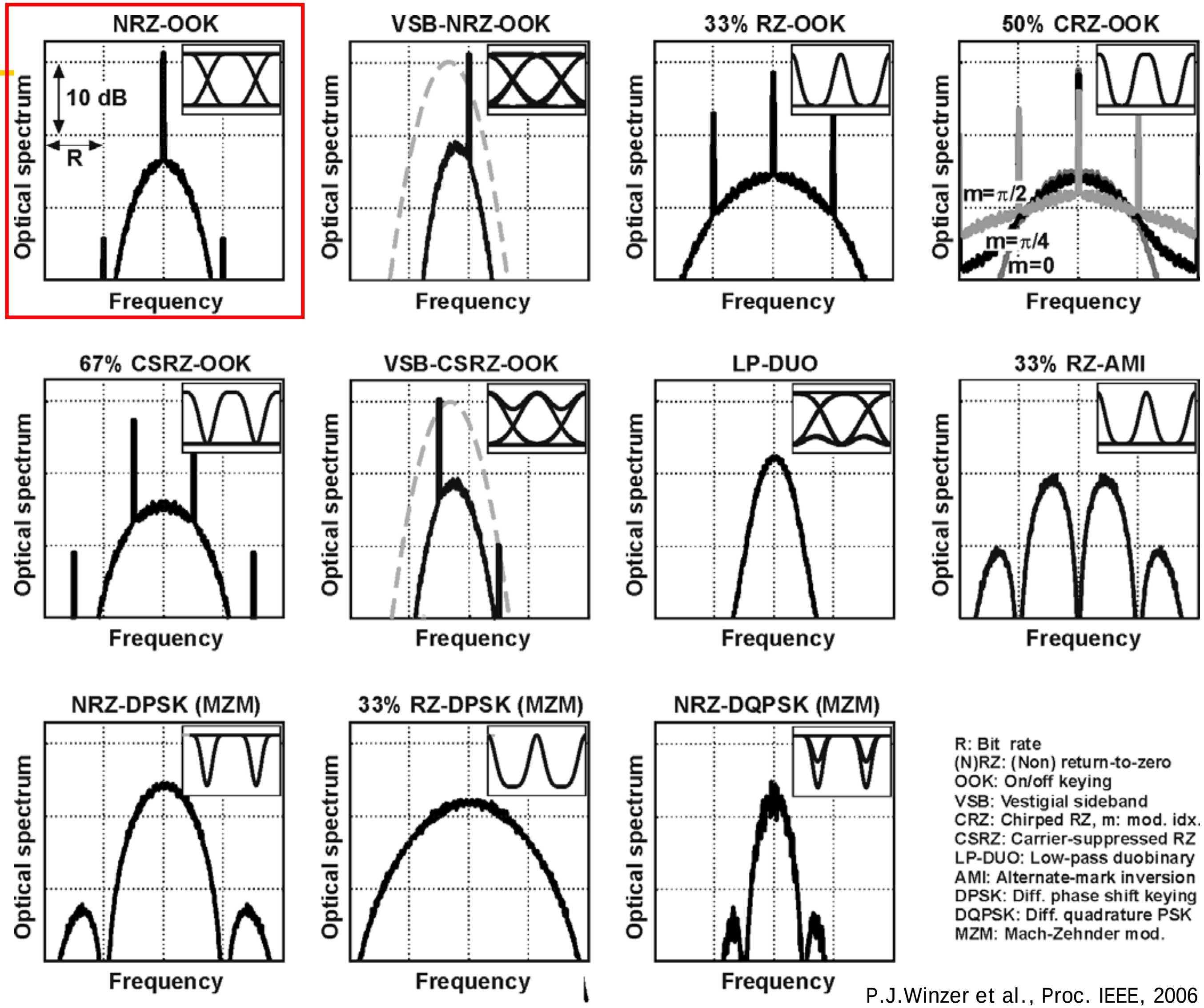
All Rights Reserved © Alcatel-Lucent 2009

Some Important Modulation Formats

1 bit/symbol

OOK





R: Bit rate
(N)RZ: (Non) return-to-zero
OOK: On/off keying
VSB: Vestigial sideband
CRZ: Chirped RZ, m: mod. idx.
CSRZ: Carrier-suppressed RZ
LP-DUO: Low-pass duobinary
AMI: Alternate-mark inversion
DPSK: Diff. phase shift keying
DQPSK: Diff. quadrature PSK
MZM: Mach-Zehnder mod.

P.J.Winzer et al., Proc. IEEE, 2006

All Rights Reserved © Alcatel-Lucent 2009

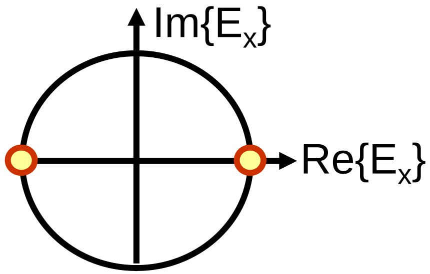
Alcatel·Lucent

Some Important Modulation Formats

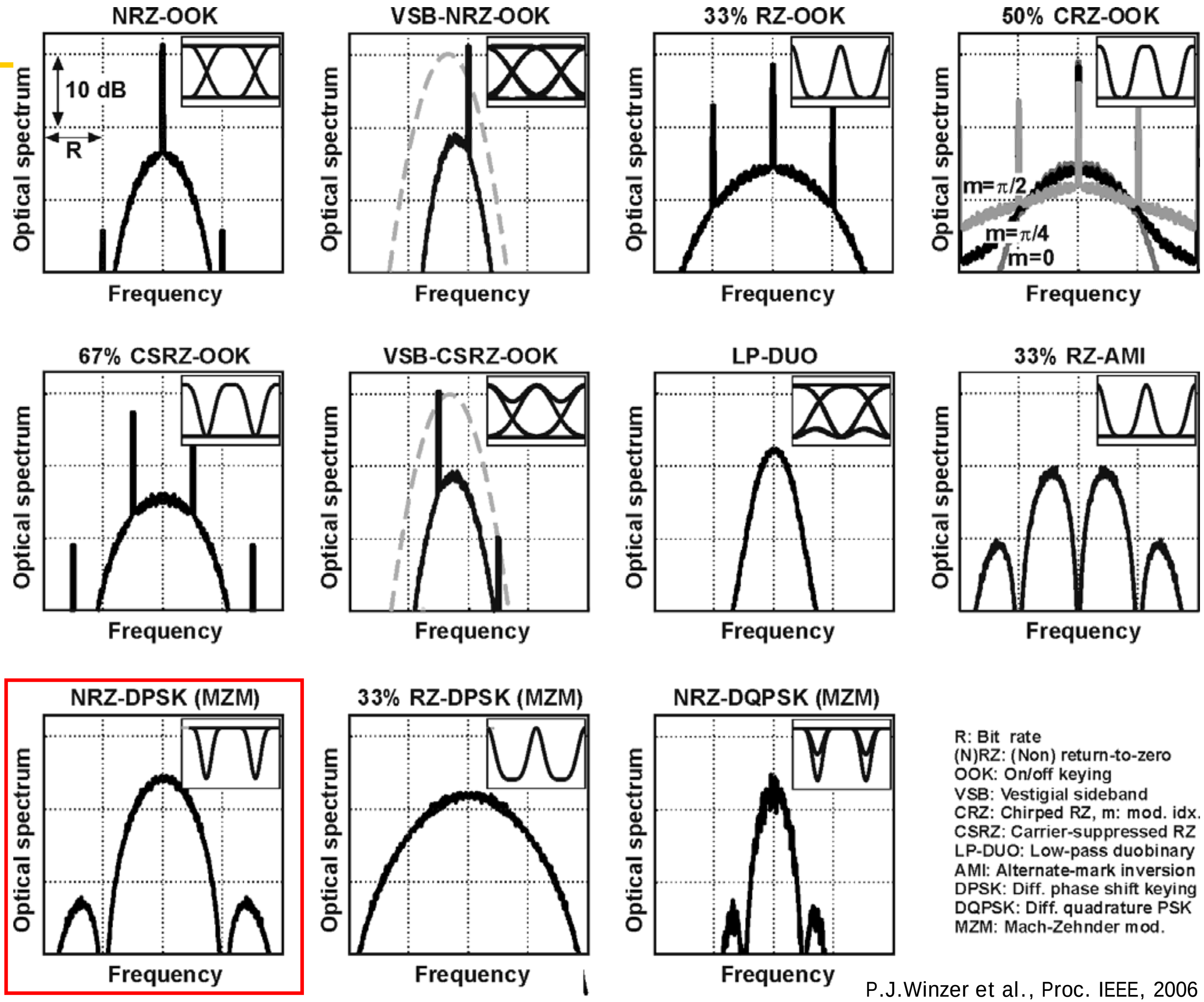
1 bit/symbol

DPSK

(Diff Phase Shift Keying)



First “Advanced” Modulation Format



R: Bit rate
(N)RZ: (Non) return-to-zero
OOK: On/off keying
VSB: Vestigial sideband
CRZ: Chirped RZ, m: mod. idx.
CSRZ: Carrier-suppressed RZ
LP-DUO: Low-pass duobinary
AMI: Alternate-mark inversion
DPSK: Diff. phase shift keying
DQPSK: Diff. quadrature PSK
MZM: Mach-Zehnder mod.

P.J.Winzer et al., Proc. IEEE, 2006

All Rights Reserved © Alcatel-Lucent 2009

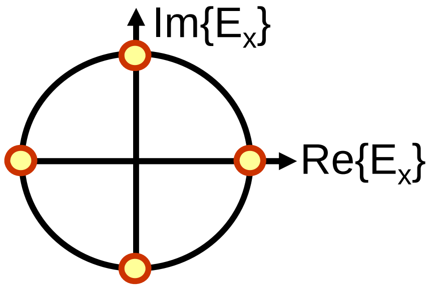
Alcatel·Lucent

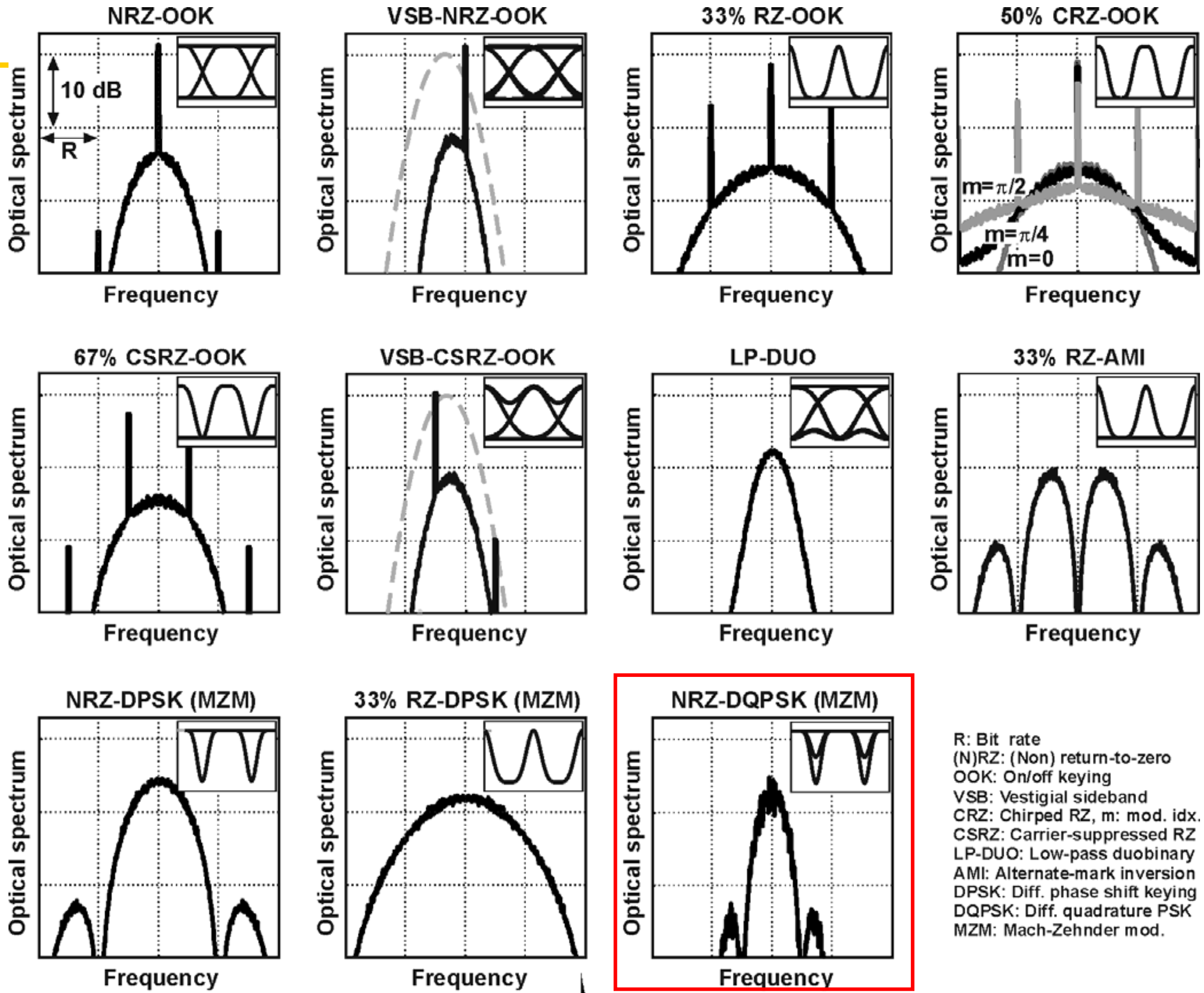
Some Important Modulation Formats

2 bits/symbol

DQPSK

(Diff Quadrature Phase Shift Keying)





R: Bit rate
(N)RZ: (Non) return-to-zero
OOK: On/off keying
VSB: Vestigial sideband
CRZ: Chirped RZ, m: mod. idx.
CSRZ: Carrier-suppressed RZ
LP-DUO: Low-pass duobinary
AMI: Alternate-mark inversion
DPSK: Diff. phase shift keying
DQPSK: Diff. quadrature PSK
MZM: Mach-Zehnder mod.

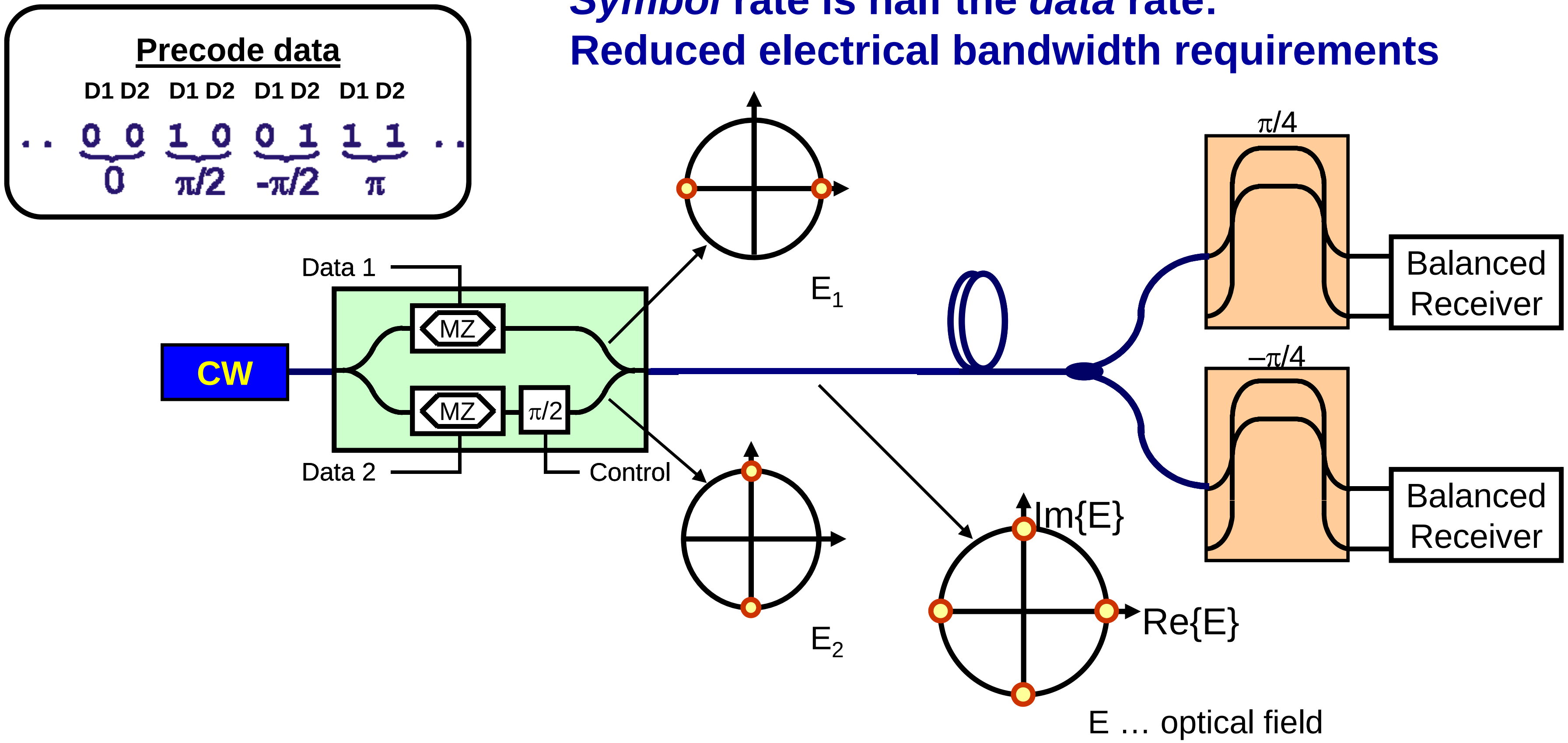
P.J.Winzer et al., Proc. IEEE, 2006

All Rights Reserved © Alcatel-Lucent 2009

DQPSK Transmission System

(Increased spectral efficiency, better dispersion tolerance)

***Symbol* rate is half the *data* rate:**
Reduced electrical bandwidth requirements



- **Increased transmitter and receiver complexity**

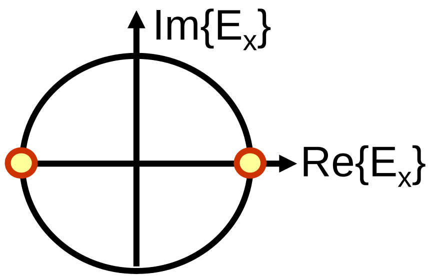
Courtesy P. Winzer

All Rights Reserved © Alcatel-Lucent 2009

MODULATION OPTIONS (e.g. for 100-Gb/s TRANSPORT)

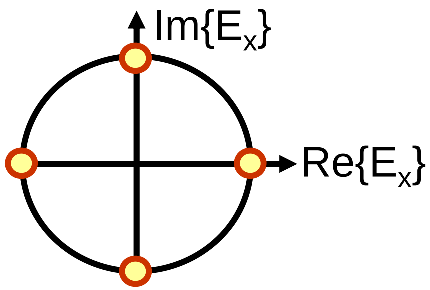
1 bit/symbol

~112 Gbaud
DPSK



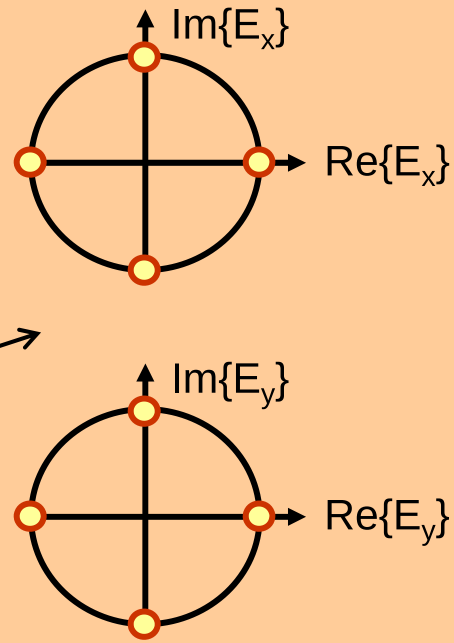
2 bits/symbol

~56 Gbaud
DQPSK



4 bits/symbol

~28 Gbaud
PDM-(D)QPSK



COHERENT DETECTION:

- More cost effective Pol Demuxing
- LO frequency tracking
- Digital processing for impairment mitigation
- High-speed ASICs required

Courtesy P. Winzer

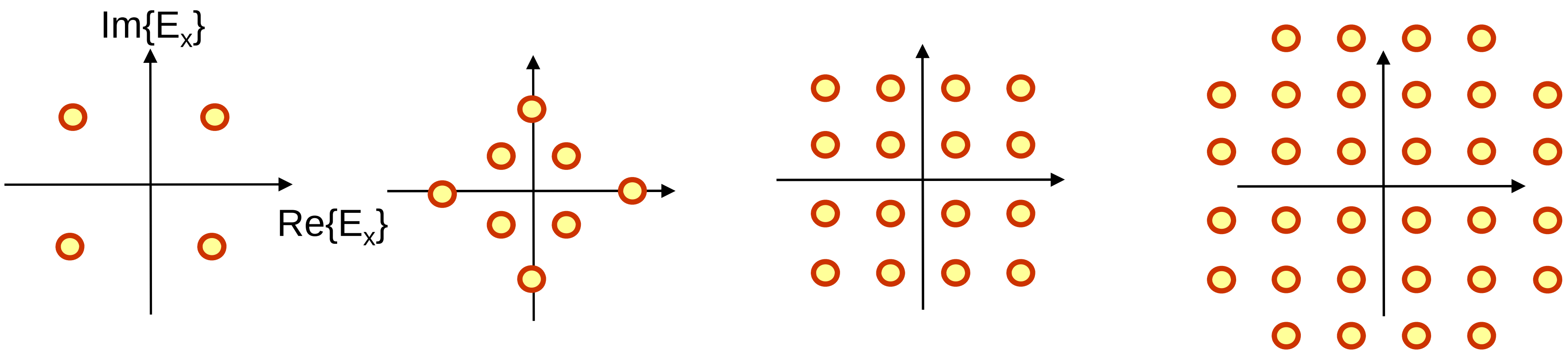
All Rights Reserved © Alcatel-Lucent 2009

Alcatel·Lucent

Capacity Scaling (to 400 Gb/s) With Constellations

Doubling the number of constellation points results in an increase of only 1 b/symbol in SE (2 b/symbol with PDM)

QPSK	8-QAM	16-QAM	32-QAM



4 bits/Symbol (Pol. Muxed)	6 b/Symbol (Pol. Muxed)	8 b/Symbol (Pol. Muxed)	10 b/Symbol (Pol. Muxed)
100 Gb/s	150 Gb/s	200 Gb/s	250 Gb/s

(28 Gbaud Pol-Muxed)

Courtesy R. Tkach

All Rights Reserved © Alcatel-Lucent 2009

Alcatel·Lucent

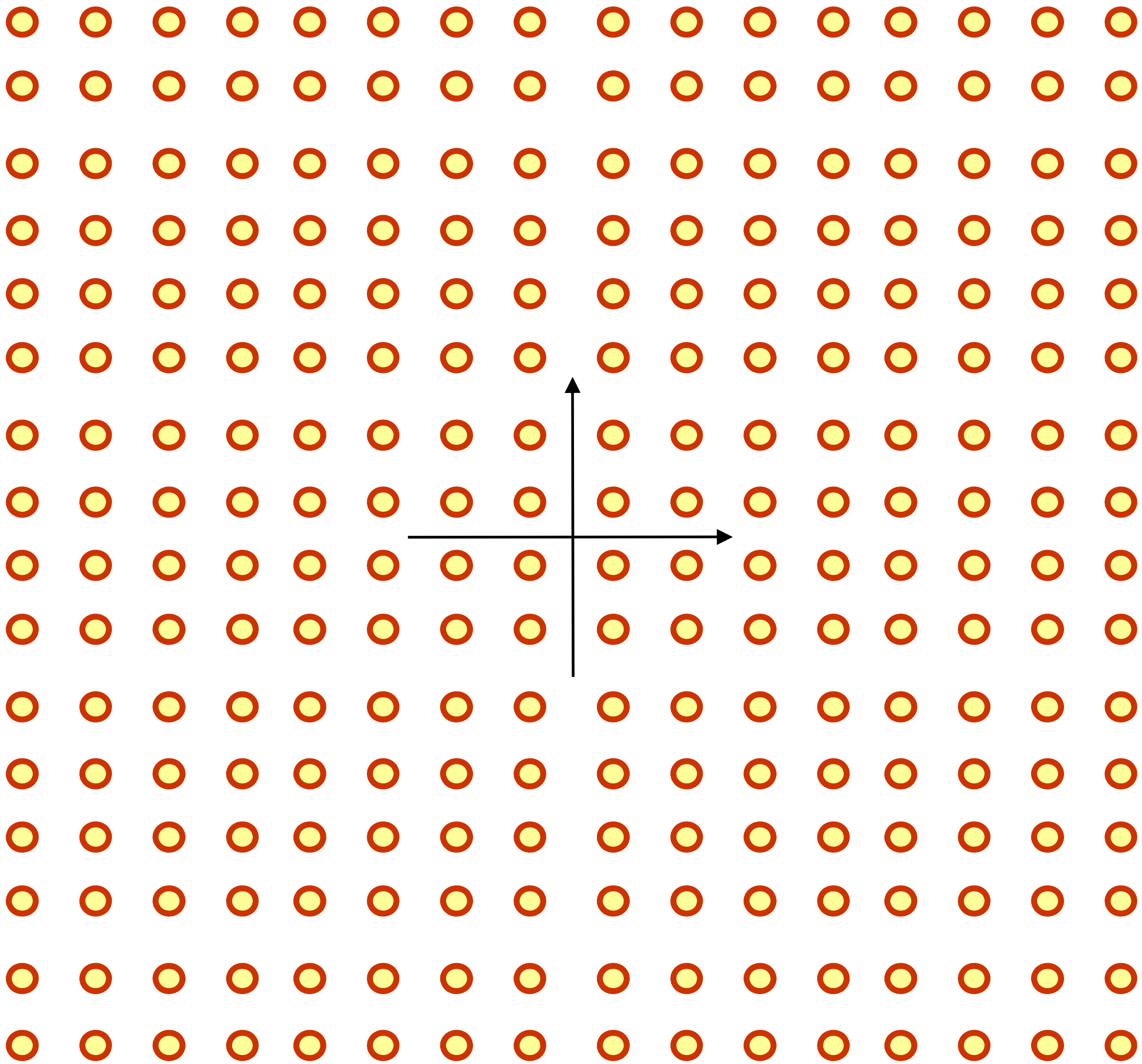
400 Gb/s (16 Bits/Symbol) Requires 256-QAM

Scaling from 100Gb/s to 400 Gb/s changes QPSK to 256-QAM

Required ADC sampling resolution unlikely to be available in 5-10 years

Extremely vulnerable to intersymbol interference in high speed circuits

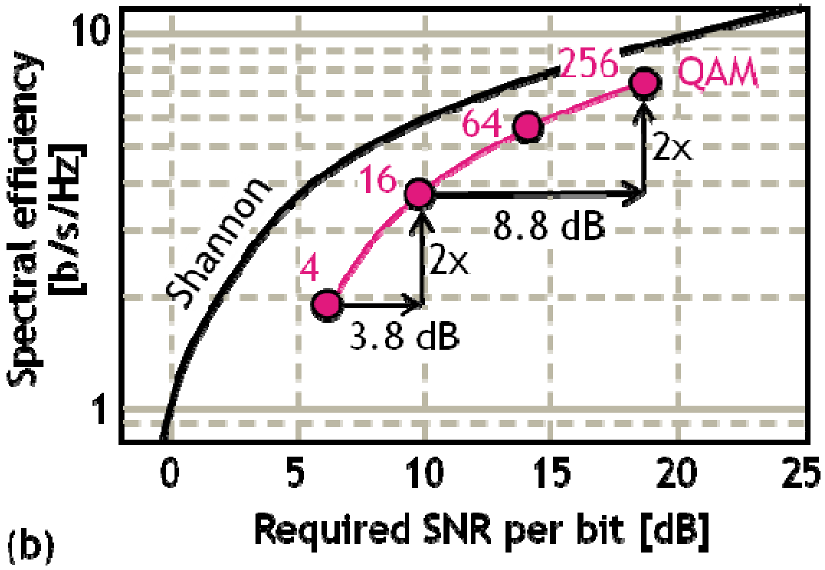
Requires extremely high OSNR



Courtesy R. Tkach

All Rights Reserved © Alcatel-Lucent 2009

SNR Requirements For Higher Constellations



Spectral efficiency comes at a *fundamental* cost:

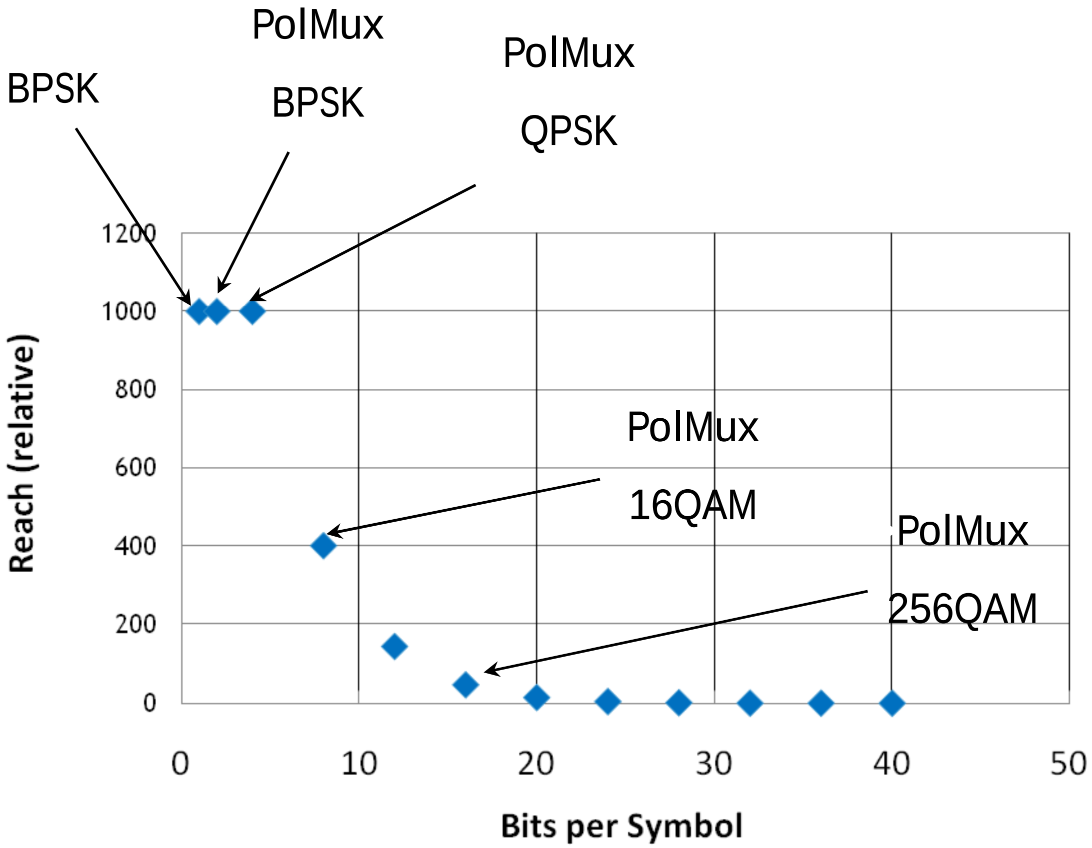
Higher signal-to-noise ratio (SNR) requirements for higher-order modulation

Spectral efficiency comes at a *practical* cost:

Implementation penalties are usually higher for higher constellations and symbol rates

All Rights Reserved © Alcatel-Lucent 2009

Scaling of Reach With Constellation Complexity



Achievable reach with constant bit rate and power for various constellations

Courtesy R. Tkach

All Rights Reserved © Alcatel-Lucent 2009

Shannon's Formula for Channel Capacity (Linear Channel with Additive White Gaussian Noise)

Shannon capacity:

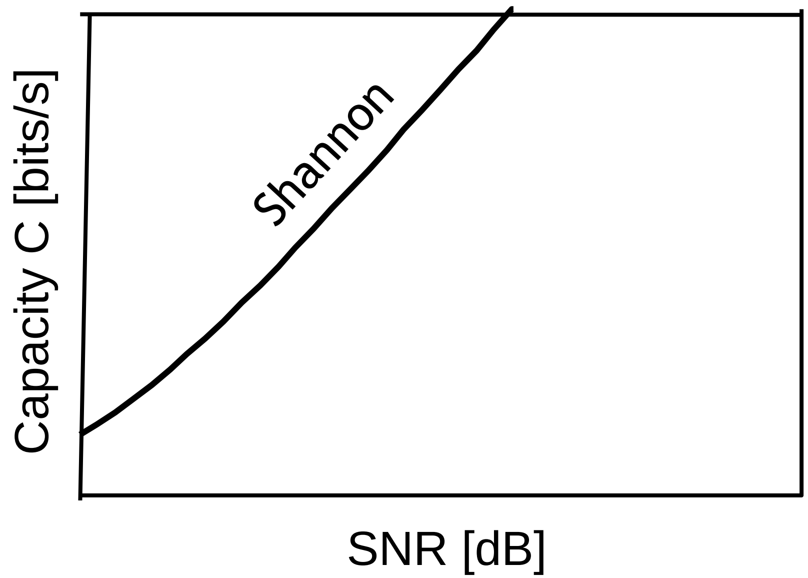
$$C = B \log_2 (1 + SNR)$$

C: Channel capacity (bits/s)

B: WDM channel bandwidth (Hz)

SNR: Signal-to-noise ratio (Signal Energy per symbol / Noise Energy per symbol)

Shannon implies using optimum coding



The only way to increase the OSNR in an existing system is to increase input optical power

Courtesy R-J. Essiambre

All Rights Reserved © Alcatel-Lucent 2009

DO OPTICAL FIBERS OBEY SHANNON SCALING?

- Classical Shannon theory applies only to linear channels
- The only way to increase the OSNR in an existing system is to increase input optical power
- As input powers increase, fibers cease to be linear transmission media

  i.e. output signal is no longer an attenuated replica of input signal (minus linear impairments such as chromatic dispersion and PMD)

  Light interacts with the medium and the medium changes the properties of light
- Rich collection of nonlinearities in fibers

  Inter-channel effects

  Intra-channel effects
- Optical nonlinearities will ultimately limit the information capacity of fiber networks

All Rights Reserved © Alcatel-Lucent 2009

Shannon's Formula for Channel Capacity

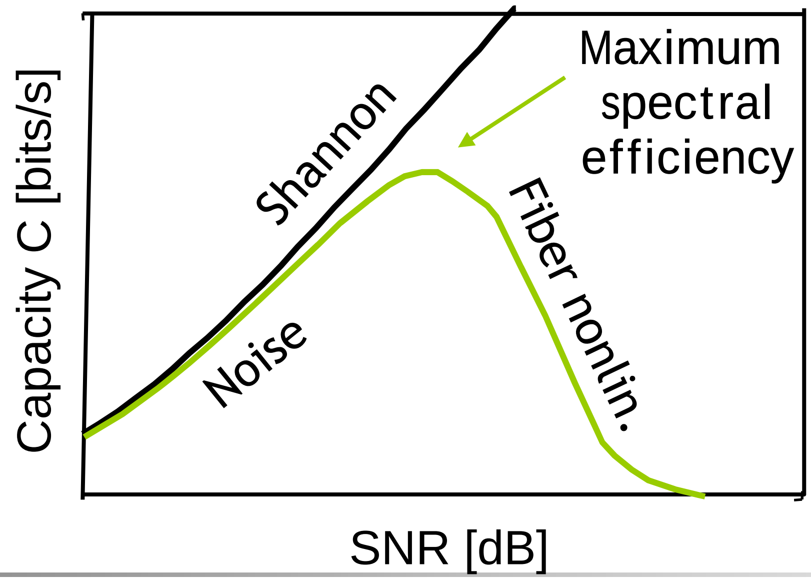
Shannon capacity:

$$C = B \log_2 (1 + SNR)$$

C: Channel capacity (bits/s)
B: WDM channel bandwidth (Hz)
SNR: Signal-to-noise ratio (Signal Energy per symbol / Noise Energy per symbol)

Shannon implies using optimum coding!

Effect of fiber nonlinearity on 'fiber capacity'

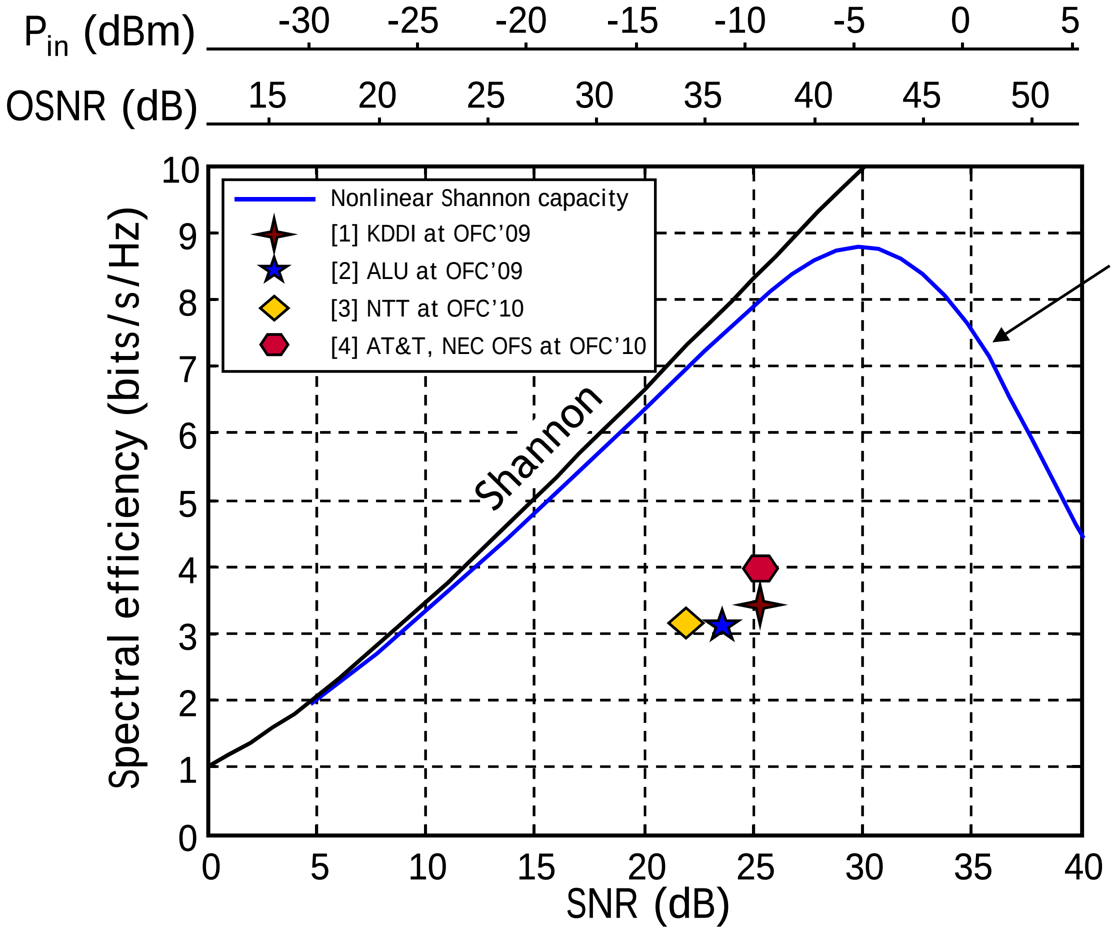


R-J. Essiambre, P. Winzer, G.Foschini, G. Kramer

Courtesy R-J. Essiambre

All Rights Reserved © Alcatel-Lucent 2009

NONLINEAR SHANNON CAPACITY LIMITS VS RECORD EXPERIMENTS



- Distance = 500 km
- Standard Single-Mode Fiber
- α = 0.2 dB/km
- A_{eff} = 80 μm^2
- D = 17 s/(nm-km)

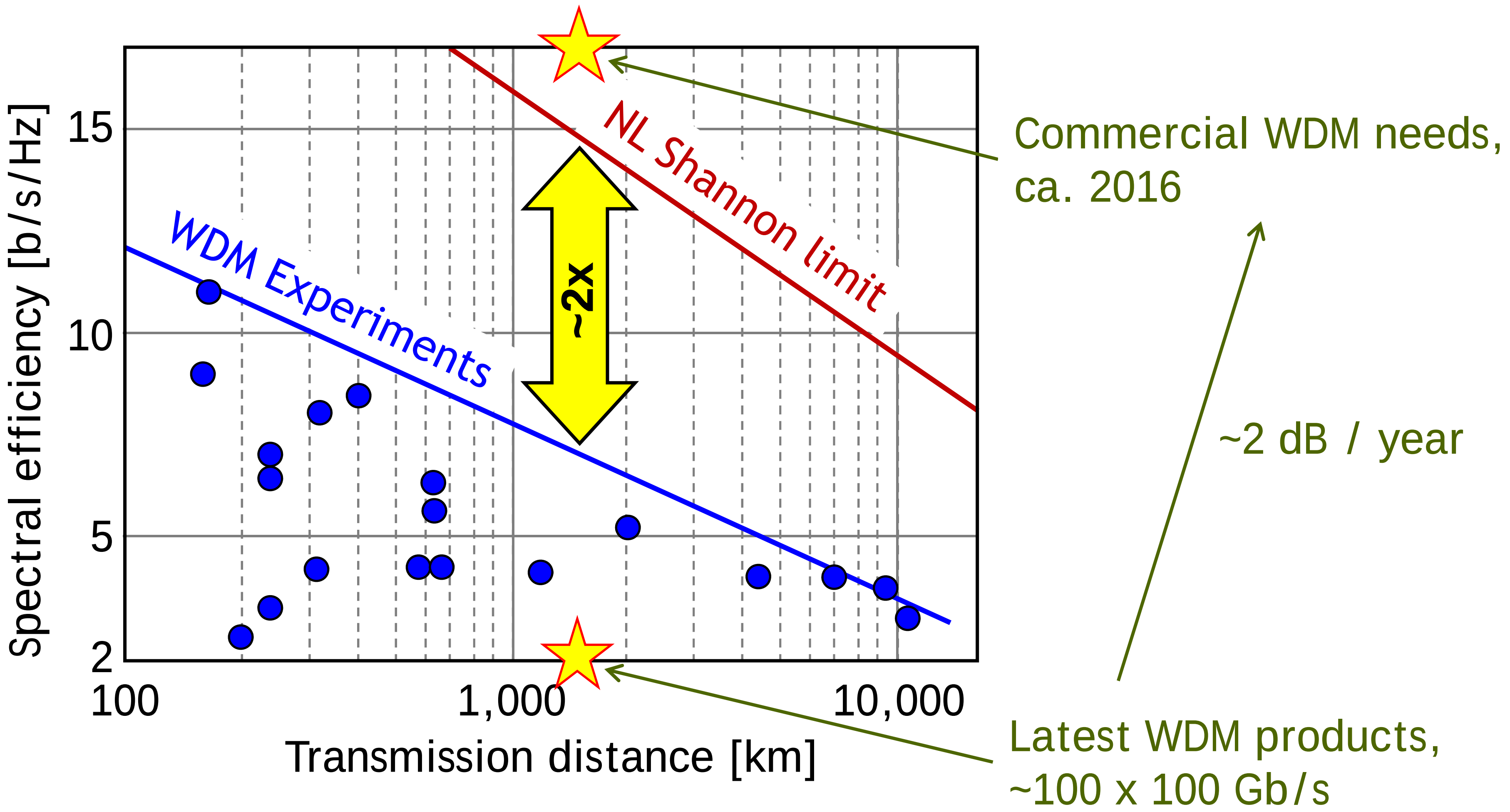
Courtesy R-J. Essiambre

All Rights Reserved © Alcatel-Lucent 2009

Alcatel·Lucent

We Are Rapidly Approaching The Nonlinear Shannon Limit

WDM: Wavelength division multiplexing

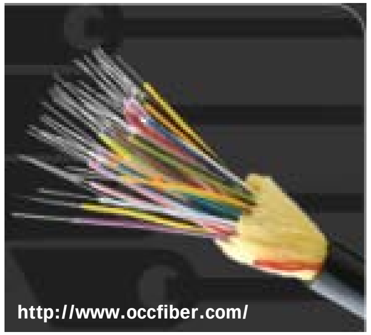


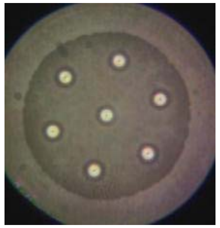
Courtesy P. Winzer

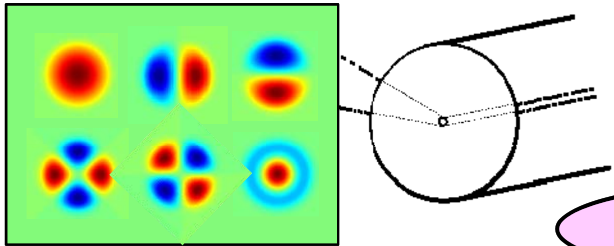
All Rights Reserved © Alcatel-Lucent 2009

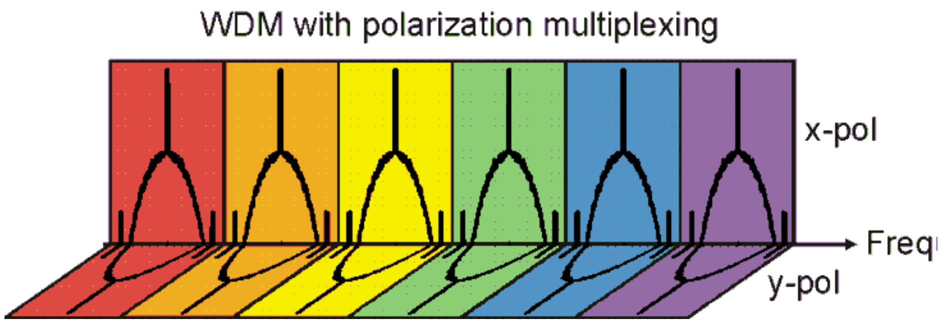
Spatial Multiplexing: The Next Frontier

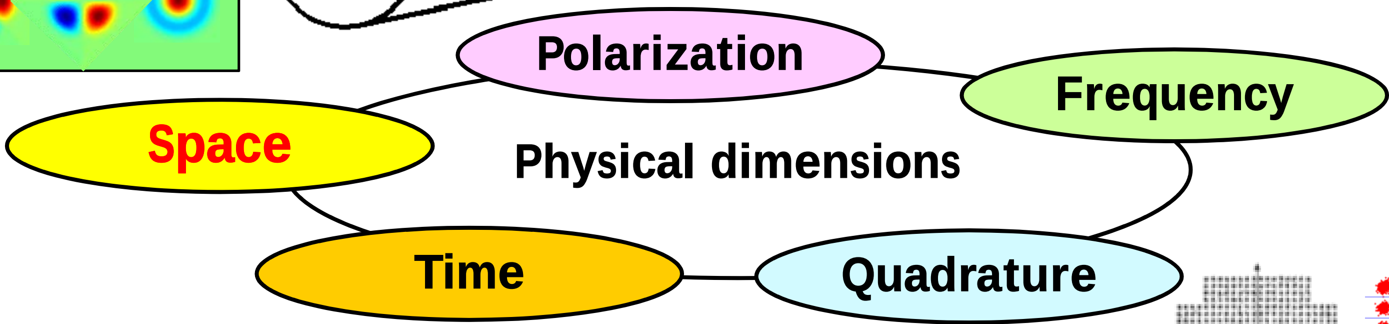
WDM: Wavelength division multiplexing

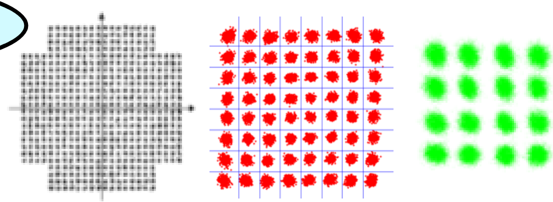








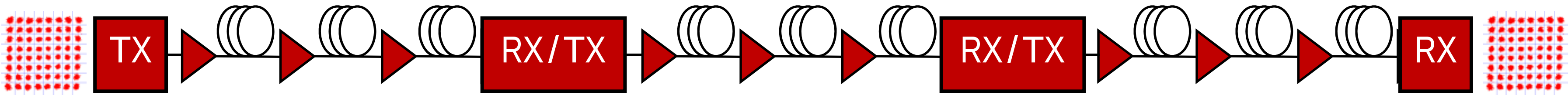




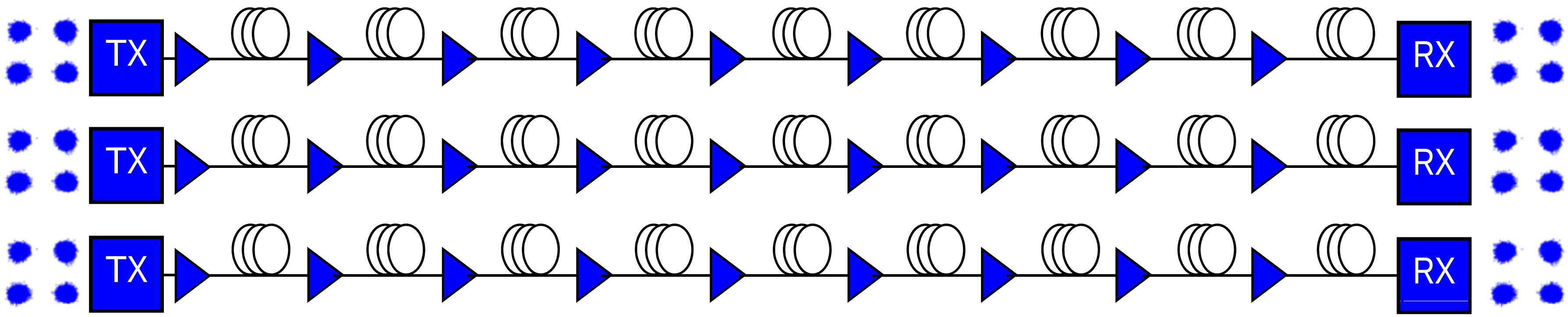
Current WDM products use all dimensions ***except space***

All Rights Reserved © Alcatel-Lucent 2009

Two Capacity Scaling Options



(a) Single-mode system using frequent regeneration (e.g., 6 bits/symbol)



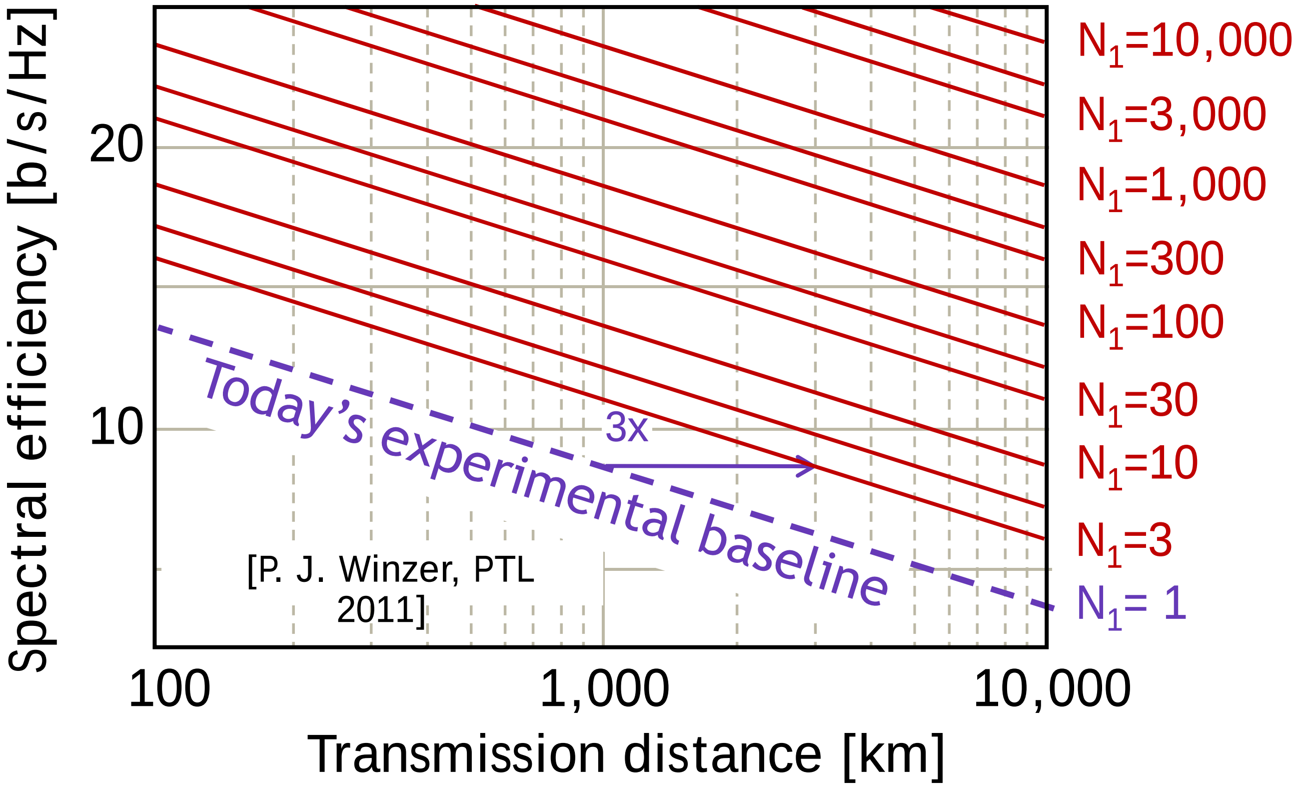
(b) Transparent system using *spatial multiplexing* (e.g., 3 x 2 bits/symbol)

Courtesy P. Winzer

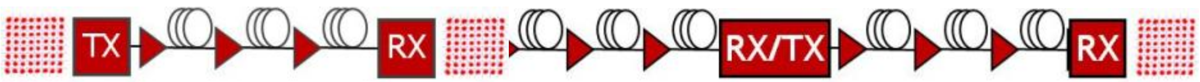
All Rights Reserved © Alcatel-Lucent 2009

Alcatel·Lucent

Comparison of Required Transponder Hardware



- N_1: Number of TX/RX in high-SE, multiply regenerated system

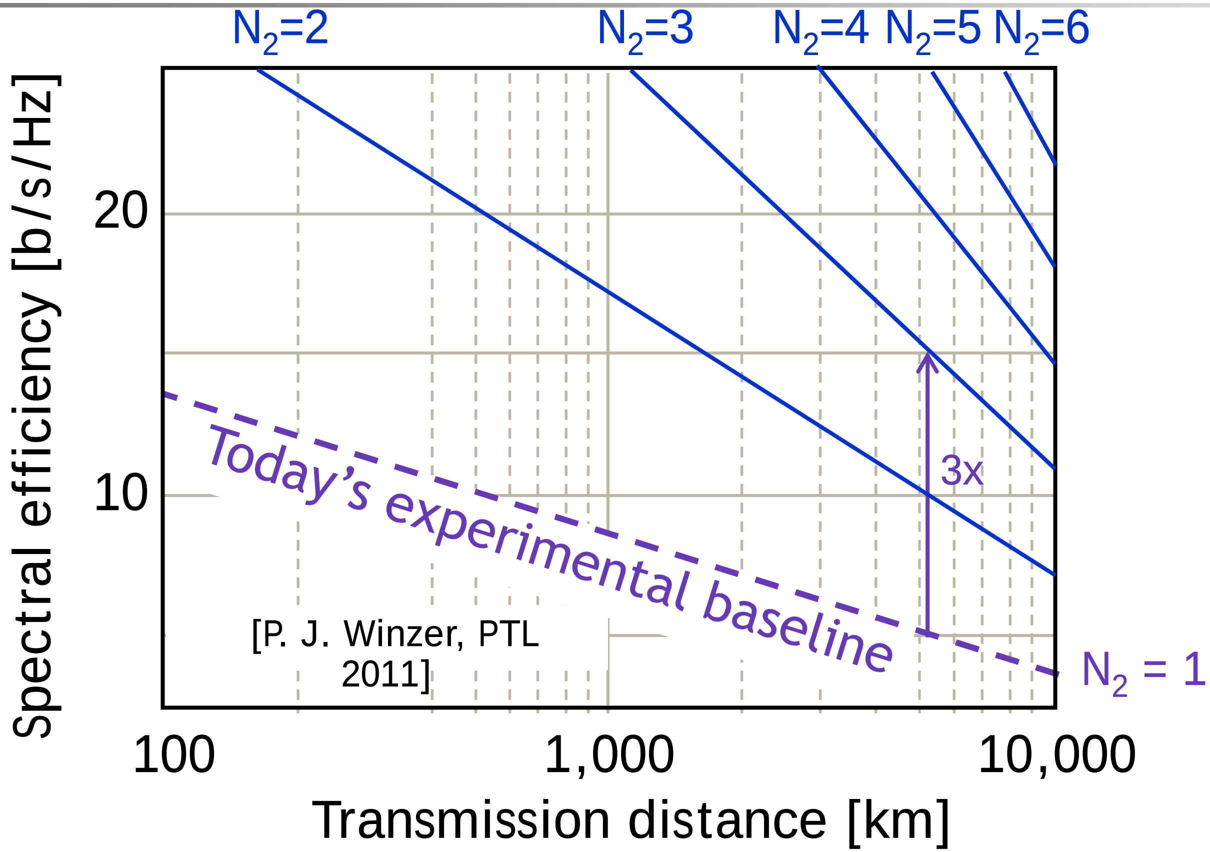


Courtesy P. Winzer

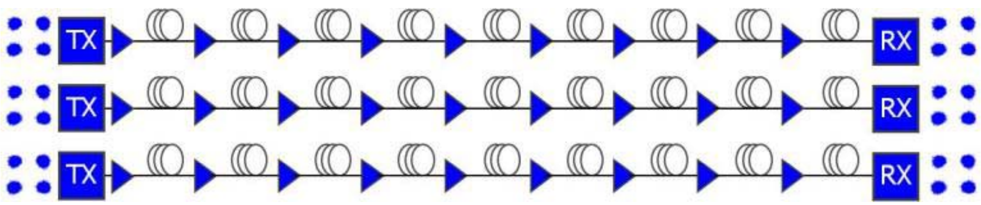
All Rights Reserved © Alcatel-Lucent 2009

Alcatel·Lucent

COMPARISON OF REQUIRED TRANSPONDER HARDWARE



- N_2: Number of TX/RX in low-SE, parallel system

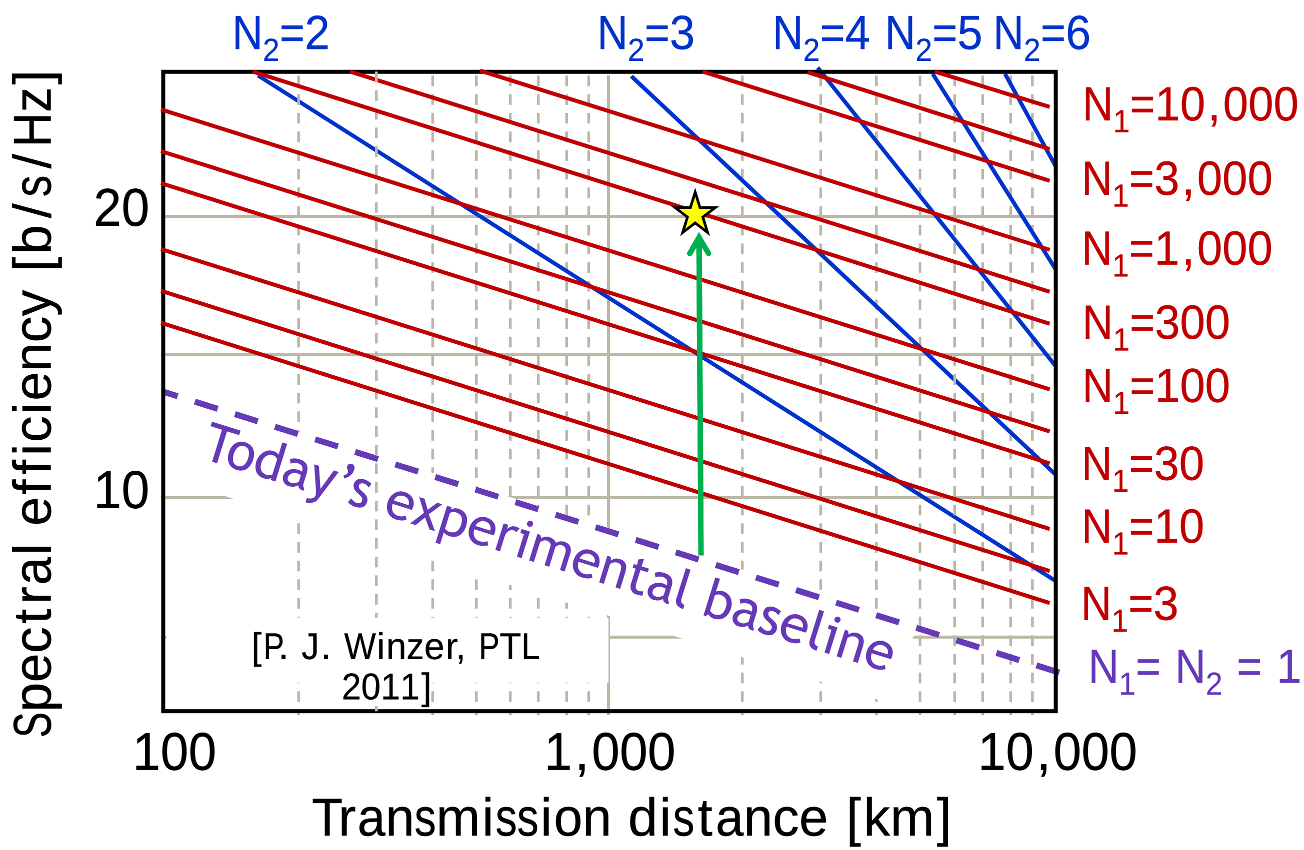


Courtesy P. Winzer

All Rights Reserved © Alcatel-Lucent 2009

Alcatel·Lucent

Comparison of Required Transponder Hardware



- N_1: Number of TX/RX in high-SE, multiply regenerated system
- N_2: Number of TX/RX in low-SE, parallel system

Courtesy P. Winzer

All Rights Reserved © Alcatel-Lucent 2009
Alcatel·Lucent

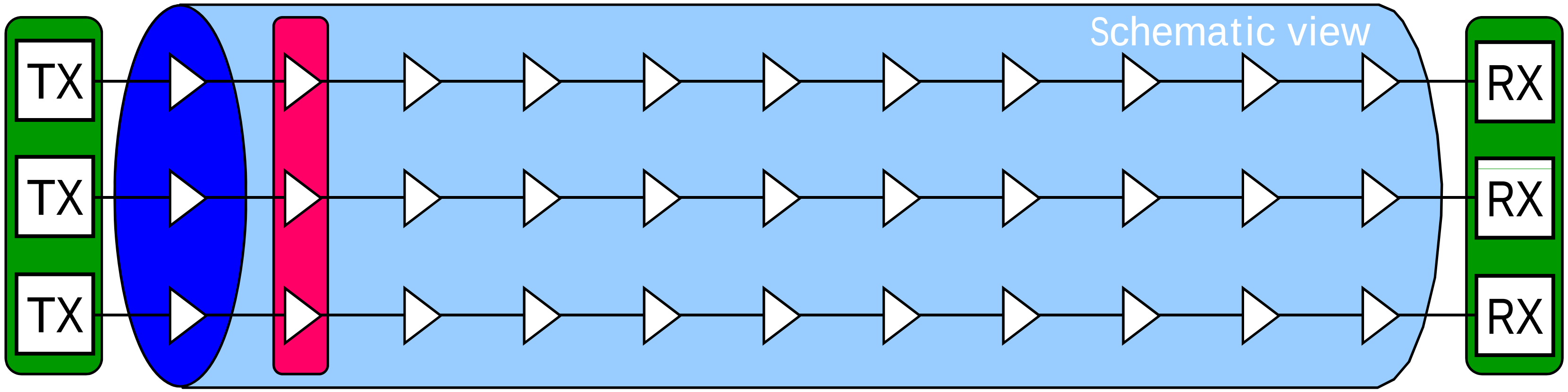
NEED INTEGRATION FOR ECONOMIC SUSTAINABILITY

Deploying *M* spatial paths is better than using multiple regenerators

But: *M* systems cost *M* times as much & consume *M* times the energy

➔ Cost/bit (or energy/bit) remains constant

➔ *Integration* is key to scale space-division multiplexed systems

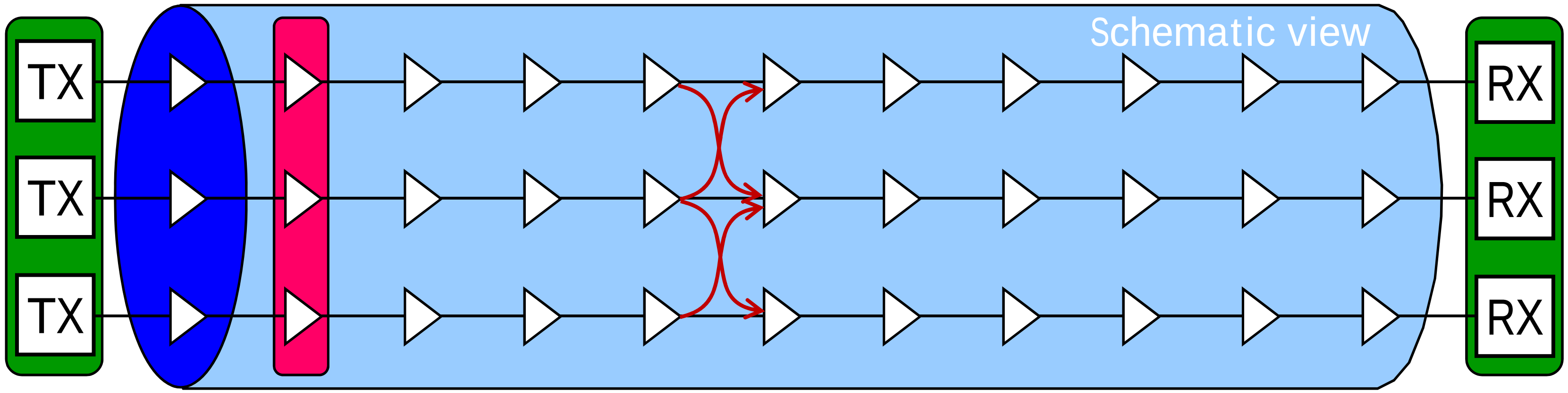


Integrated transponders, *Integrated* amplifiers, Multi-mode or Multi-core fiber

Courtesy P. Winzer

All Rights Reserved © Alcatel-Lucent 2009

INTEGRATION CAN LEAD TO CROSSTALK



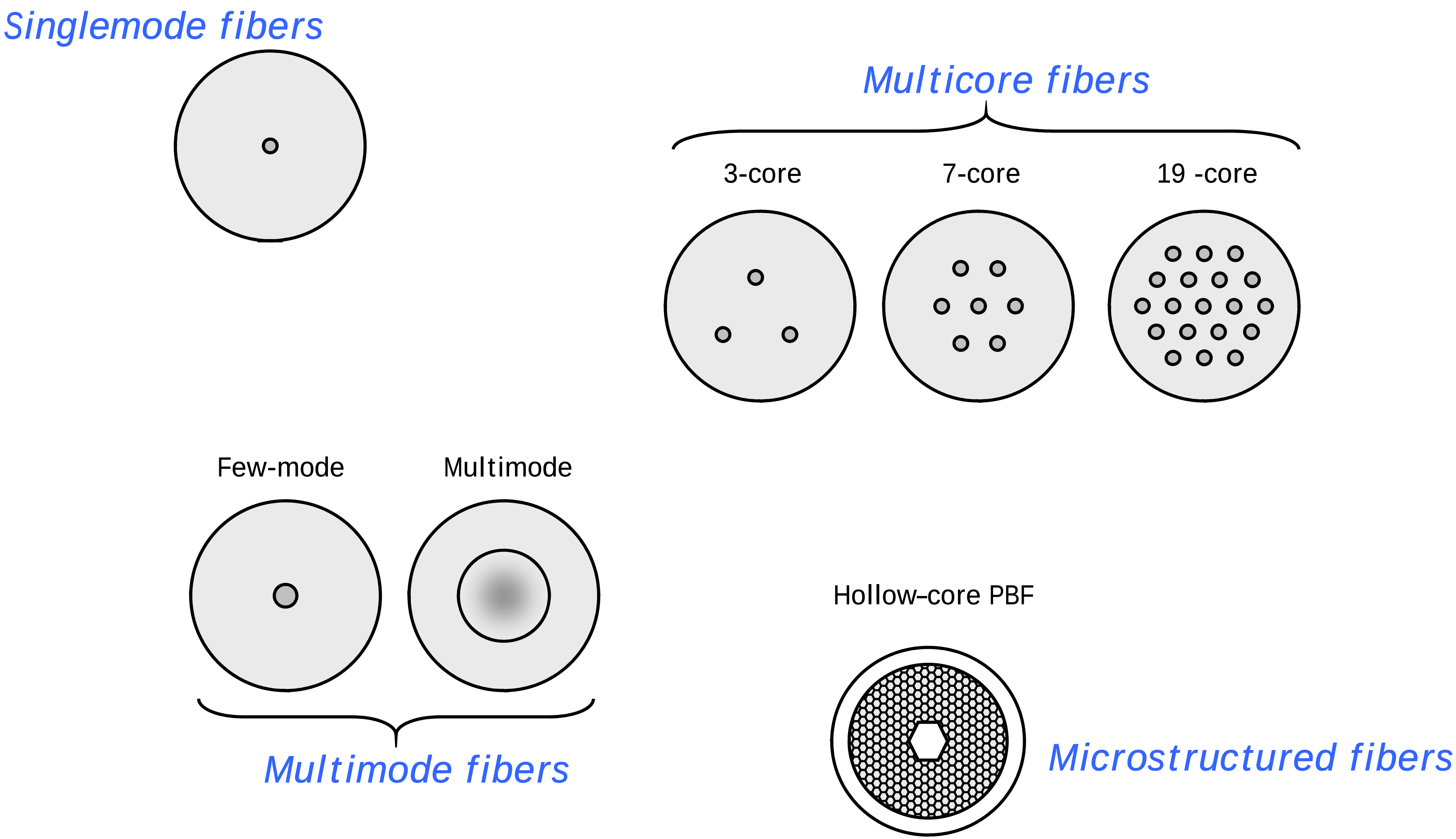
- If *crosstalk* between spatial multiplexing paths is unacceptably high:
  ➔ Need multiple-input multiple-output (MIMO) digital signal processing

- Multiple-input multiple-output (MIMO) is a very successfully crosstalk cancellation technique, applied widely in wireless systems today
- (*Caveat:* MIMO in optical has different boundary conditions from wireless; all outputs must be captured and processed together)

Courtesy P. Winzer

All Rights Reserved © Alcatel-Lucent 2009

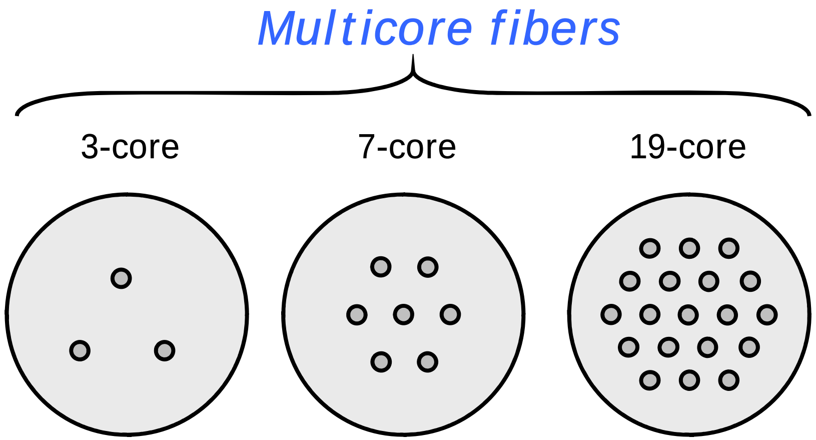
Spatial Multiplexing in Fibers



Courtesy R. Essiambre

All Rights Reserved © Alcatel-Lucent 2009

Spatial Multiplexing in Fibers

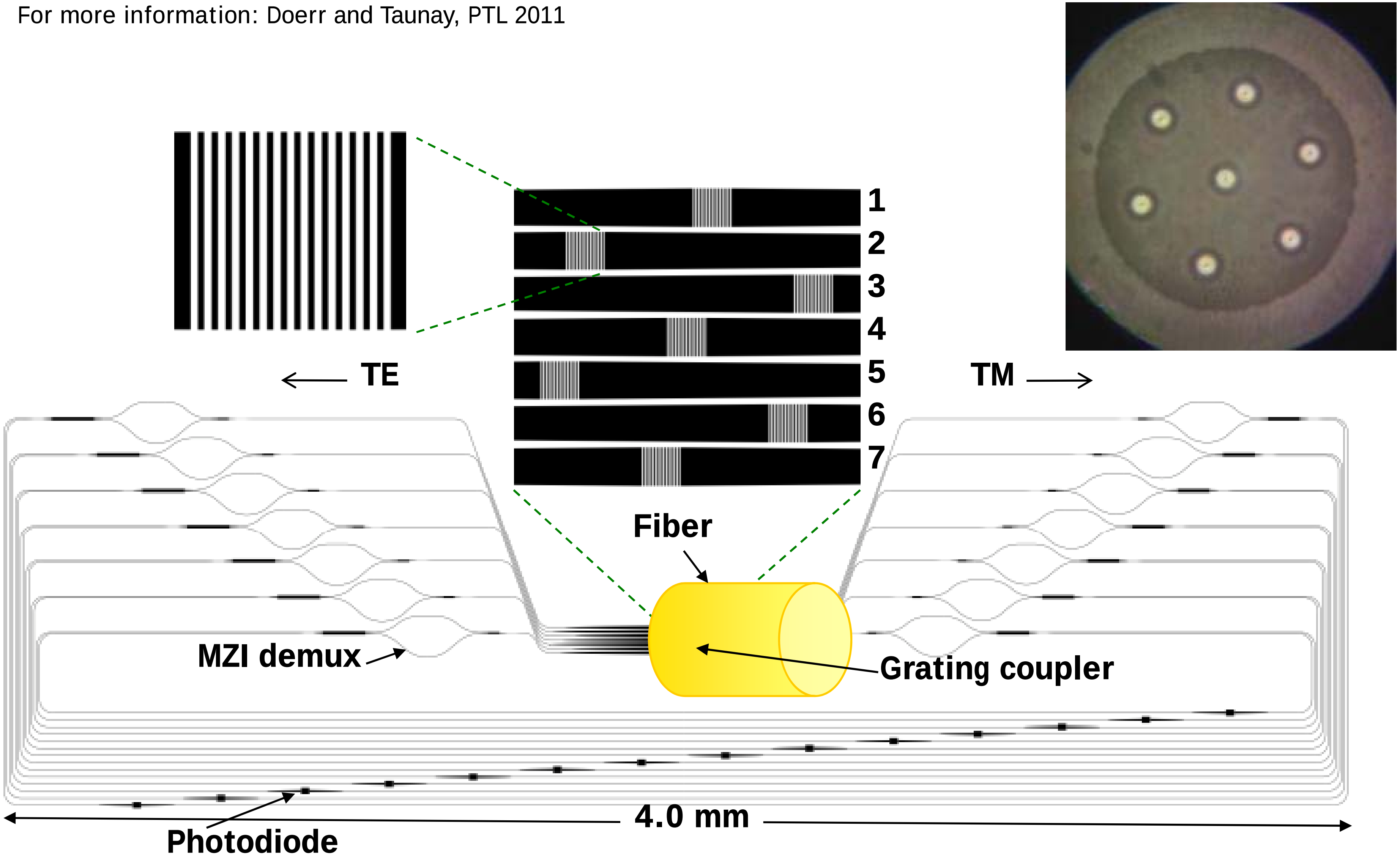


- All core are **selectively** addressed and coherently detected
- Cores can be very weakly coupled => individually detected
- Cores can be strongly coupled => collectively detected and MIMO processed

All Rights Reserved © Alcatel-Lucent 2009

Fully Integrated Receiver For 7-Core Fiber

For more information: Doerr and Taunay, PTL 2011



All Rights Reserved © Alcatel-Lucent 2009

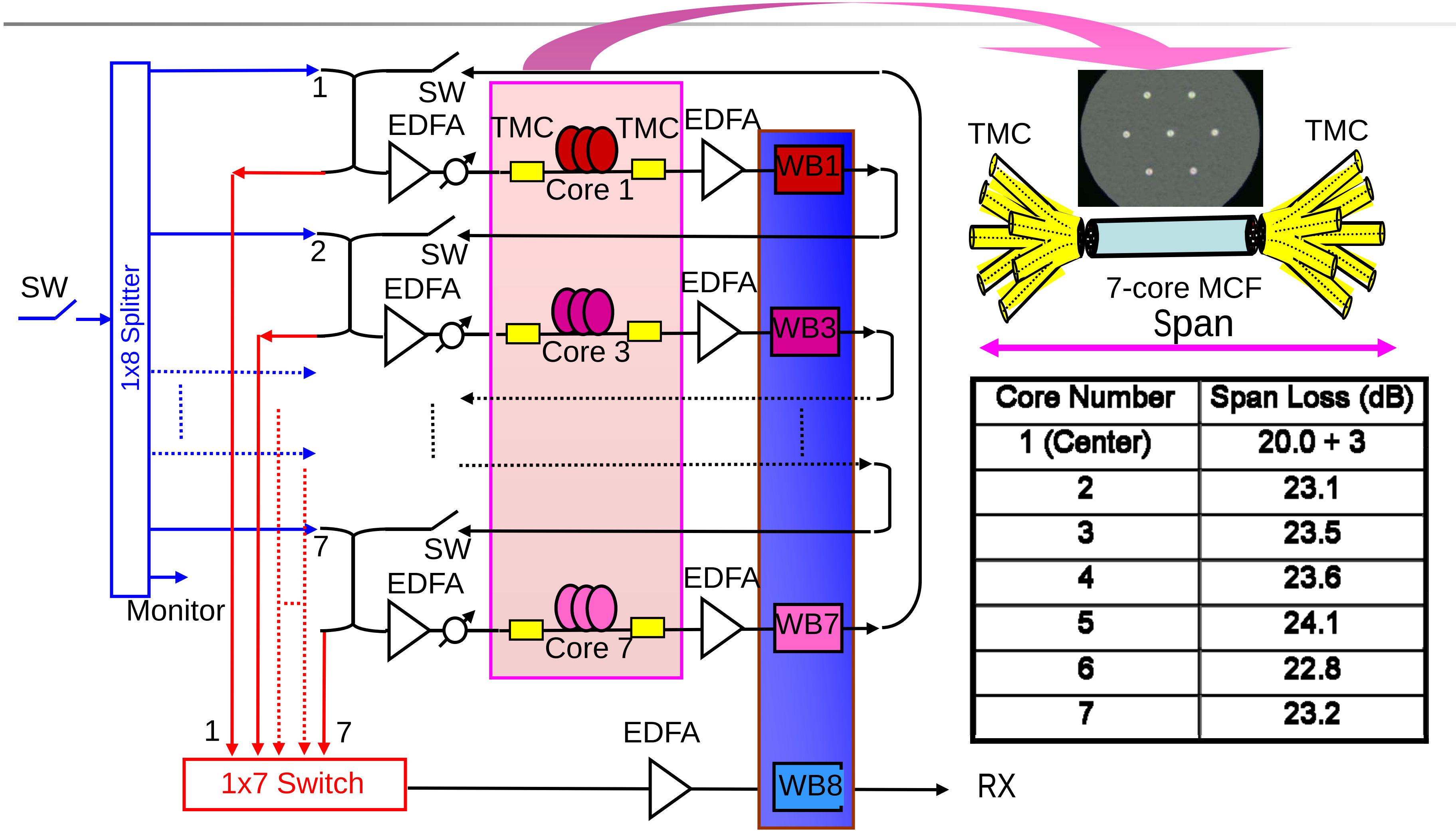
Alcatel·Lucent

Alcatel·Lucent

WDM/SDM Transmission of 10 x 128-Gb/s PDM-QPSK over 2688-km 7-Core Fiber with a per-Fiber Net Aggregate Spectral-Efficiency Distance Product of 40,320 km·b/s/Hz

C. Sethumadhavan, et al, ECOC Post Deadline Paper PD C.4

7 Independent Re-Circulating Loops Running Synchonously



Core Number	Span Loss (dB)
1 (Center)	20.0 + 3
2	23.1
3	23.5
4	23.6
5	24.1
6	22.8
7	23.2

√ Core-to-core cyclic rotation: output of one loop connected to input of next loop

Courtesy S. Chandrasekhar

All Rights Reserved © Alcatel-Lucent 2009

1.12-Tb/s 32-QAM-OFDM Superchannel with 8.6-b/s/Hz Intrachannel Spectral Efficiency and Space-Division Multiplexing with 60-b/s/Hz Aggregate Spectral Efficiency

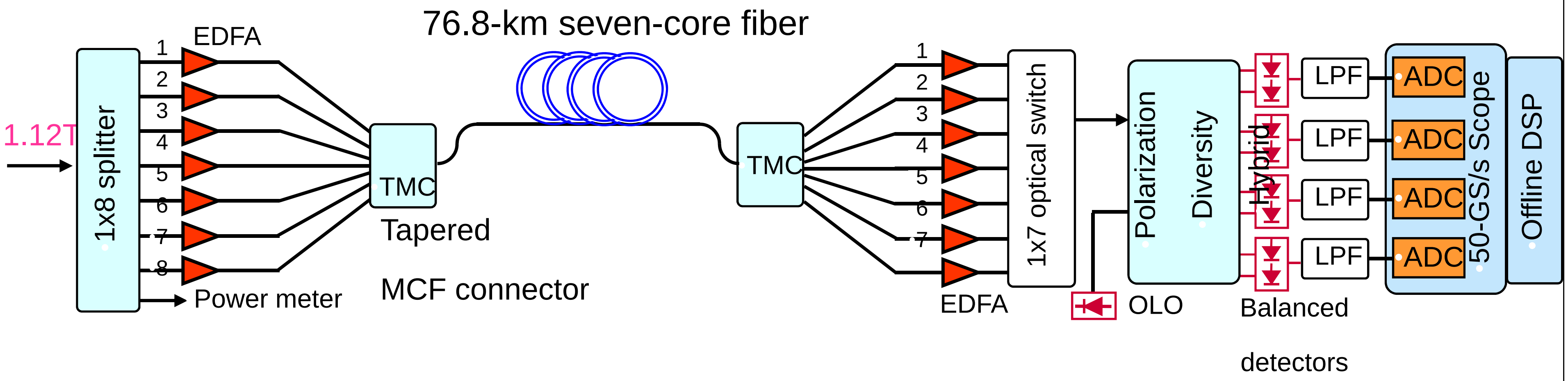
Xiang Liu[1], S. Chandrasekhar[1], X. Chen[1,2], P. J. Winzer[1], Y. Pan[1], B. Zhu[3], T. F. Taunay[3], M. Fishteyn[3], M. F. Yan[3], J. M. Fini[3], E.M. Monberg[3], and F.V. Dimarcello[3]

ECOC'11, PostdeadlineTh.13.B.1

All Rights Reserved © Alcatel-Lucent 2009

Alcatel·Lucent

SDM Using 32 QAM-OFDM Modulation in 7-Core Fiber



Key MCF parameters [1]:

Loss: ~24 dB per span

(including TMCs)

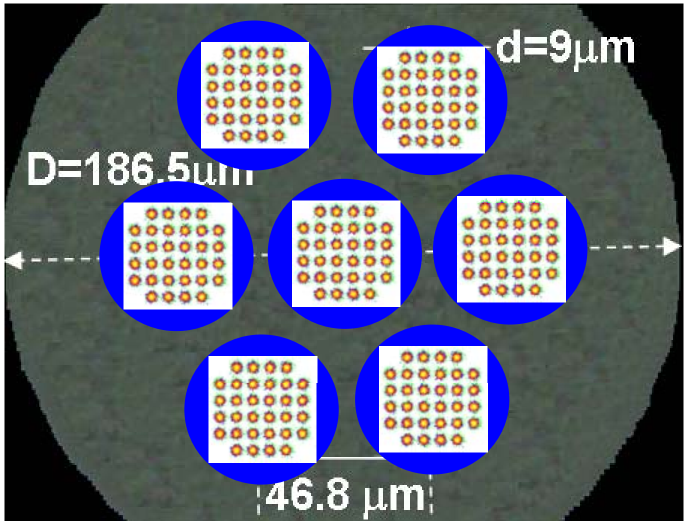
Dispersion: 17 ps/km/nm

Core-to-core crosstalk:

~ -43 dB

Outer-to-center-core crosstalk:

~ -35 dB

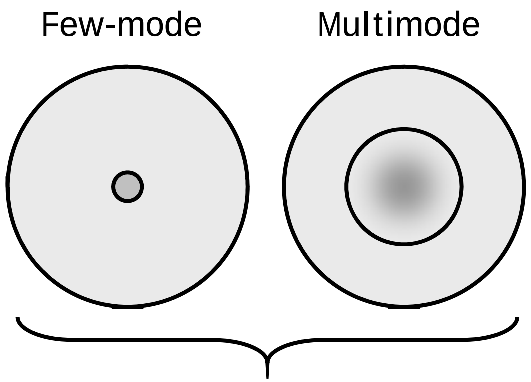


[1] B. Zhu, et al., “112-Tb/s (7x160x107Gb/s) space-division multiplexed DWDM transmission over a 76.8-km 7-core-fiber …” ECOC’11, Tu.5.B.5.

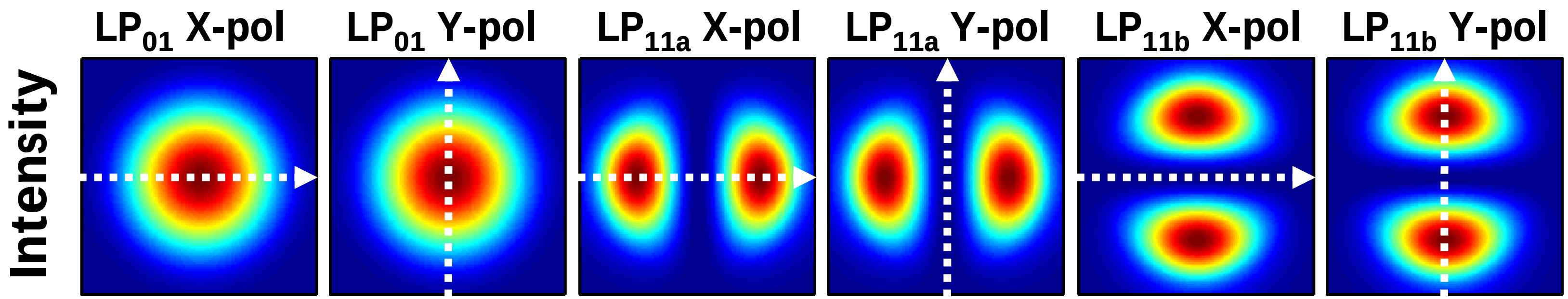
All Rights Reserved © Alcatel-Lucent 2009

Alcatel·Lucent

Spatial Multiplexing in Fibers



Multimode fibers

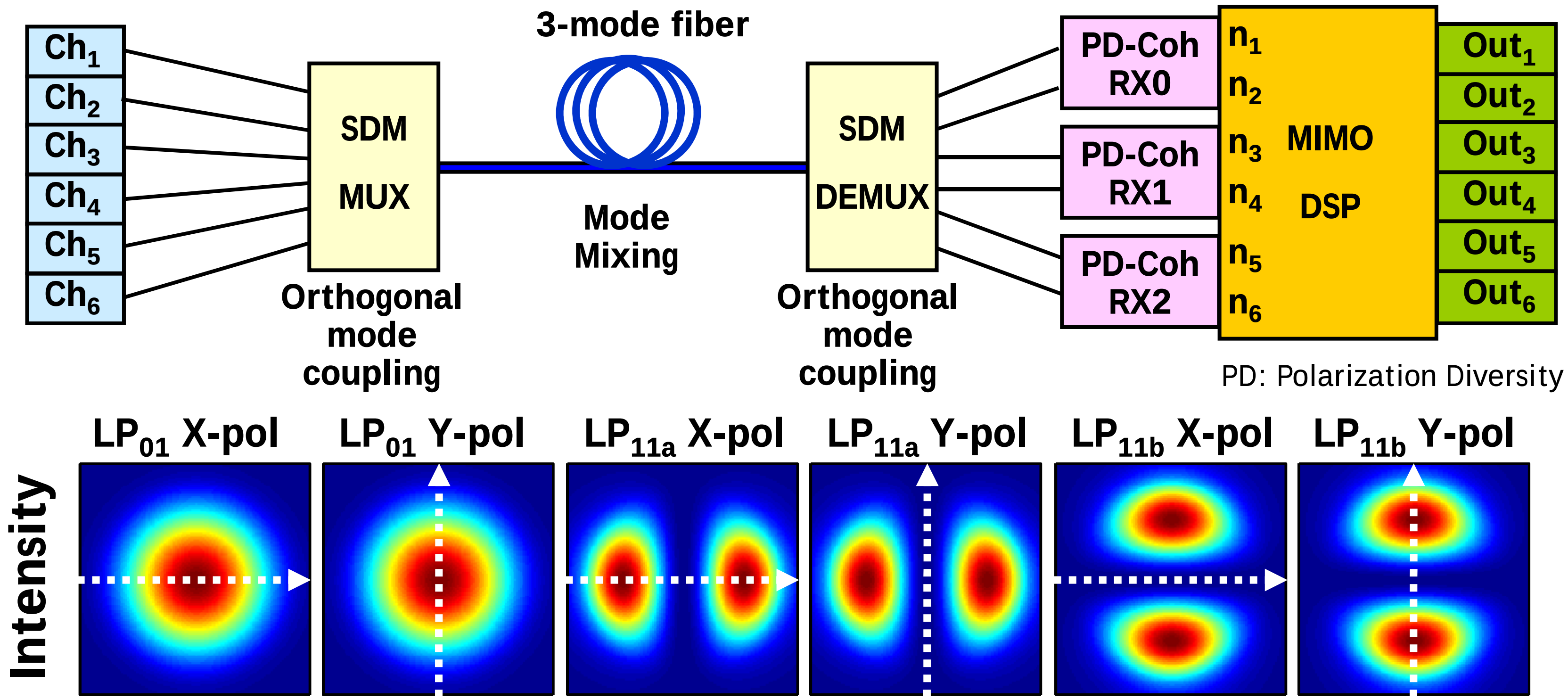


- **All** guided modes are **selectively** launched and coherently detected
- Modes are **strongly coupled** during propagation in the fiber

MIMO Processing Required

All Rights Reserved © Alcatel-Lucent 2009

First Experimental Results Using 3 Coupled Spatial Modes

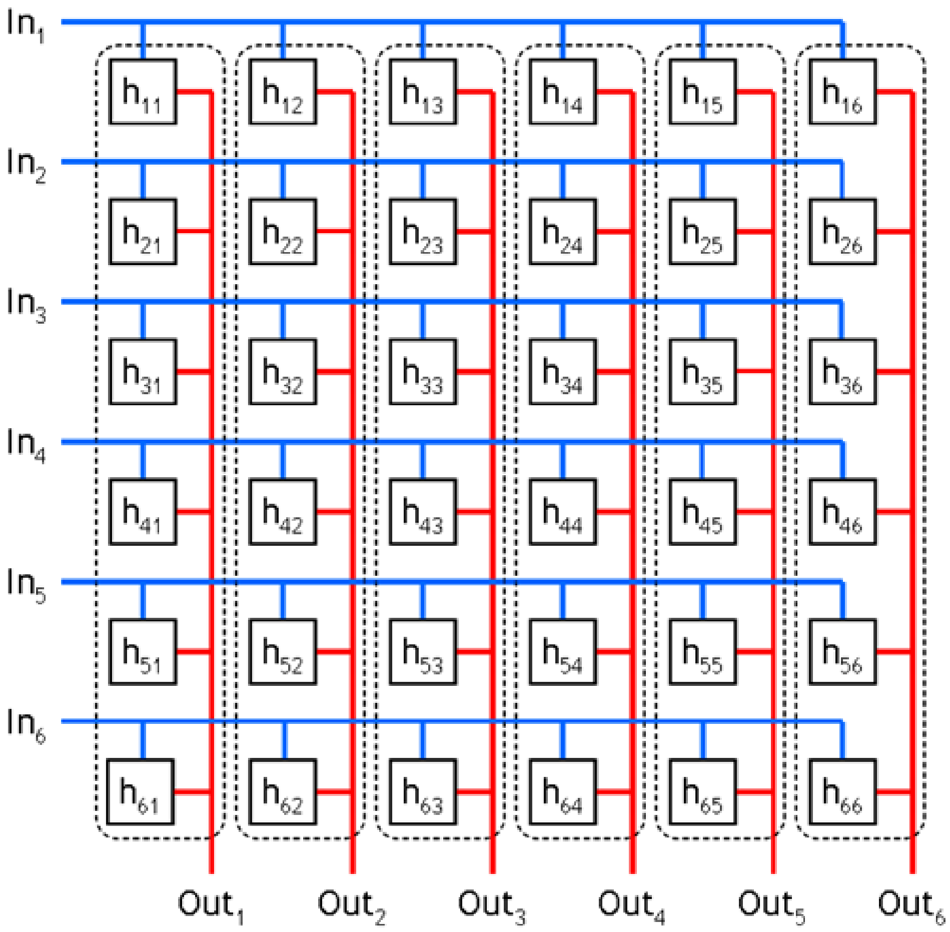


- **All** guided modes are **selectively** launched and coherently detected (otherwise: **High system outage**)
- Modes are **strongly coupled** during propagation in the fiber
- **Digital 6x6 MIMO signal processing** decouples received signals

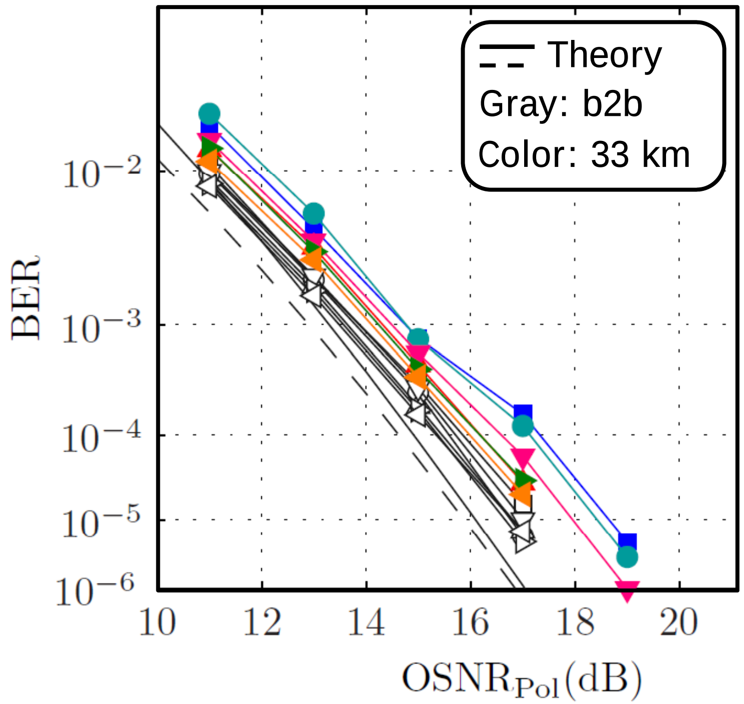
For more information: S. Randel et al., OptEx 2011

All Rights Reserved © Alcatel-Lucent 2009
Alcatel·Lucent

DIGITAL SIGNAL PROCESSING FOR 28-GBAUD 6 × 6 MIMO



- Network of 36 feed-forward equalizers (FFEs)
- ~100 taps per filter



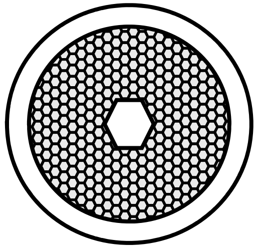
For more information: S. Randel et al., OptEx 2011

All Rights Reserved © Alcatel-Lucent 2009

Alcatel·Lucent

Spatial Multiplexing in Fibers

Hollow-core PBF



Microstructured fibers

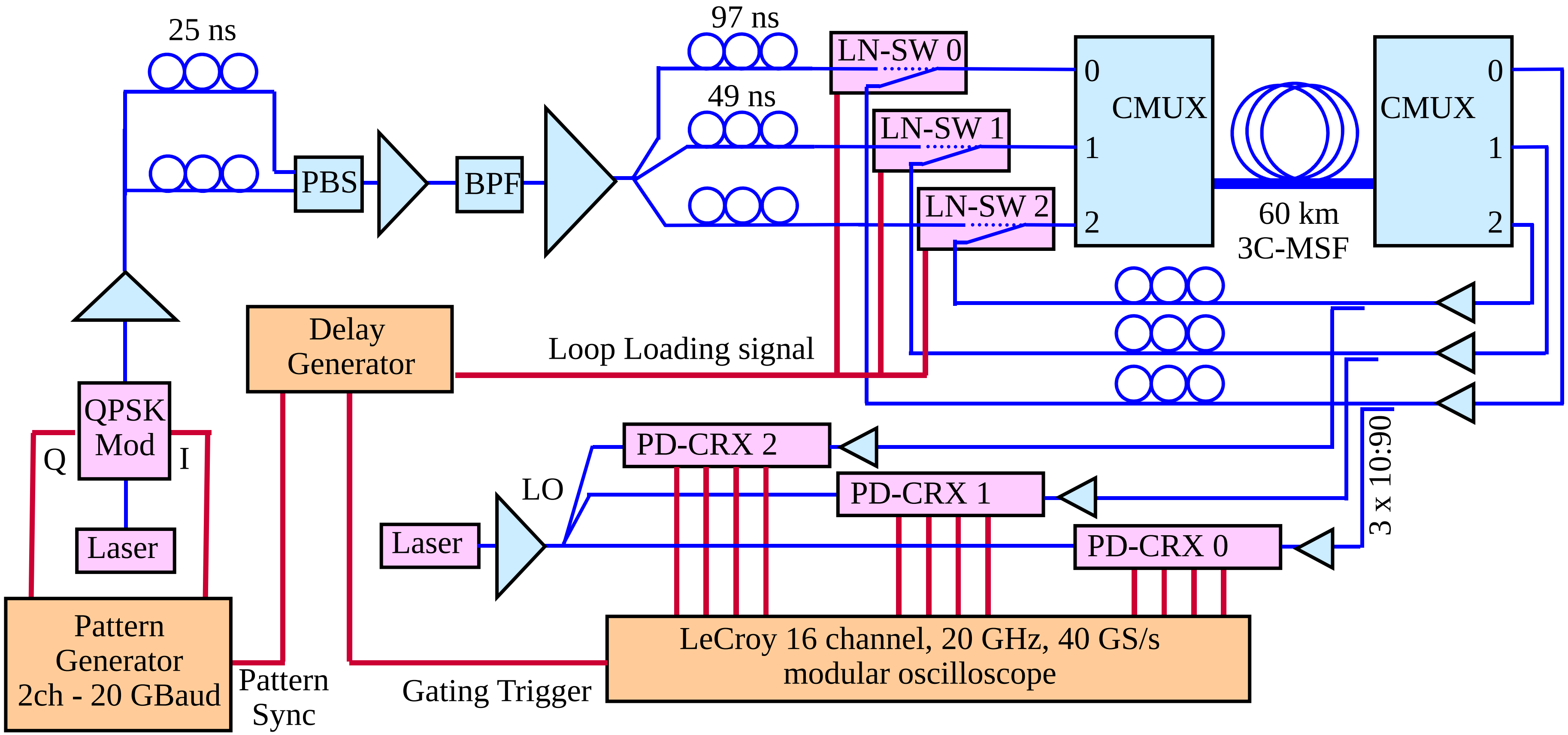
All Rights Reserved © Alcatel-Lucent 2009

Alcatel·Lucent

COHERENT 1200-km 6 x 6 MIMO MODE-MULTIPLEXED TRANSMISSION OVER 3-CORE MICROSTRUCTURED FIBER

R. Ryf, et al, ECOC 2012 Post Deadline Paper PD C.1

20 X 60 km Loop MODE-MULTIPLEXING OVER 3-CORE MICROSTRUCTURED FIBER

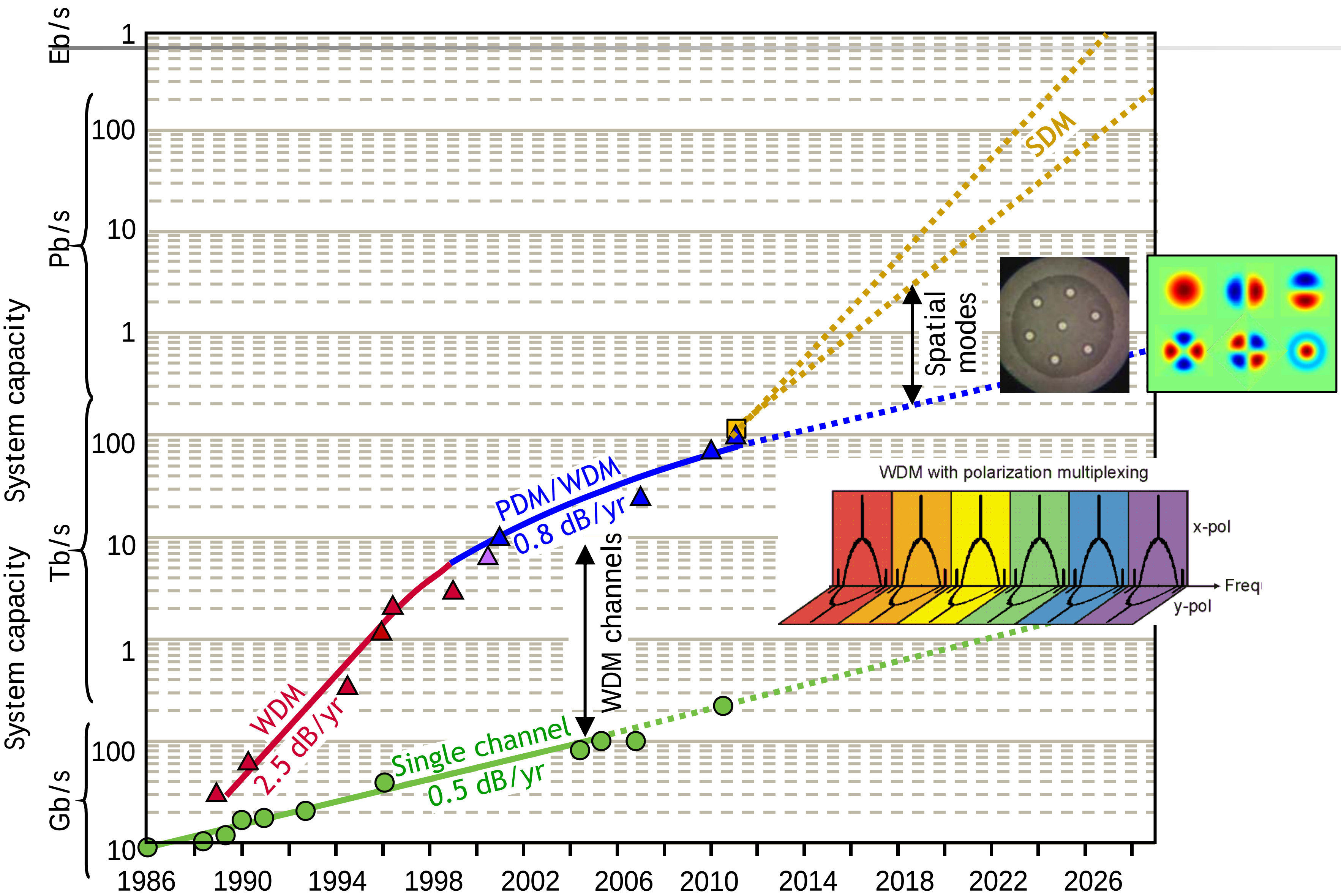


Path length difference between the 3 loops has to be < 1 cm

All Rights Reserved © Alcatel-Lucent 2009

Alcatel·Lucent

Will We Approach Petabit/s or Exabit/s Cable Capacities?



All Rights Reserved © Alcatel-Lucent 2009

We Will Have Our Hands Full Innovating

New optical fiber (multi-core & multi-mode)
New linear and non-linear fiber propagation physics
New fiber coupling, connecting, splicing
New optical amplifiers
New network elements (ROADMs, Crossconnects, ...)
New MIMO digital signal processing
New electronic/photonic integration

All Rights Reserved © Alcatel-Lucent 2009

SUMMARY

- Spatial multiplexing ***will*** be needed to scale system capacity beyond WDM
  - Integrated *optical amplifier* technologies
  - Integrated *transponder* technologies
  - Multi-core, multi-mode fibers
- If coupling between spatial multiplexing paths cannot be neglected
  - Need MIMO signal processing to undo crosstalk at receiver
- There is *a lot* of exciting research ahead of us!

All Rights Reserved © Alcatel-Lucent 2009

www.alcatel-lucent.com