OPTICAL NETWORKING BEYOND WDM

SPATIAL MULTIPLEXING AND MIMO FOR THE PETABIT ERA

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1 Traffic evolution in data networks

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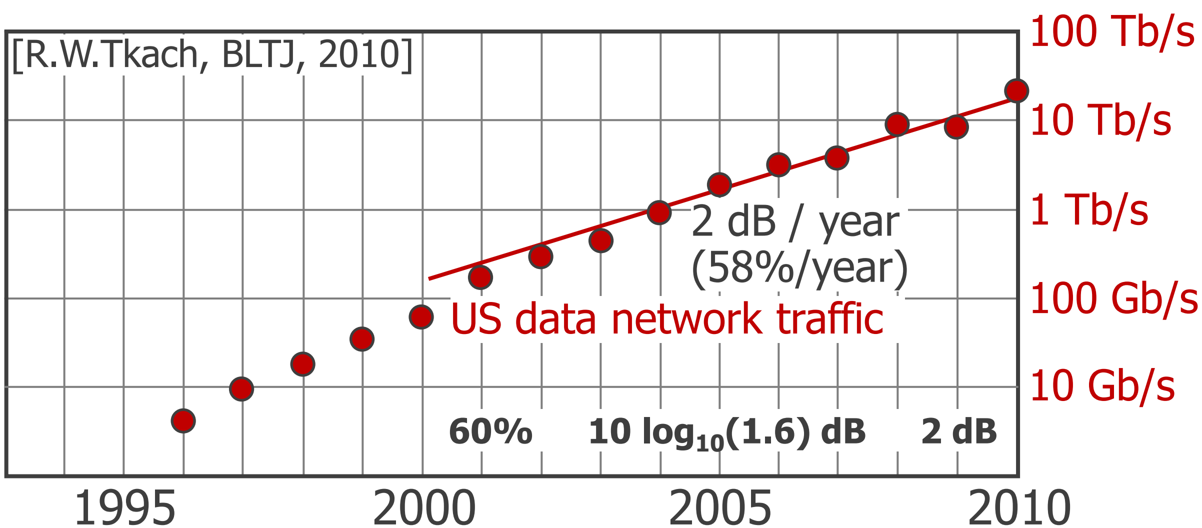
HUMAN-DRIVEN TRAFFIC GROWTH

Human desire to communicate in a multi-media manner

Huge *transport capacities* (especially for non-cacheable real time apps)



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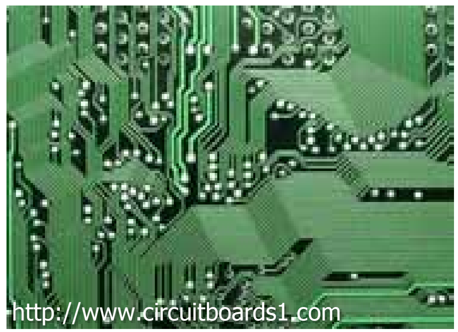
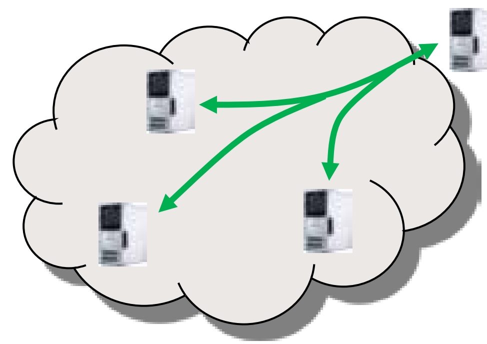
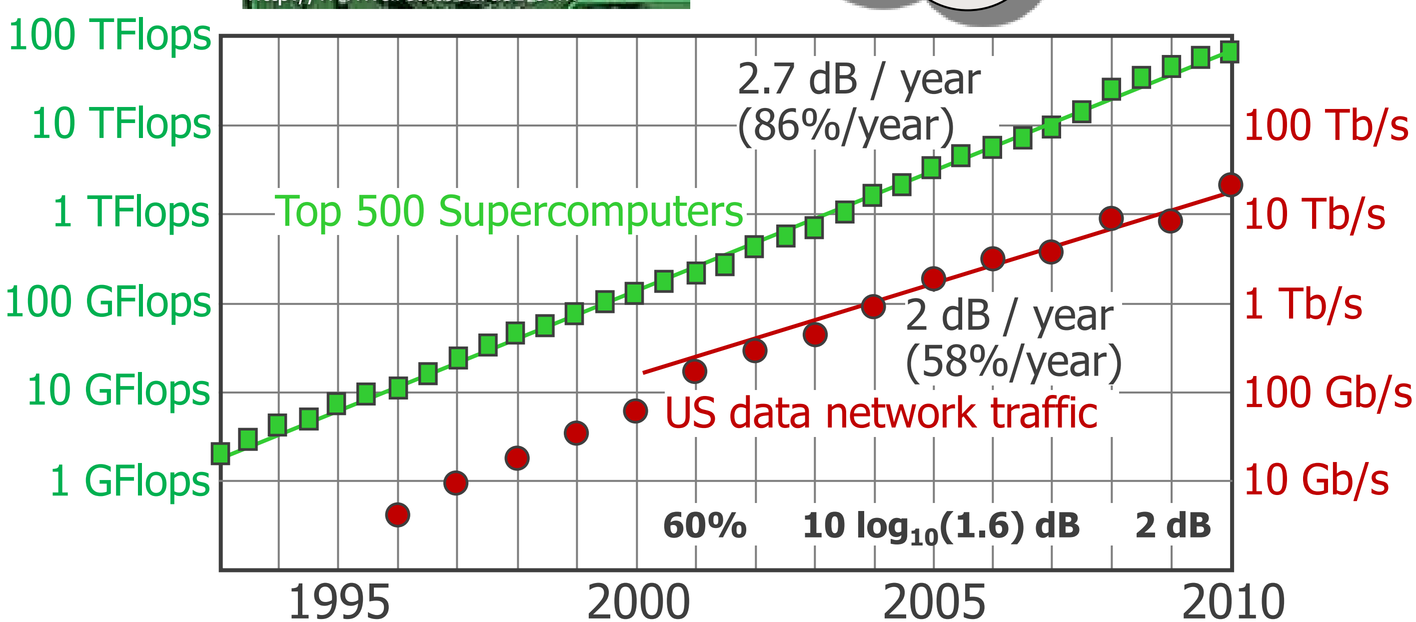
MACHINE-DRIVEN TRAFFIC GROWTH

Amdahl's rule of thumb

- 1 Floating point operation (Flop) triggers ~1 Byte/s of transport
- Cloud services couple network traffic to exponential growth of processor power







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2 The role of optical transmission technologies

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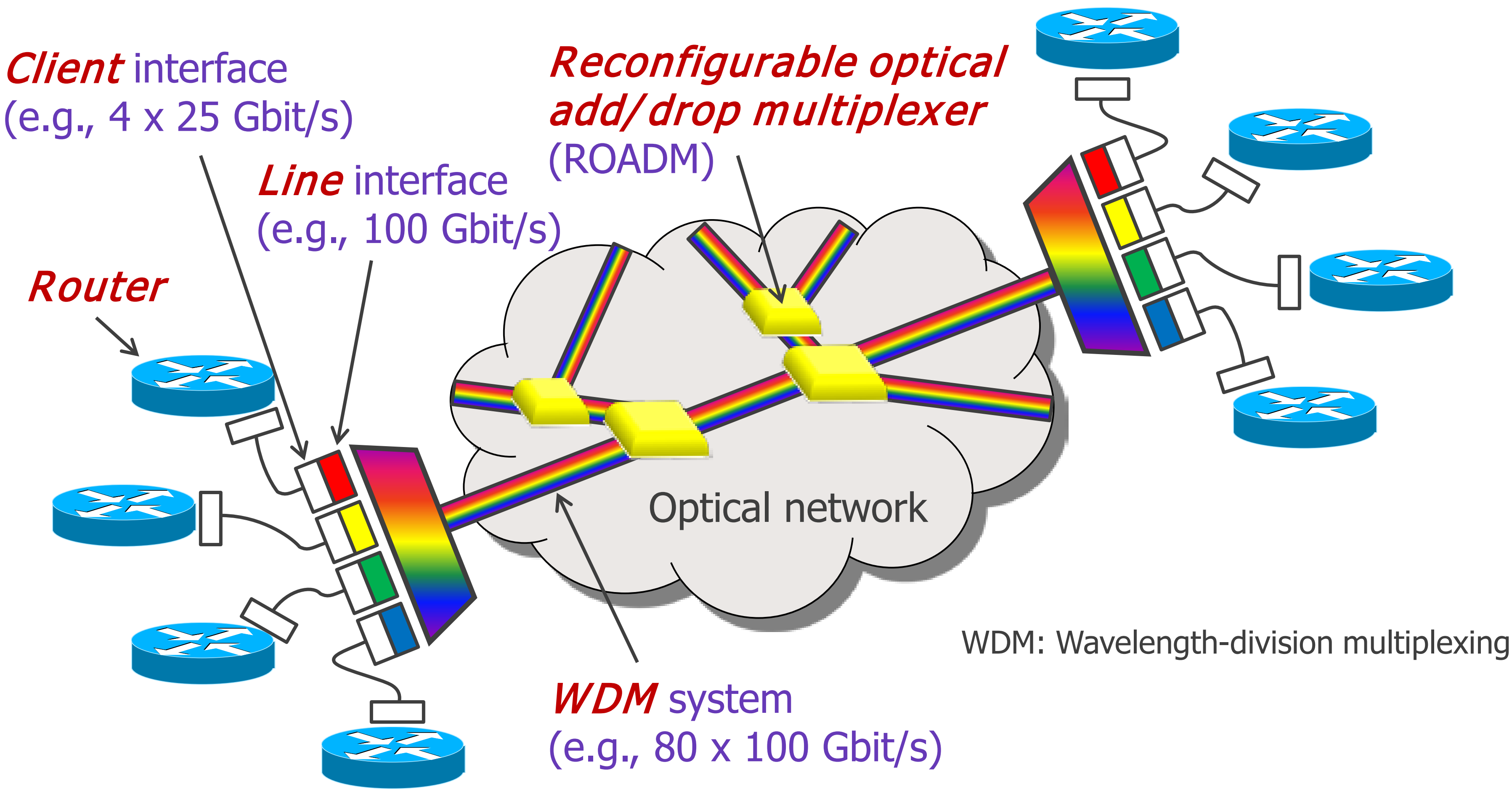
OPTICAL NETWORKS: WORKHORSE OF THE INTERNET



Objectives:

Increase per-wavelength interface rates (client and line side)

Increase per-fiber aggregate capacities (line side)

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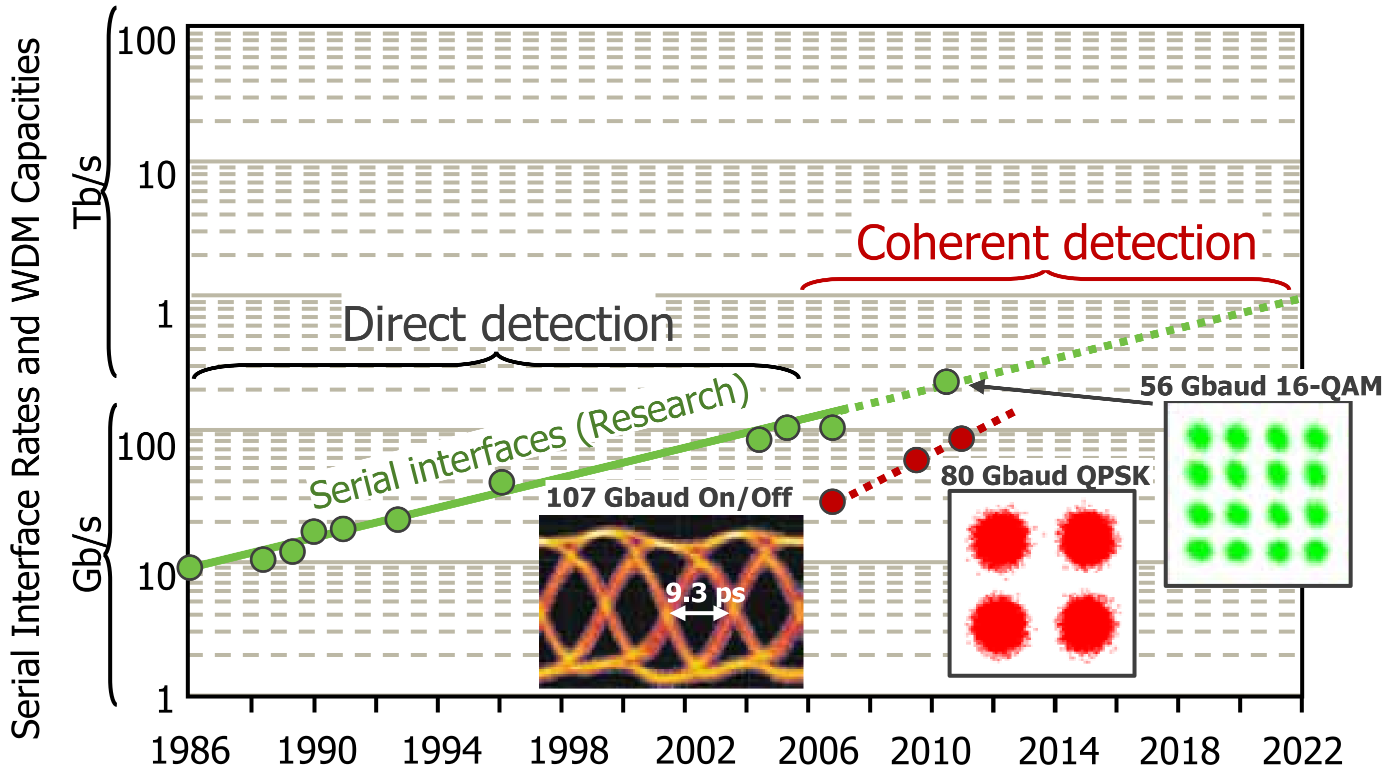
HIGH-SPEED OPTICAL INTERFACE EVOLUTION



- From direct (envelope) detection to coherent (field) detection
- Polarization multiplexed 16-QAM at 448 Gb/s demonstrated

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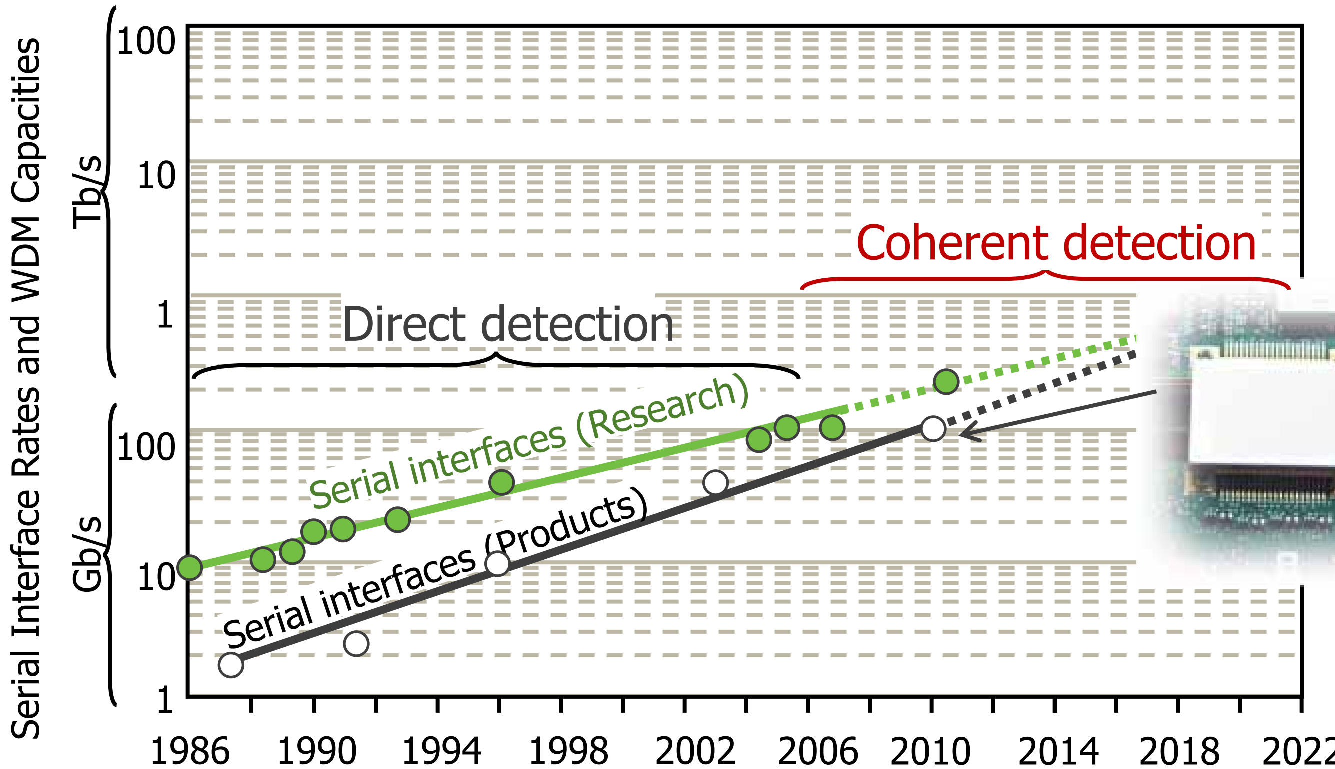
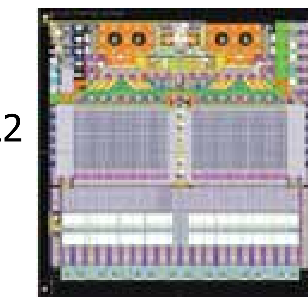
HIGH-SPEED OPTICAL INTERFACES – PRODUCTS



ASIC: 70M+ gates



- From direct (envelope) detection to coherent (field) detection
- Polarization multiplexed 16-QAM at 448 Gb/s demonstrated
- 112-Gbit/s coherent interfaces commercially available since June 2010

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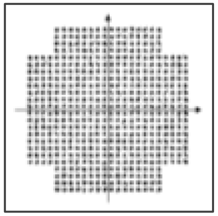
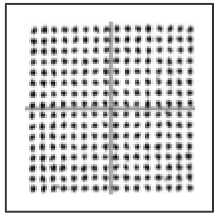
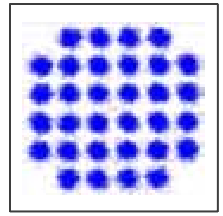
SCALING INTERFACES TO TERABIT ETHERNET



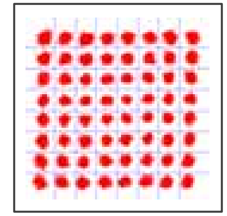
PDM 512-QAM
3 GBaud (**54 Gb/s**)
[Okamoto et al., ECOC'10]



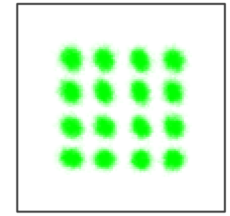
PDM 256-QAM
4 GBaud (**64 Gb/s**)
[Nakazawa et al., OFC'10]



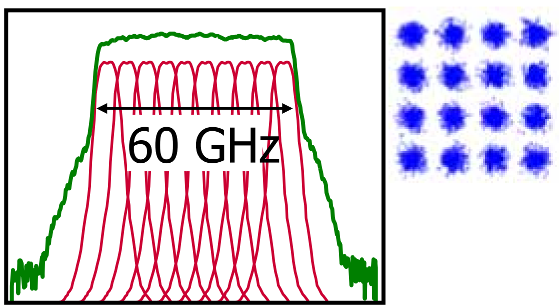
PDM 32-QAM
9 GBaud (**90 Gb/s**)
[Zhou et al., OFC'11]



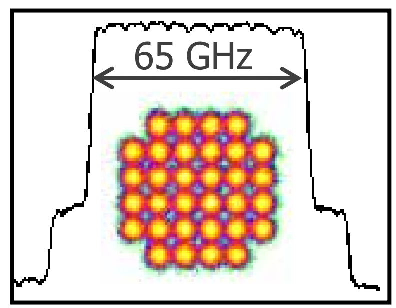
PDM 64-QAM
21 GBaud (**256 Gb/s**)
[Gnauck et al., OFC'11]



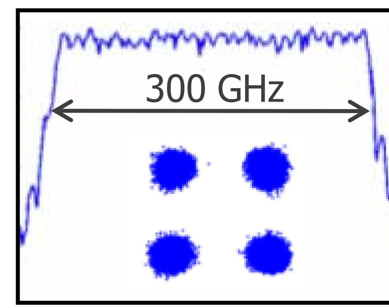
PDM 16-QAM
56 GBaud (**448 Gb/s**)
[Winzer et al., ECOC'10]



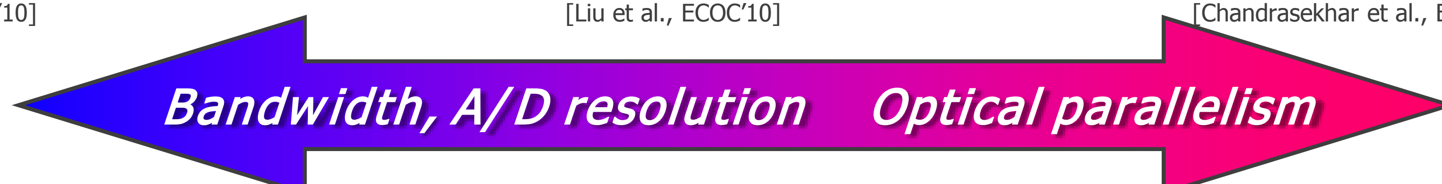
448 Gb/s (10 subcarriers) 16-QAM
5 bit/s/Hz
2000 km transm.
[Liu et al., OFC'10]



606 Gb/s (10 subcarriers) 32-QAM
7 bit/s/Hz
2000 km transm.
[Liu et al., ECOC'10]



1.2 Tb/s (24 subcarriers) QPSK
3 bit/s/Hz
7200 km transm.
[Chandrasekhar et al., ECOC'09]



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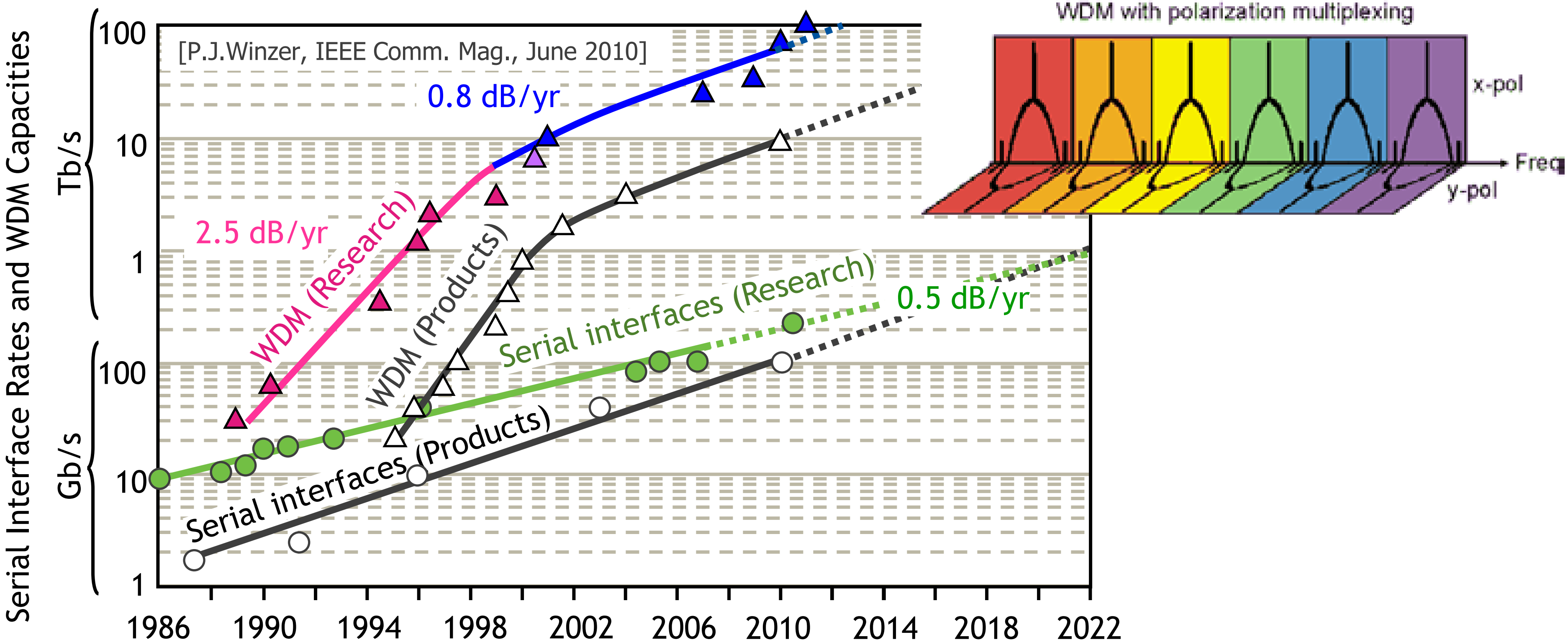
THE SCALING OF WAVELENGTH-DIVISION MULTIPLEXING



~10 Terabit/s WDM systems are now commercially available

~100 Terabit/s WDM systems have been demonstrated in research

Growth of WDM system capacities has noticeably slowed down since ~2000

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3 Fiber nonlinearities and the "nonlinear Shannon limit"

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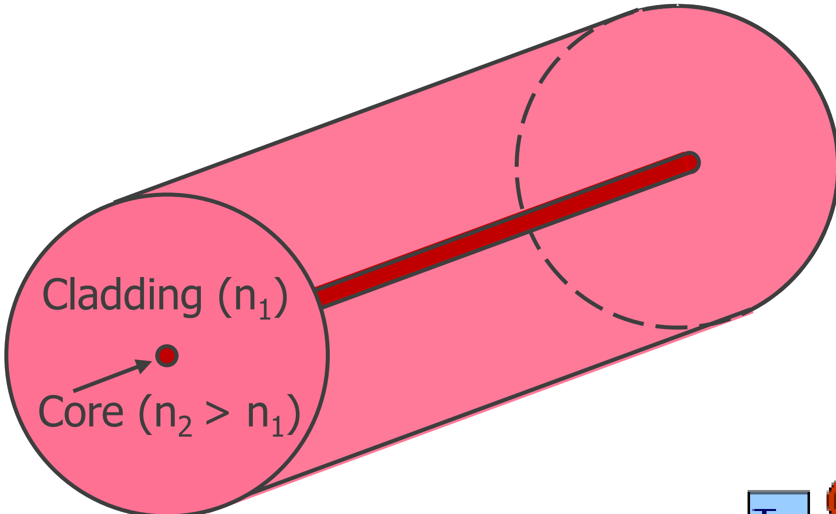
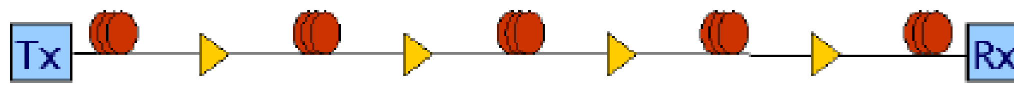
WHY IS AN OPTICAL FIBER NONLINEAR ?





- Core diameter ~8 mm
- Cladding diameter ~125 mm
- Light is kept within the core (total internal reflection)

Megawatt / cm^2 optical intensities $n_2 = n_{2,0} + n_{2,2} P_{opt} + \dots$

(Kerr effect)

Leads to *nonlinear distortions* over hundreds of kilometers

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PHYSICAL PHENOMENA AT PLAY

$A = A(z,t)$ … Optical field propagating in the fiber's transverse mode

$$\frac{\partial A}{\partial z} = -\alpha A - j\beta \frac{\partial^2 A}{\partial t^2} + j\gamma |A|^2 A + N$$ (Nonlinear Schrödinger Equation)

$$A(z,t) = A(0,t)\mathrm{e}^{-\alpha z}$$

$$A(z,t) = A(0,t)\mathrm{e}^{j\gamma |A(0,t)|^2 z}$$

$$A_{\mathcal{F}}(z,\omega) = A_{\mathcal{F}}(0,\omega)\mathrm{e}^{j\beta\omega^2 z}$$

Fiber Nonlinearity

Filtering Effects

Noise

Chromatic Dispersion
Optical Filtering (ROADMs)

Spontaneous emission from in-line optical amplifiers

ROADM … Reconfigurable optical add/drop multiplexer

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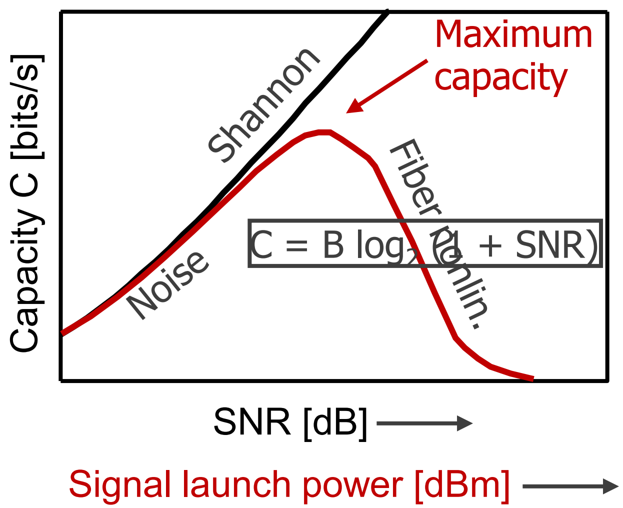
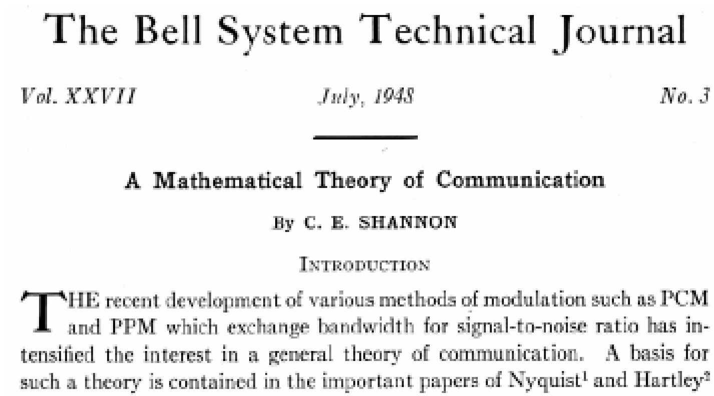
THE NONLINEAR SHANNON LIMIT

Increasing the signal power (i.e. the SNR) creates signal distortions from fiber nonlinearity, eventually limiting system performance





The Bell System Technical Journal

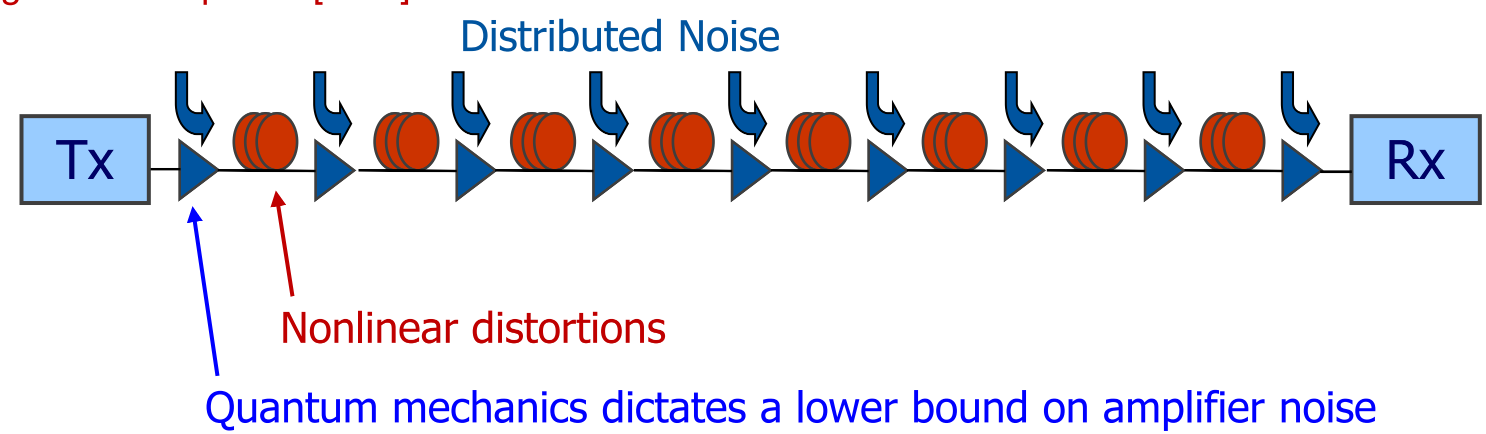
Vol. XXVII *July, 1948* *No. 3*

A Mathematical Theory of Communication

By C. E. SHANNON

INTRODUCTION

THE recent development of various methods of modulation such as PCM and PPM which exchange bandwidth for signal-to-noise ratio has intensified the interest in a general theory of communication. A basis for such a theory is contained in the important papers of Nyquist[1] and Hartley[2]



[R.-J. Essiambre et al., Phys. Rev. Lett. (2008) or J. Lightwave Technol. (2010)]

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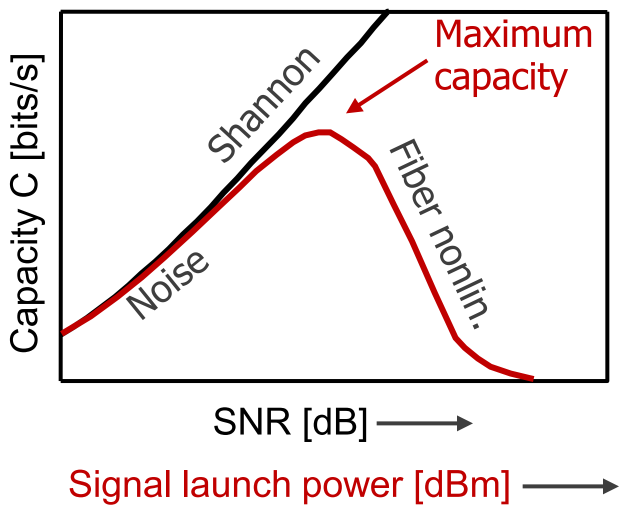
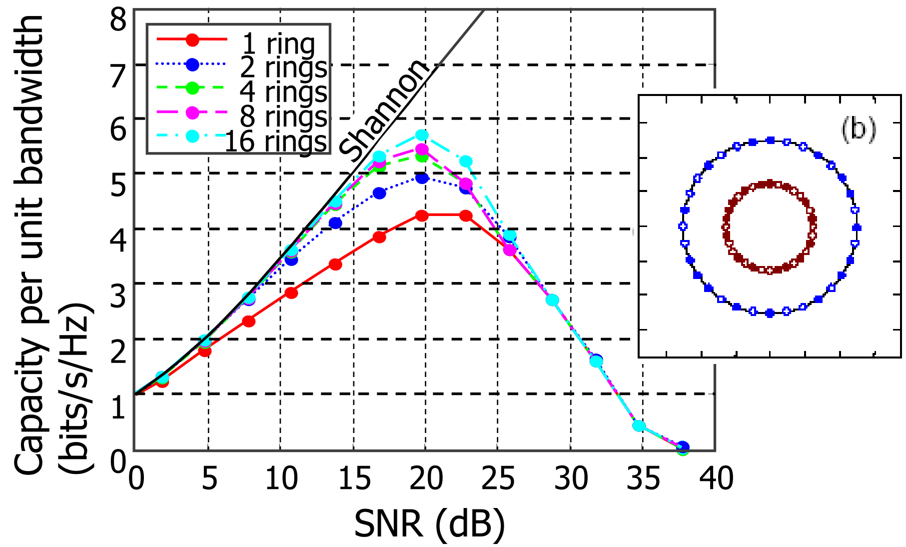
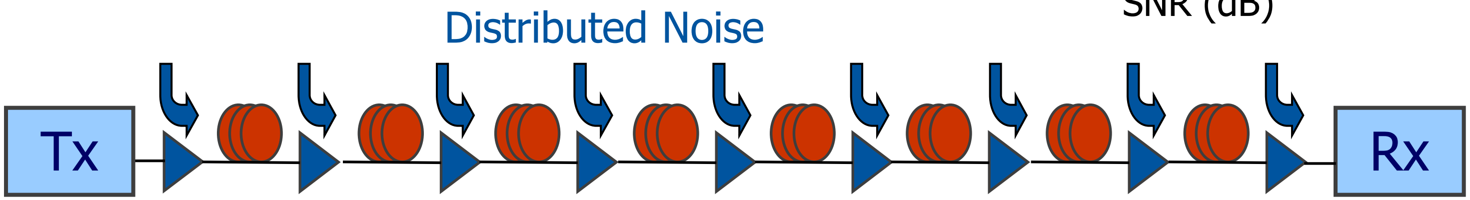
AN LOWER BOUND ESTIMATE FOR THE SHANNON LIMIT

- Assume ring constellations
- Deterministic signal back-propagation to remove (most of the) channel memory
- Numerical solution of nonlinear Schrödinger equation



Numerical statistics





$$\frac{\partial E}{\partial z} + \frac{i}{2}\beta_2 \frac{\partial^2 E}{\partial t^2} - i\gamma|E|^2 E = i\,\mathbf{n}(z,t)$$

Numerical statistics

$$\begin{aligned} C/B &= H(Y) - H(Y|X) \\ &= -\int p_Y(y)\log_2 p_Y(y)\,dy \\ &\quad + \iint p_{Y,X}(y,x)\log_2 p_{Y|X}(y|x)\,dy\,dx \end{aligned}$$

[R.-J. Essiambre et al., Phys. Rev. Lett. (2008) or J. Lightwave Technol. (2010)]

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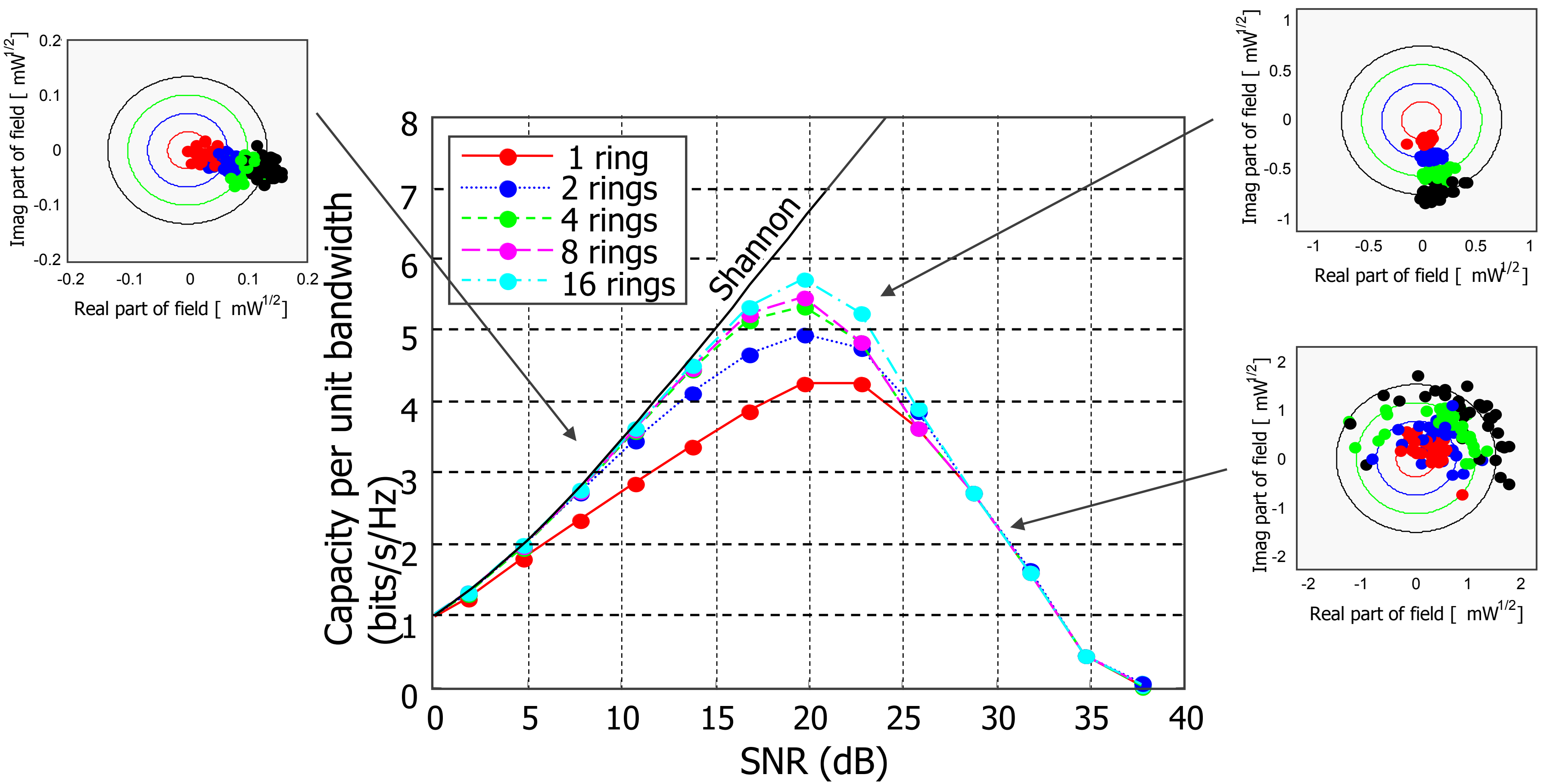
SOME EXAMPLE RESULTS



Note: Capacity maximum occurs at fairly high SNRs

R.-J. Essiambre et al., Phys. Rev. Lett. (2008) or J. Lightwave Technol. (2010)

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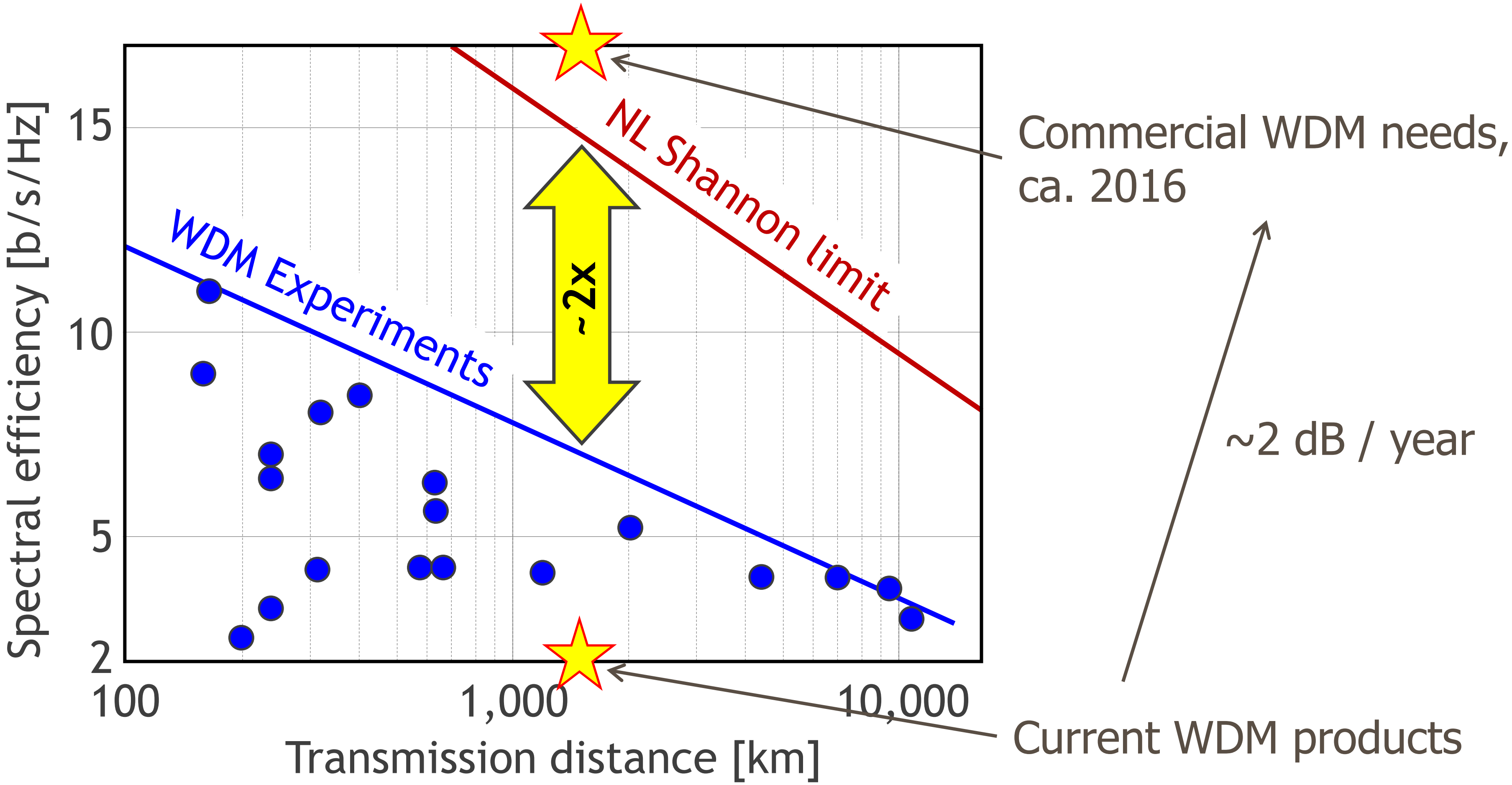
REALITY CHECK: WHERE ARE WE EXPERIMENTALLY ?



WDM: Wavelength division multiplexing
NL: Nonlinear

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4 Spatial multiplexing: The next frontier

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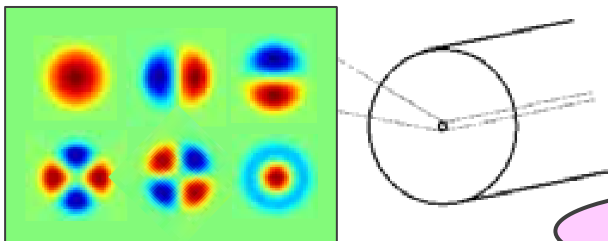
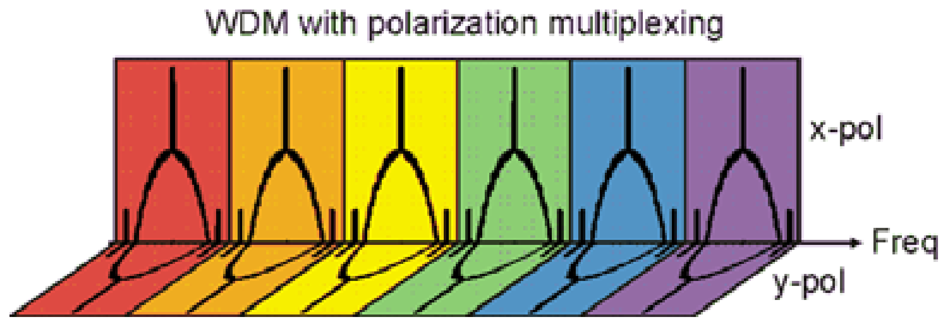
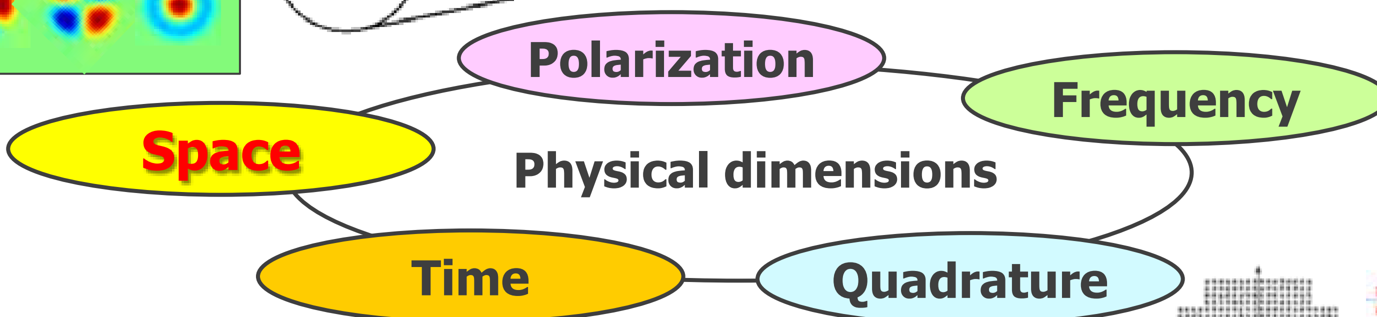
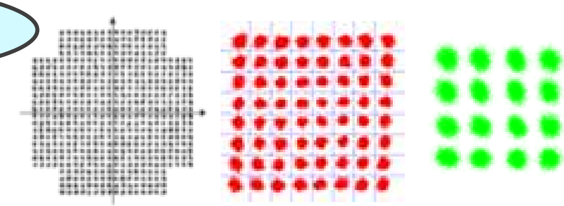
DIMENSIONS FOR MODULATION AND MULTIPLEXING

WDM: Wavelength division multiplexing









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

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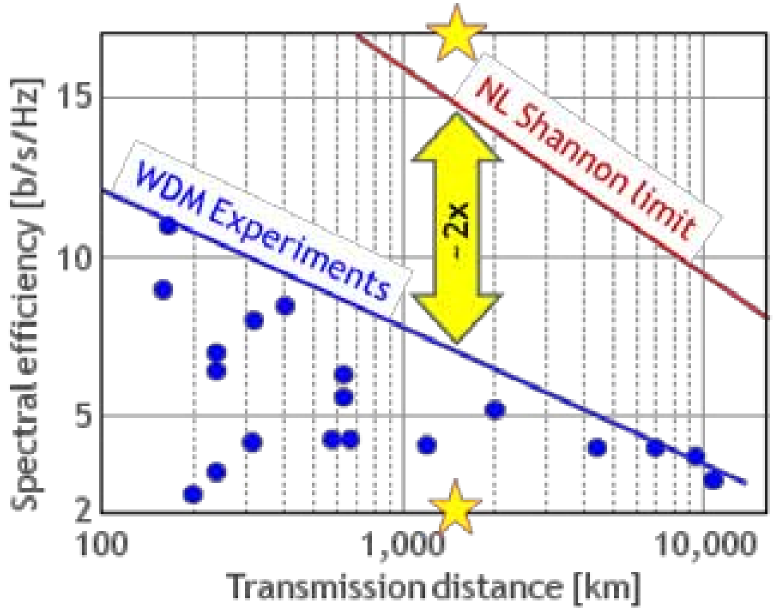
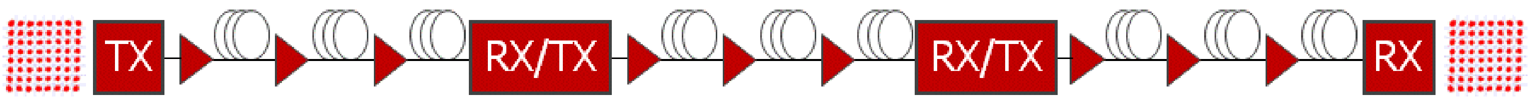
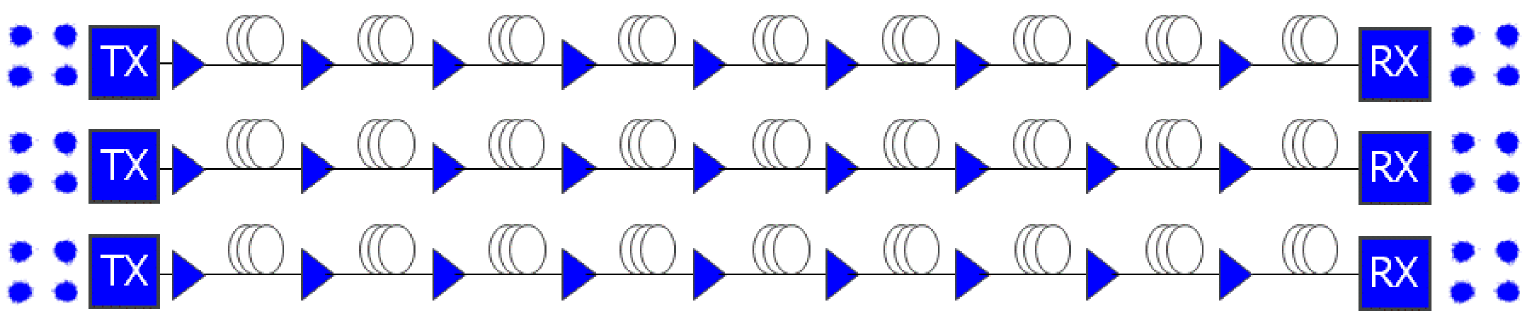
TWO OPTIONS TO REACH OUR 2016 CAPACITY GOAL





(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)

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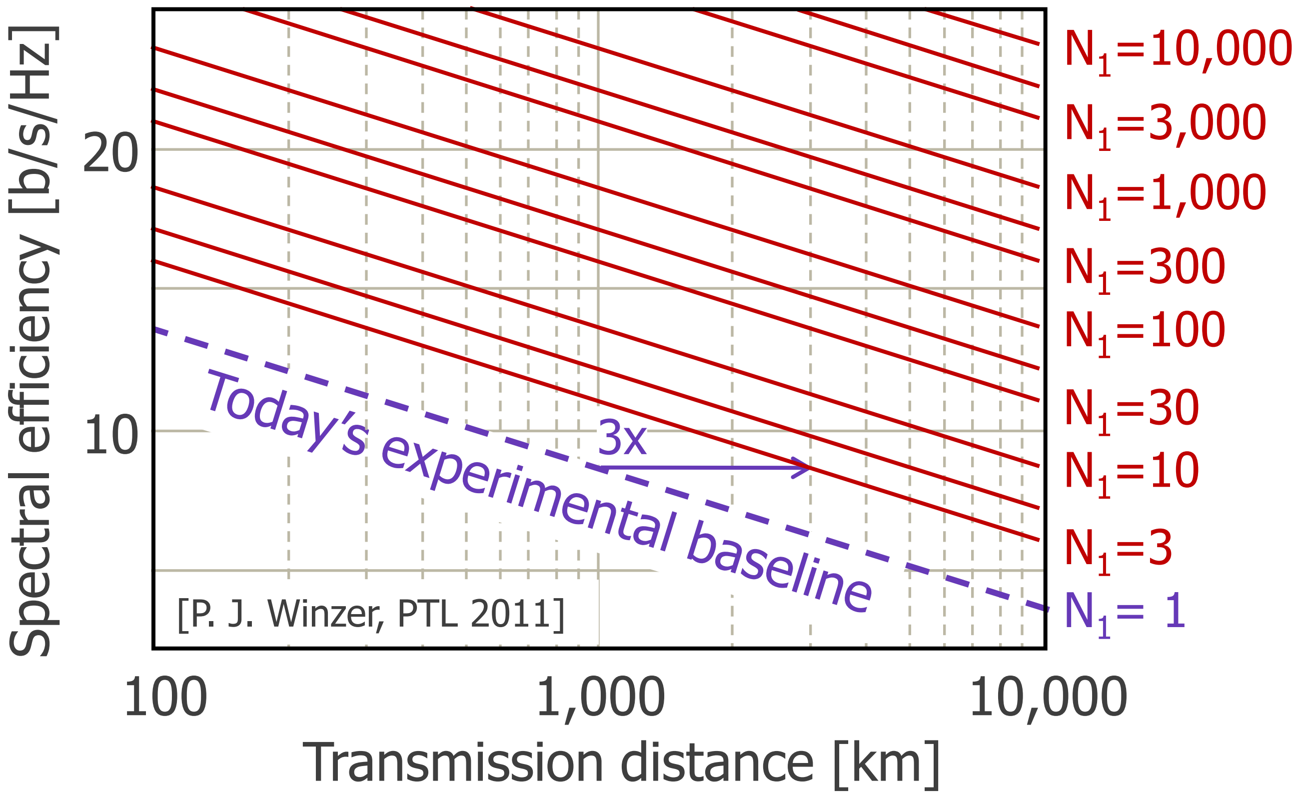
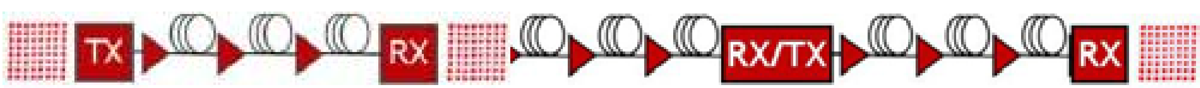
COMPARISON OF REQUIRED TRANSPONDER HARDWARE



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



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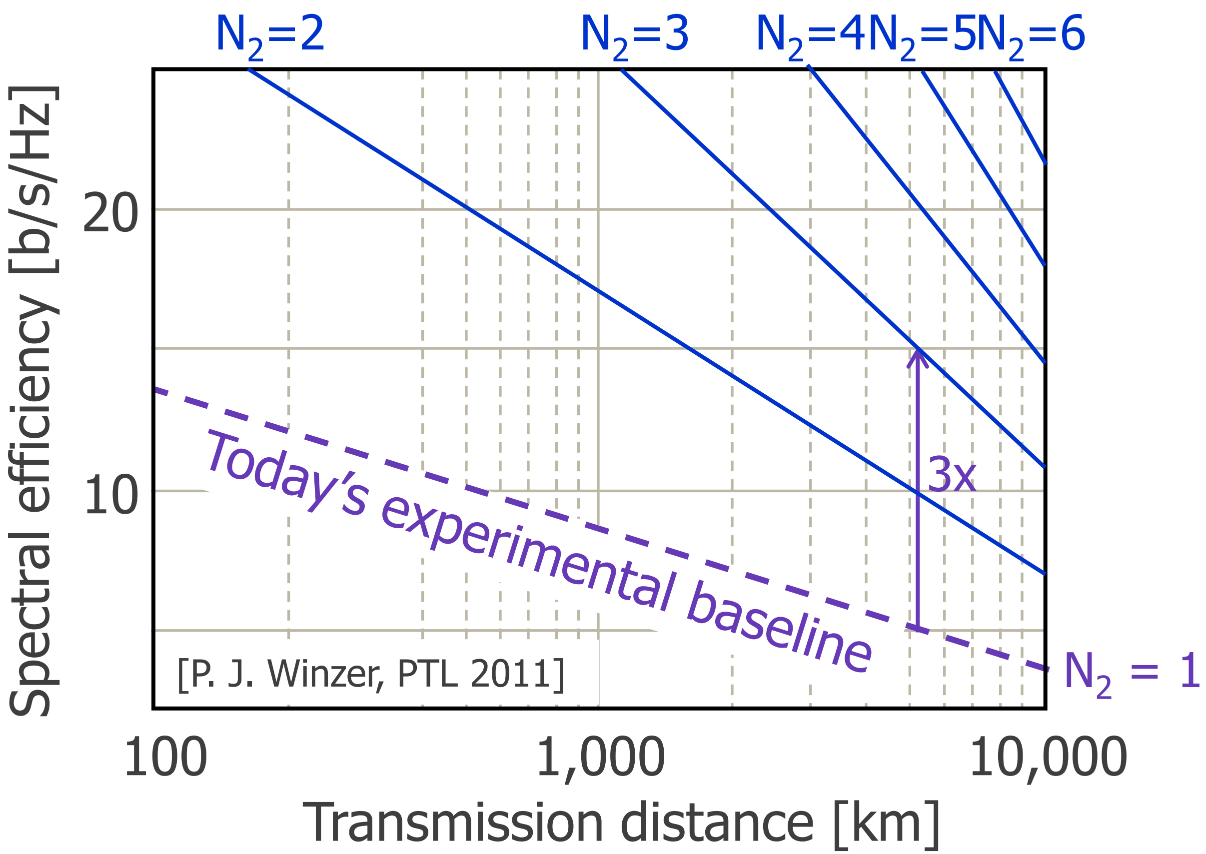
COMPARISON OF REQUIRED TRANSPONDER HARDWARE



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

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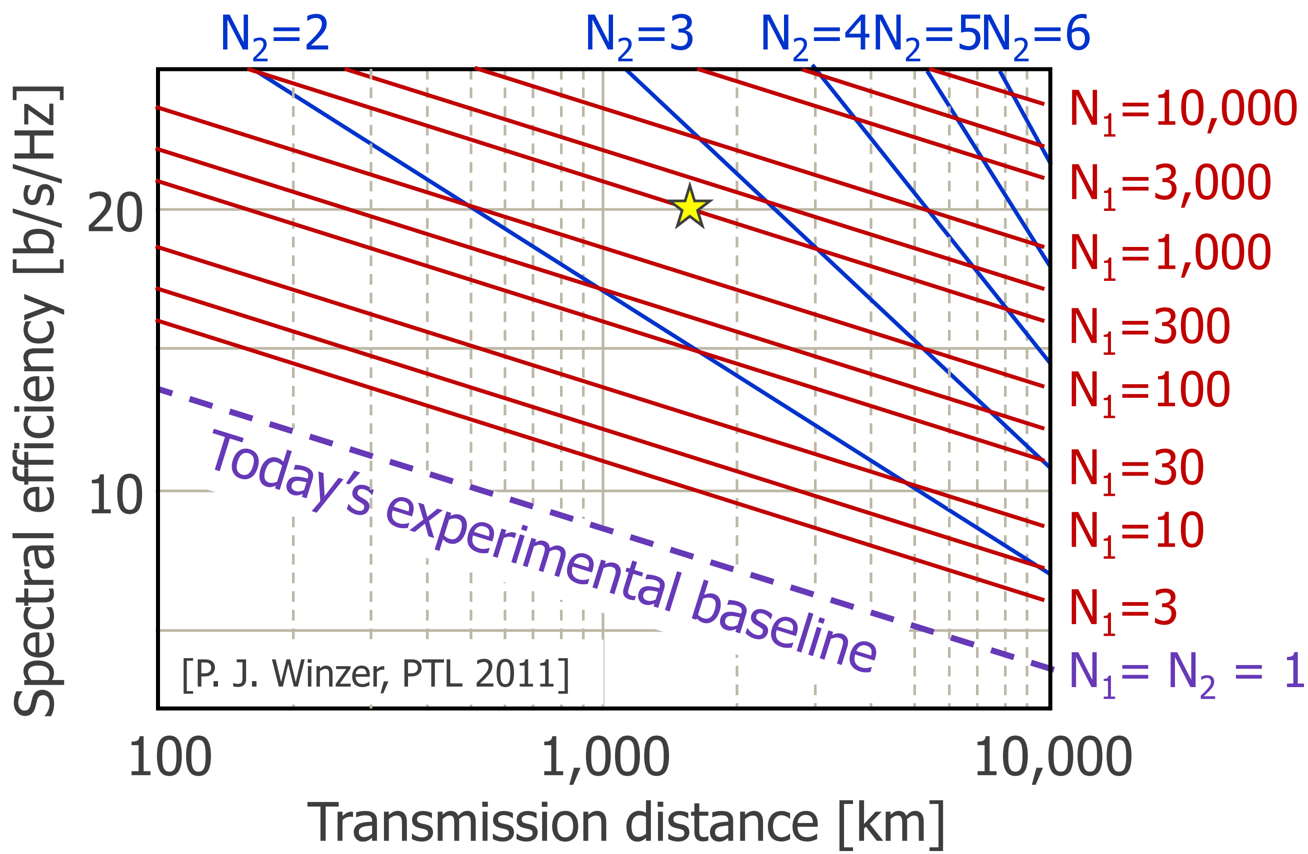
COMPARISON OF REQUIRED TRANSPONDER HARDWARE



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

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

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5 Spatial multiplexing: The integration challenge

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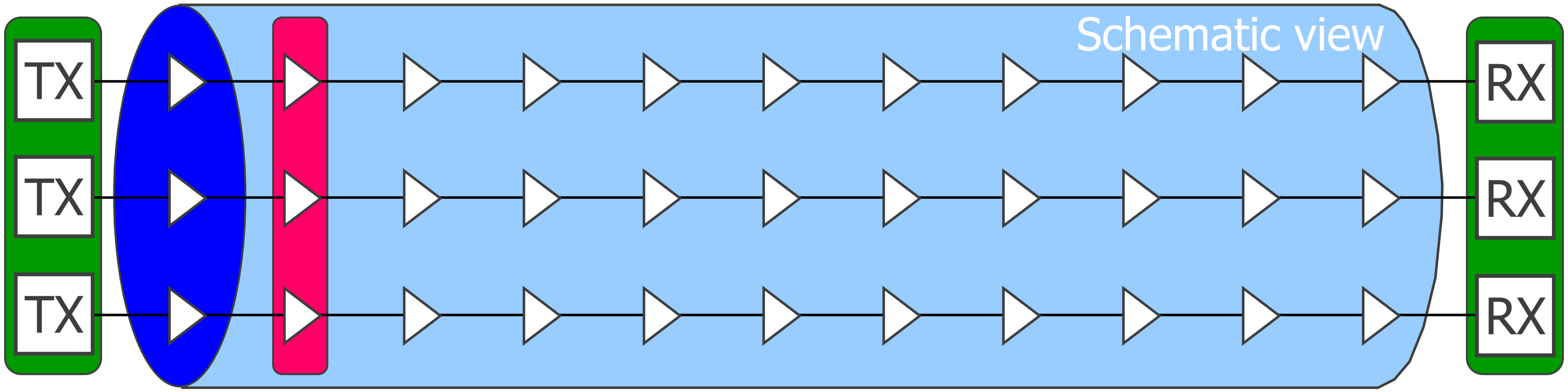
NEED INTEGRATION FOR ECONOMIC SUSTAINABILITY

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

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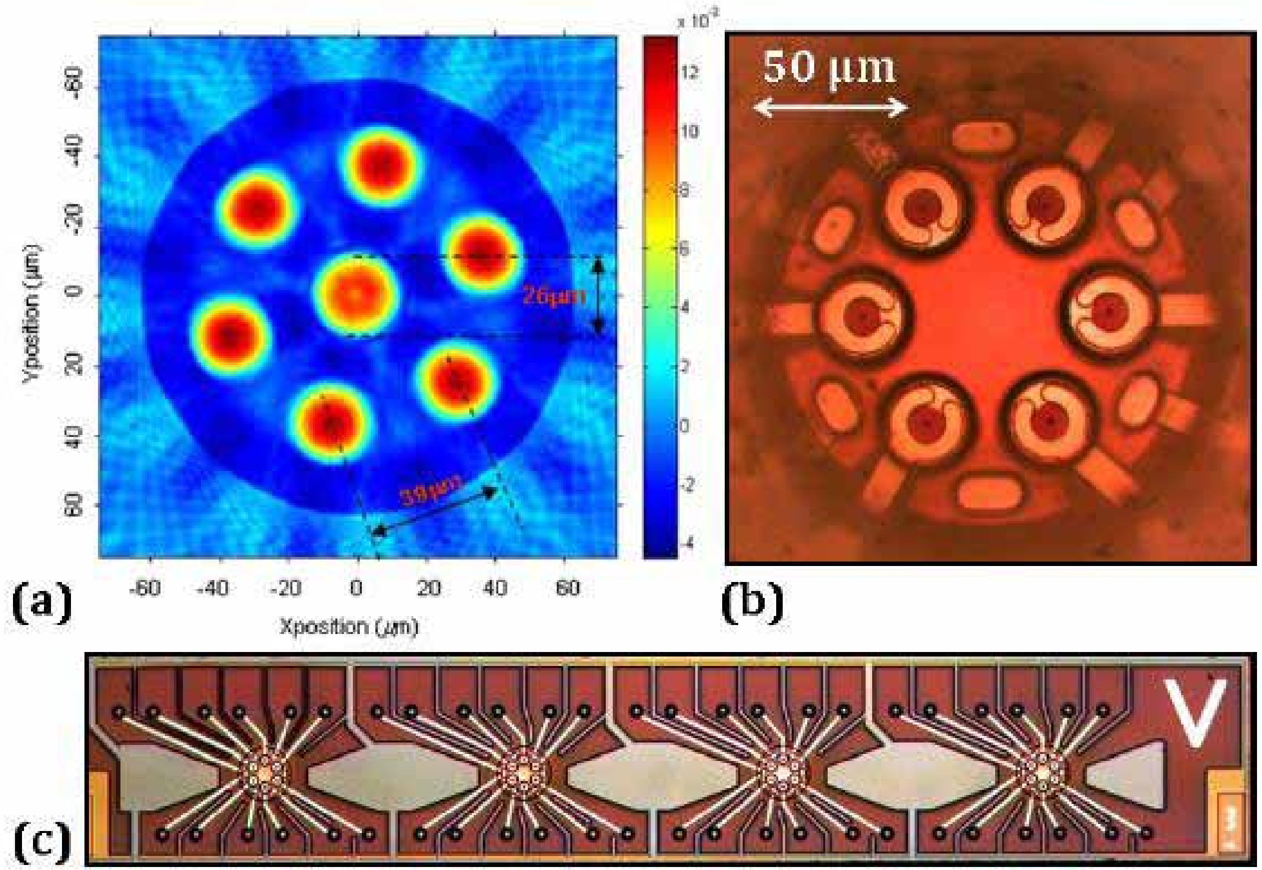
INTEGRATED 7-CORE MULTI-MODE INTERCONNECT

[B. G. Lee et al., IEEE Photonics Society Summer Topicals, 2010]



Fiber coupled to VCSEL array for 100-m interface at 120 Gb/s

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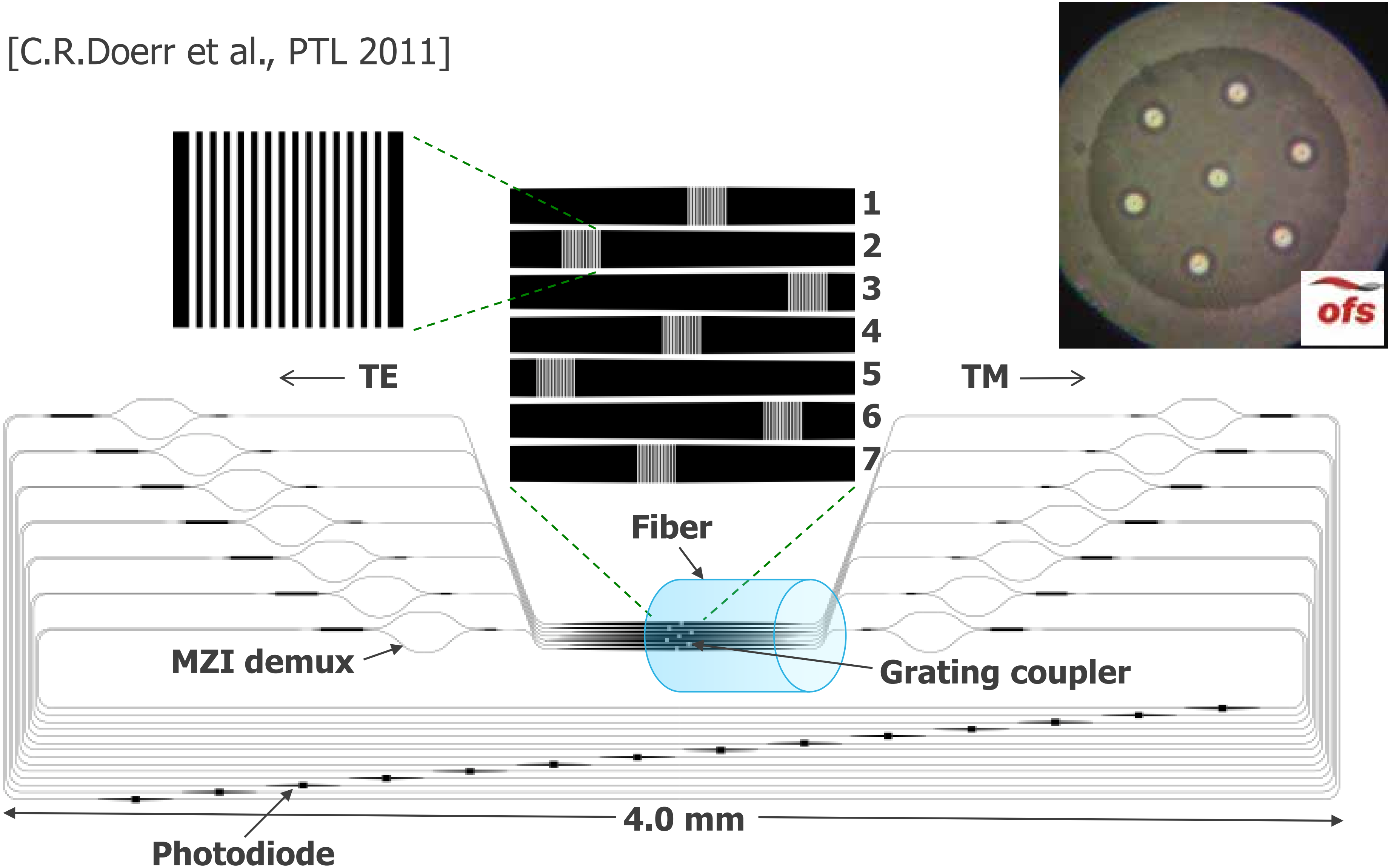
INTEGRATED 7-CORE SINGLE-MODE RECEIVER

[C.R.Doerr et al., PTL 2011]



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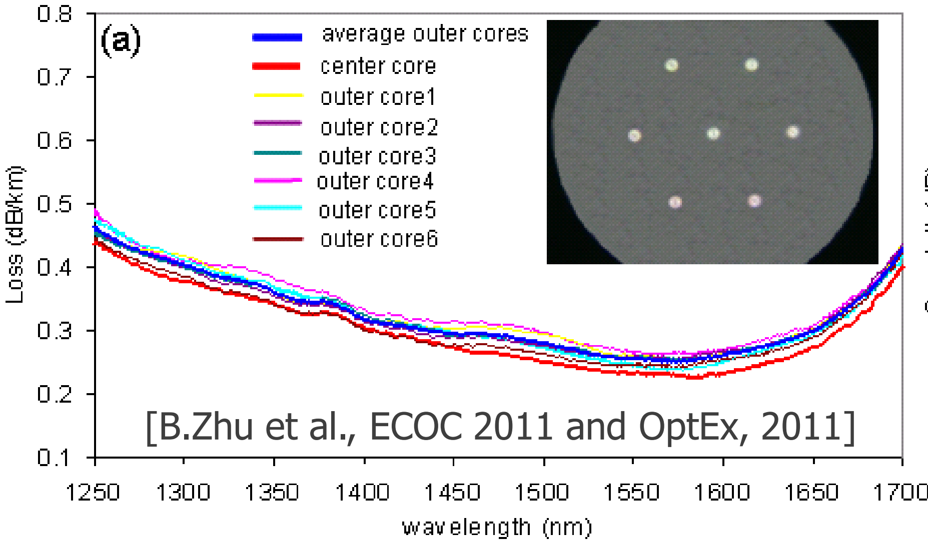
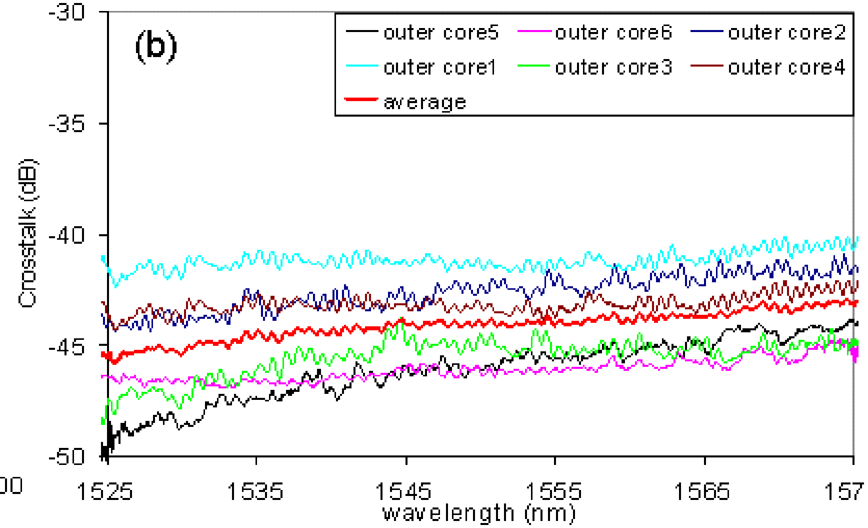
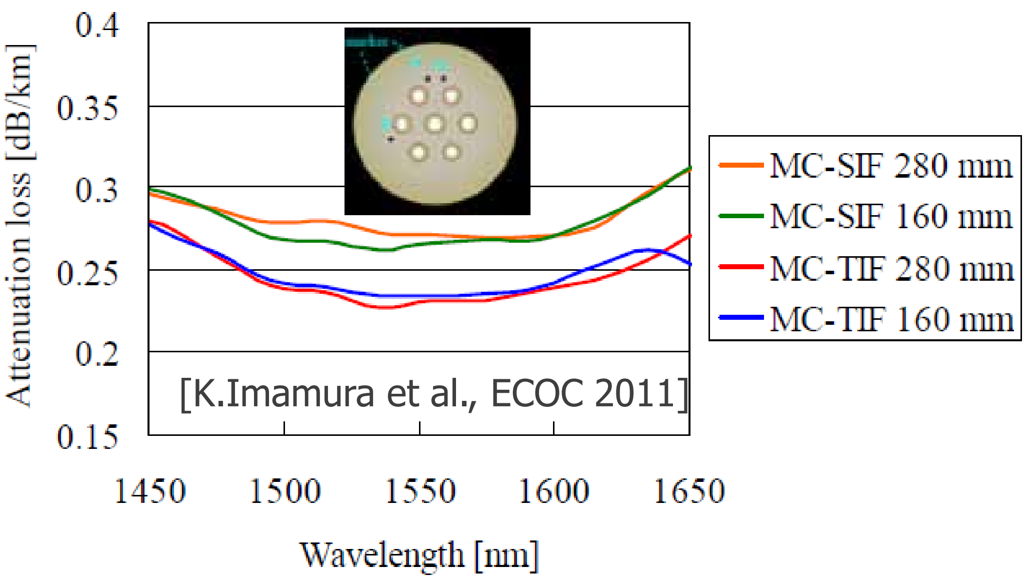
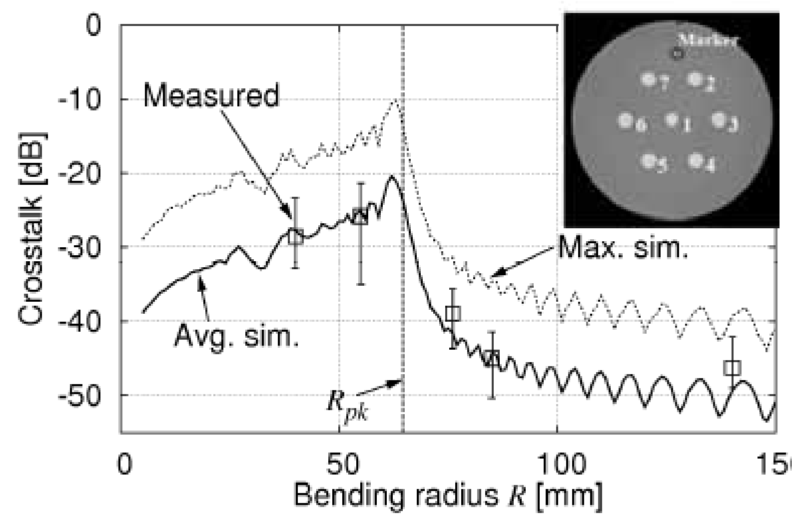
7-CORE FIBER: LOW LOSS AND LOW CROSSTALK









[T. Hayashi et al., ECOC 2011]

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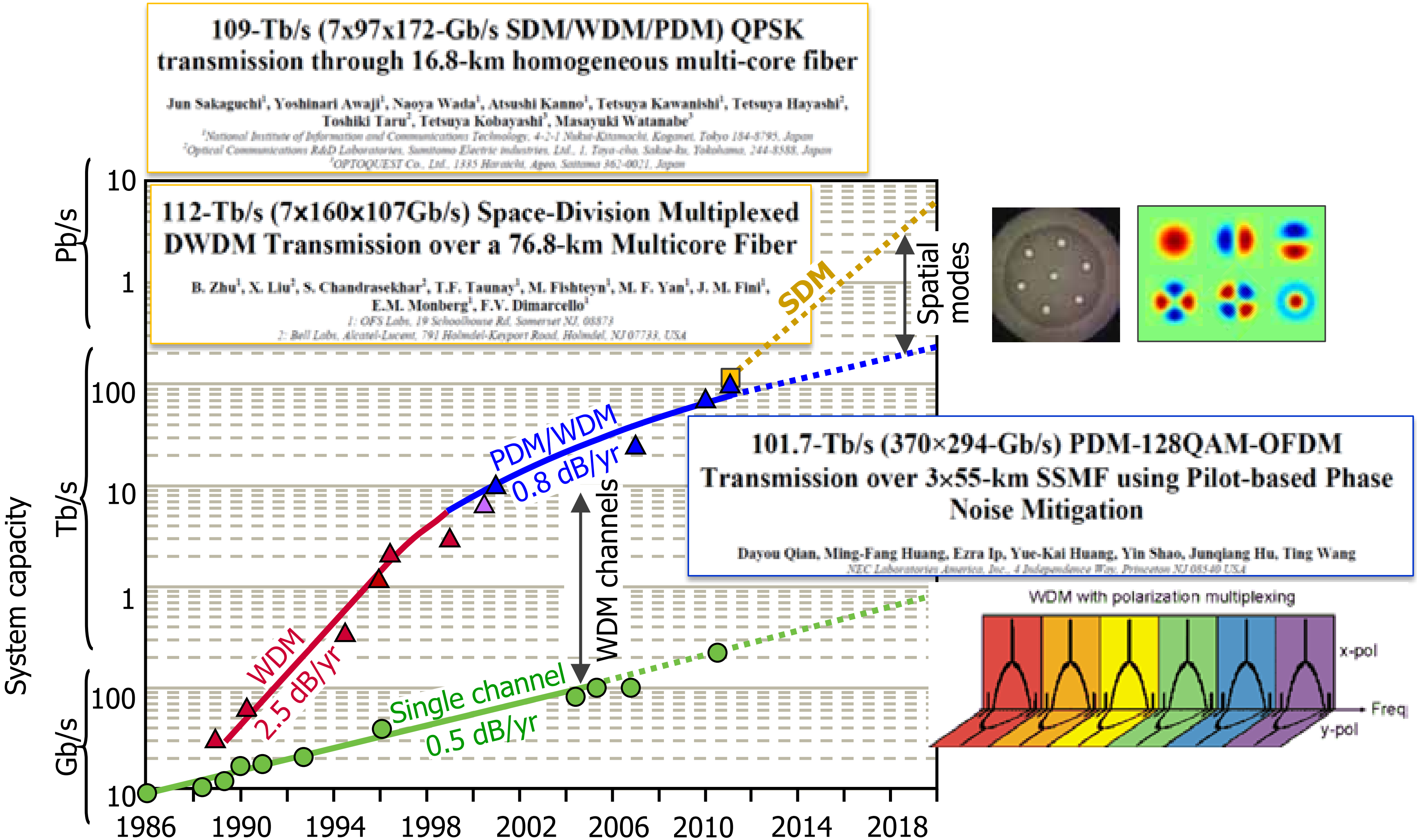
SPATIAL MULTIPLEXING SETS FIRST CAPACITY RECORD



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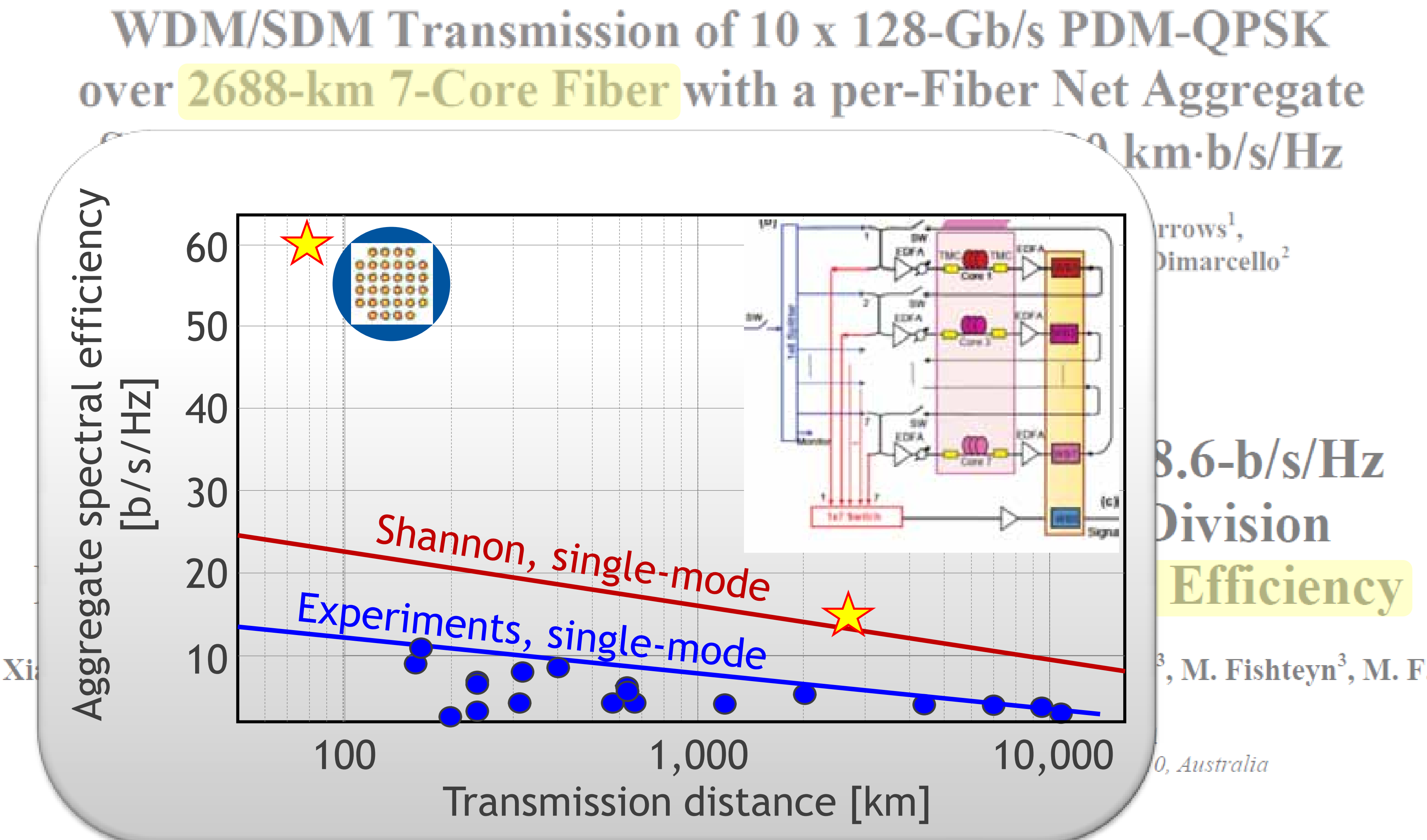
LONG DISTANCES AND HIGH SPECTRAL EFFICIENCIES



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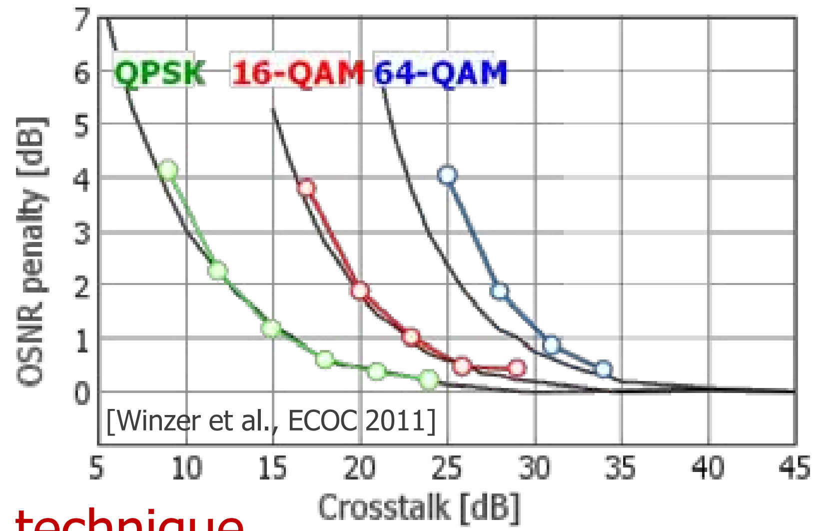
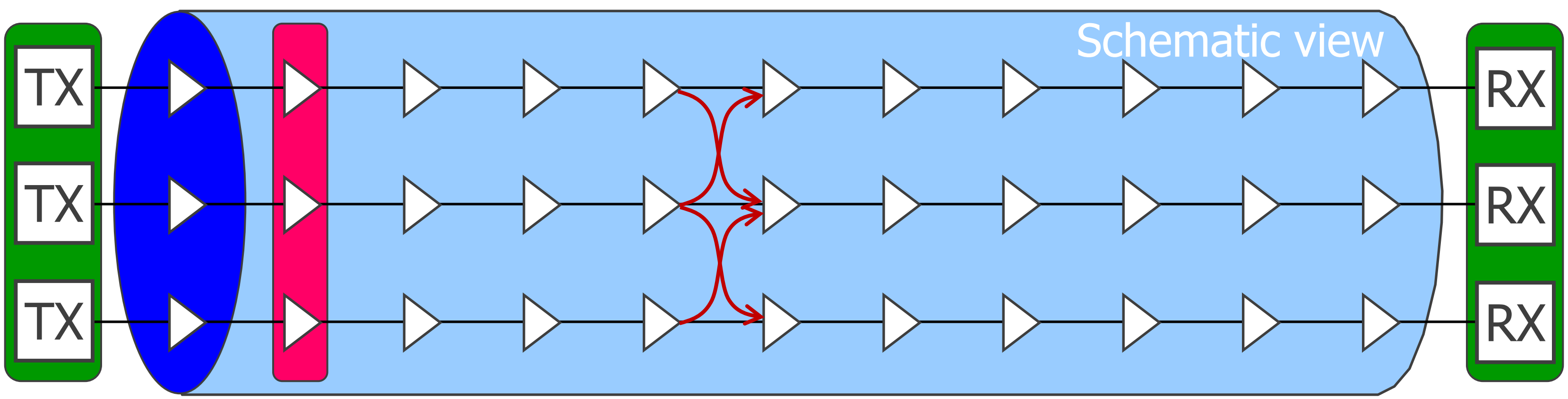
ULTIMATELY, INTEGRATION WILL LEAD TO CROSSTALK

How much *crosstalk* is tolerable?



Multiple-input multiple-output (MIMO) is a very successfully crosstalk cancellation technique...

(*Caveat:* MIMO in optical has different boundary conditions from wireless)



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

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6 SPATIAL MULTIPLEXING USING MIMO

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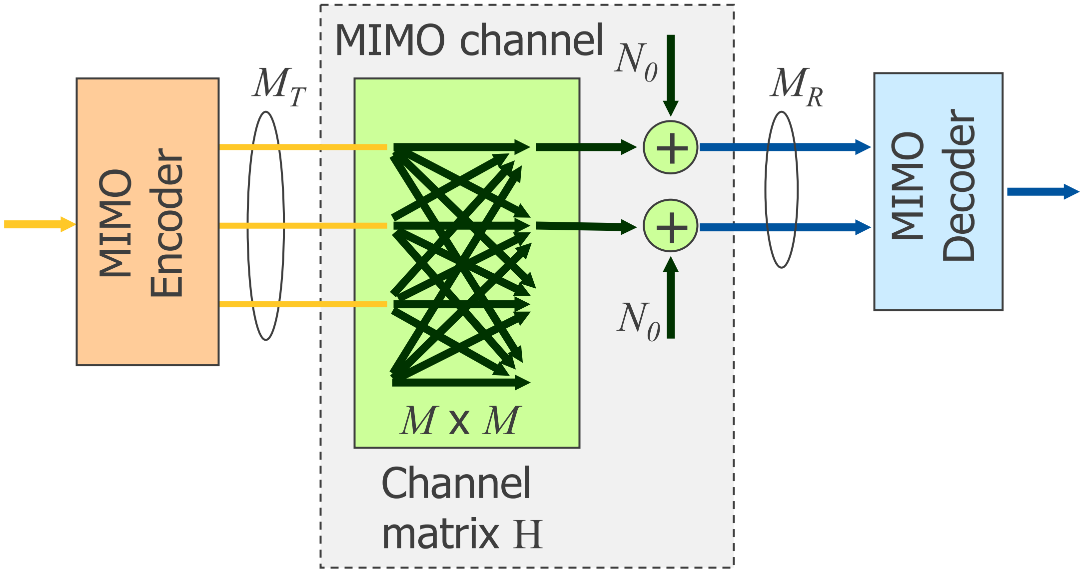
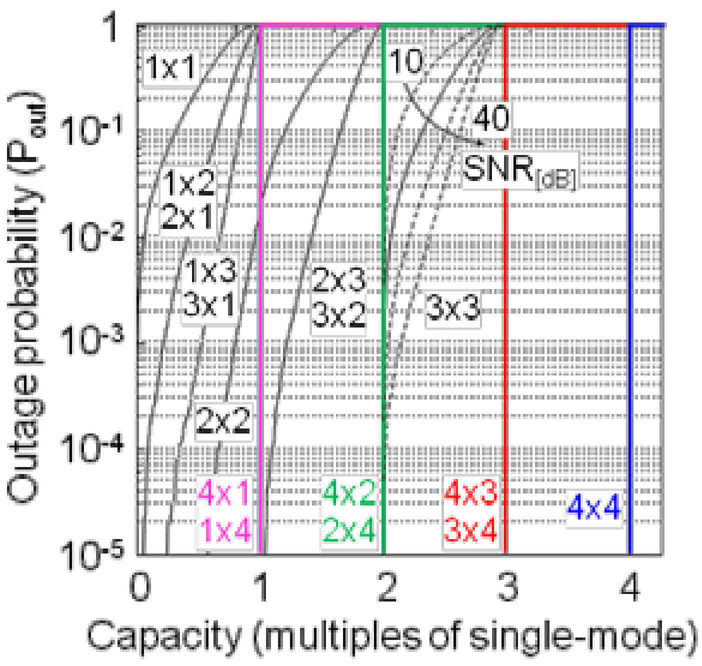
MIMO-SDM IN FIBER – DIFFERENCES TO WIRELESS

- Potential addressability of *all* propagation modes (*complete set*)
- "Perturbed unitary" channel (mode-dependent loss)
- Fiber nonlinearity (likely to set per-mode peak-power constraints)
- High reliability requirements (99.999%), low outage probabilities (10^{-5})
- Distributed noise
- RX → TX feedback almost always impossible
- Nonlinear MIMO signal processing ?





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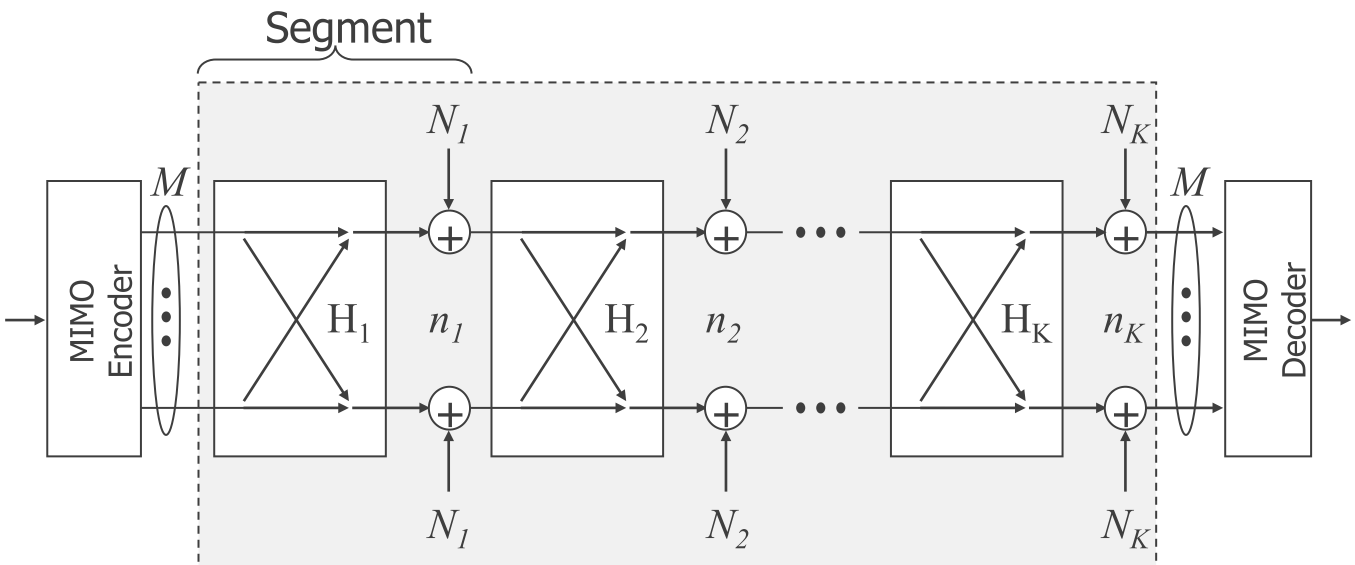
DISTRIBUTED NOISE LOADING

In optics, noise loading is usually distributed over propagation (e.g., on a "per-span" or "per-segment" basis)



Spatial noise correlation

$$R_{\boldsymbol{n}} = \langle \boldsymbol{n}\boldsymbol{n}^{\dagger} \rangle = \left(N_1 H_K \cdots H_3 H_2 H_2^{\dagger} H_3^{\dagger} \cdots H_K^{\dagger} + N_2 H_K \cdots H_3 H_3^{\dagger} \cdots H_K^{\dagger} + \cdots + N_{K-1} H_K H_K^{\dagger} + N_K I_M \right)$$

If segment matrices are unitary: $R_{\boldsymbol{n}} = \sum_{i=1}^{K} N_i I_M = N_0 I_M$

[Winzer and Foschini, Optics Express, 2011]

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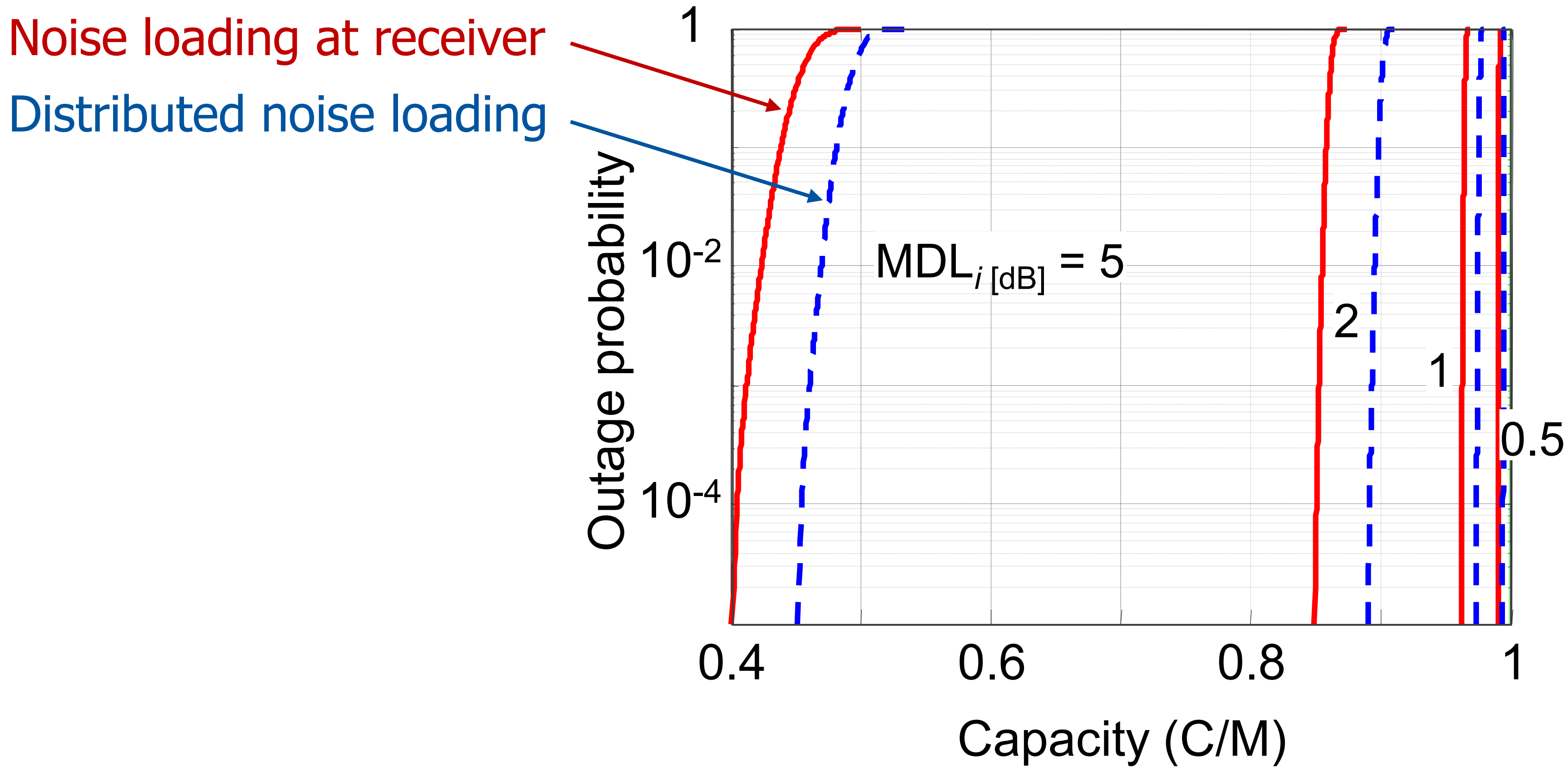
MODE-DEPENDENT LOSS

Outage probabilities for M = 16 modes, K = 64 segments

Mode-dependent loss MDL_i per segment



Noise loading at receiver is worse than distributed noise loading

A per-segment MDL of 1 dB only reduces capacity by <5%

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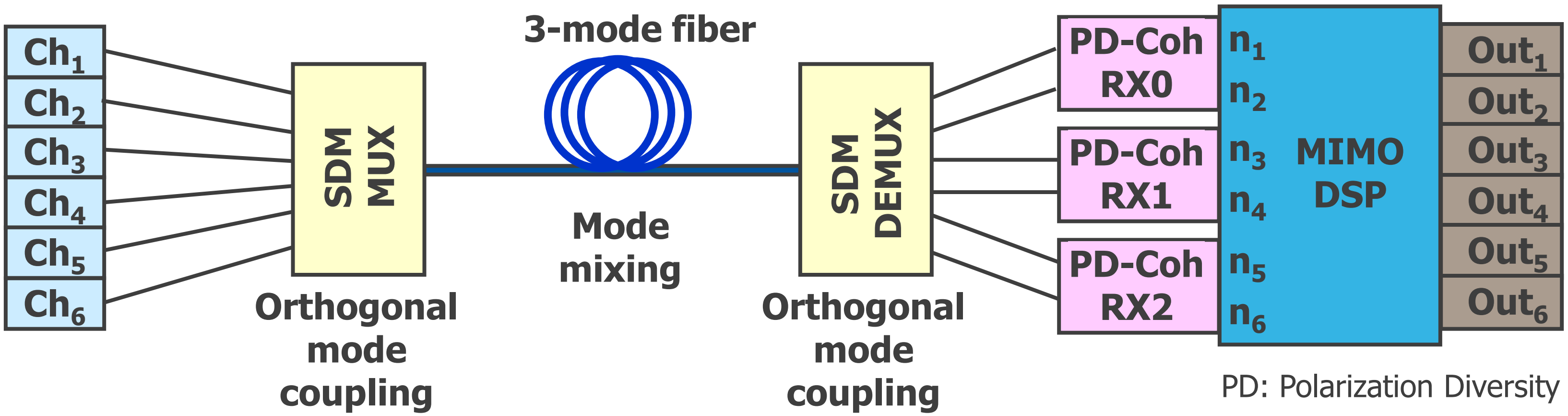
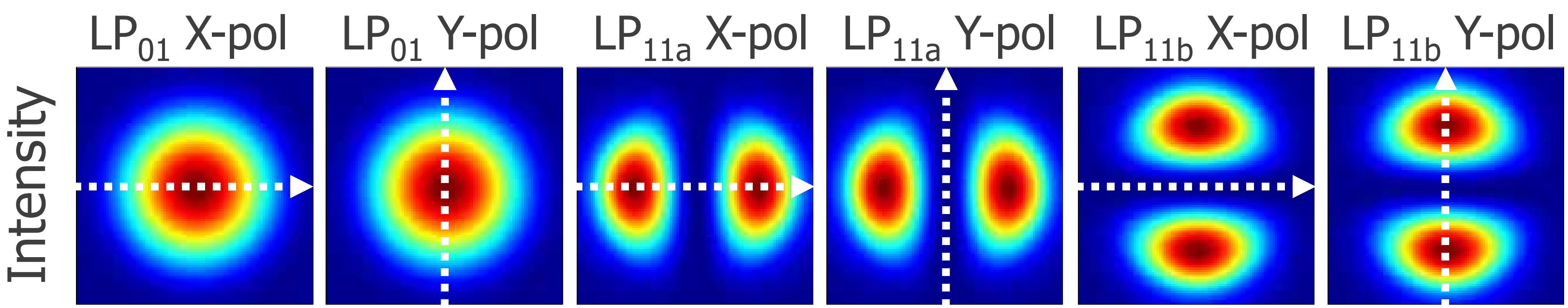
THE FIRST 6x6 OPTICAL MIMO EXPERIMENT





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

[R. Ryf et al., OFC 2011; S. Randel et al., Optics Express 2011]

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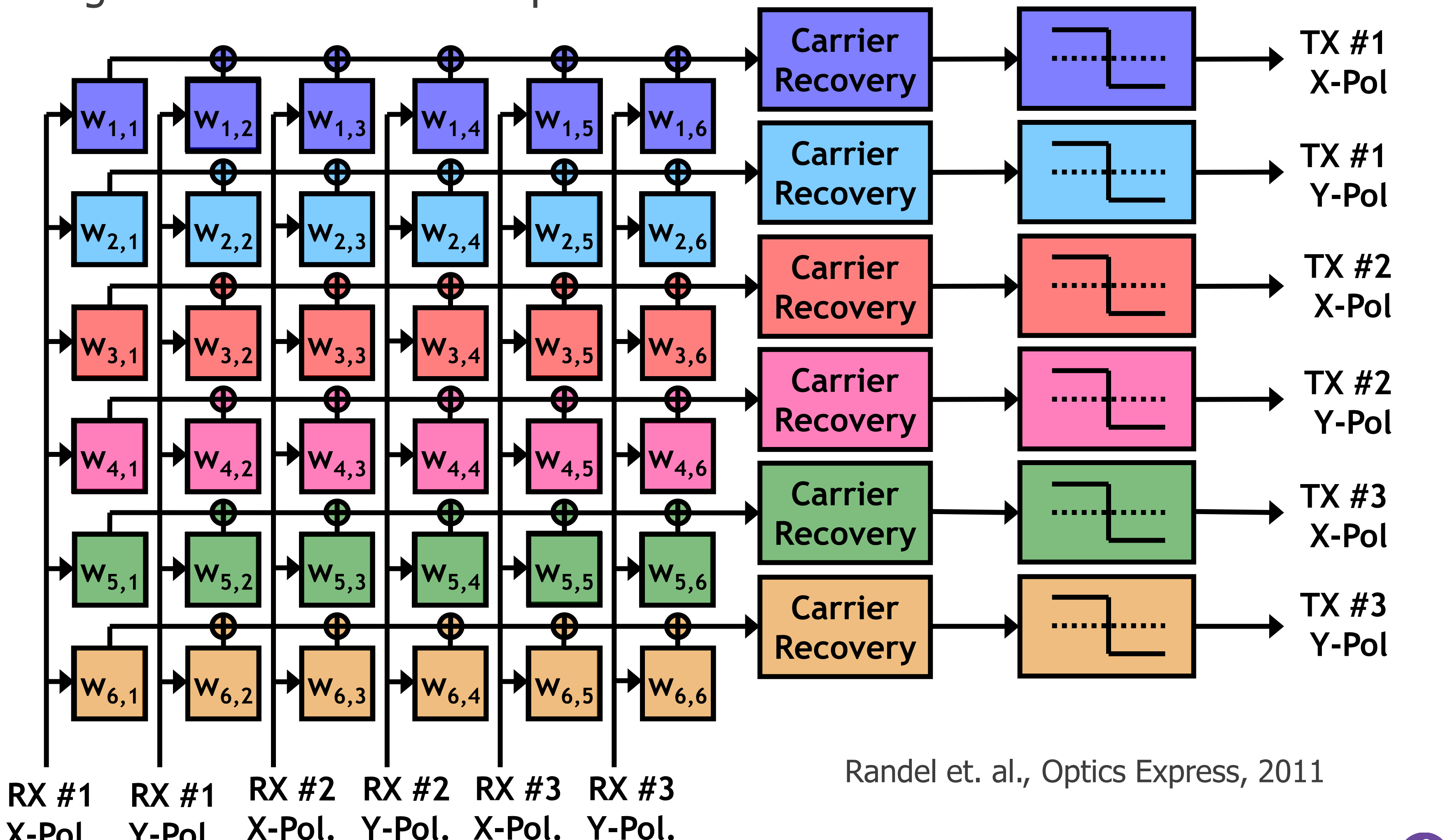
6 6 ADAPTIVE MIMO EQUALIZER STRUCTURE

- Crosstalk between 3 cores with 2 polarizations each can be compensated using a linear 6 6 MIMO equalizer



Randel et. al., Optics Express, 2011

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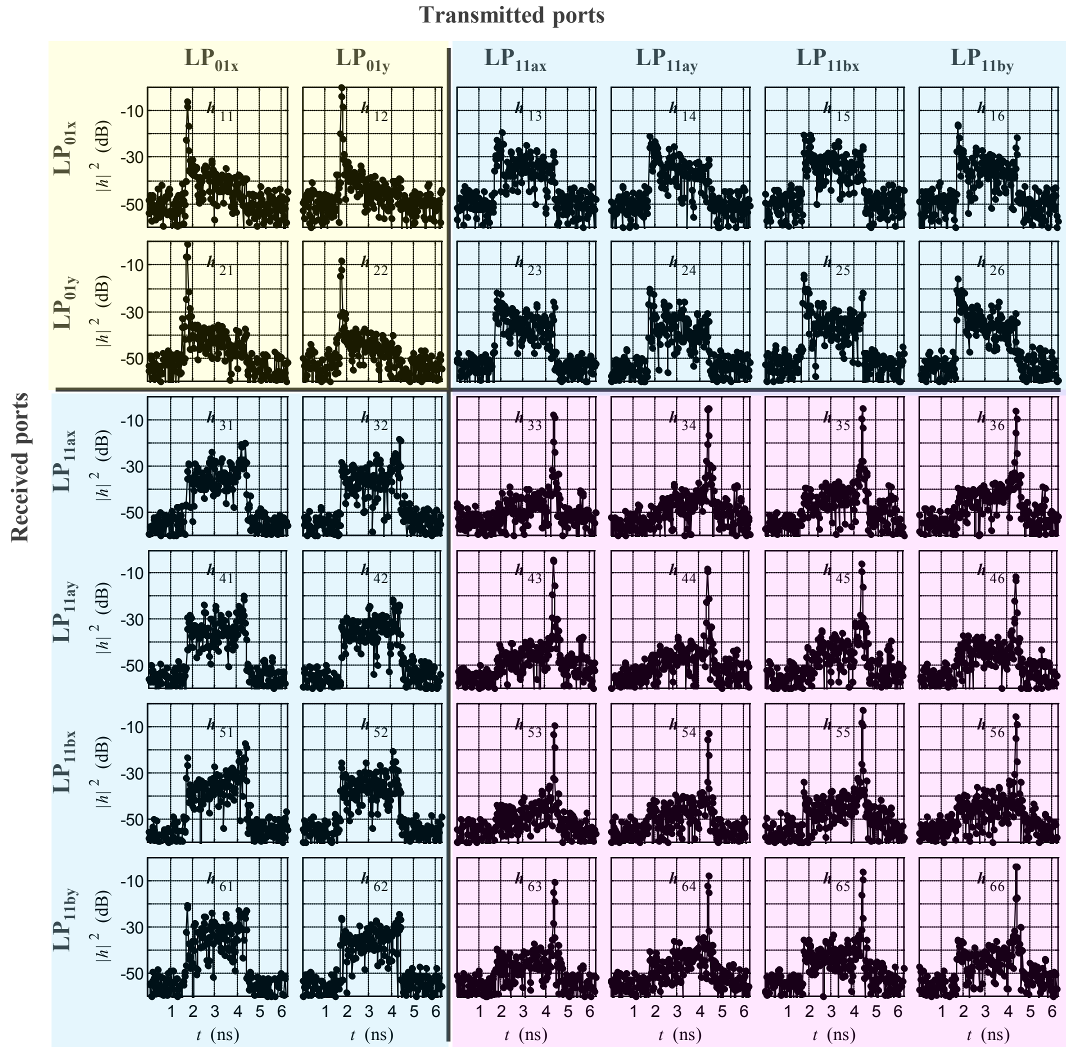
IMPULSE RESPONSE MATRIX
FOR 96-km 6-MODE FEW-MODE FIBER

- The impulse response was characterized for all 6 outputs as function of all 6 inputs
- Strong coupling is observed within the LP_{01} and the LP_{11} mode
- Weaker coupling is observed between the LP_{01} and LP_{11} mode



Ryf et. al., J. Lightwave Technol., 2012

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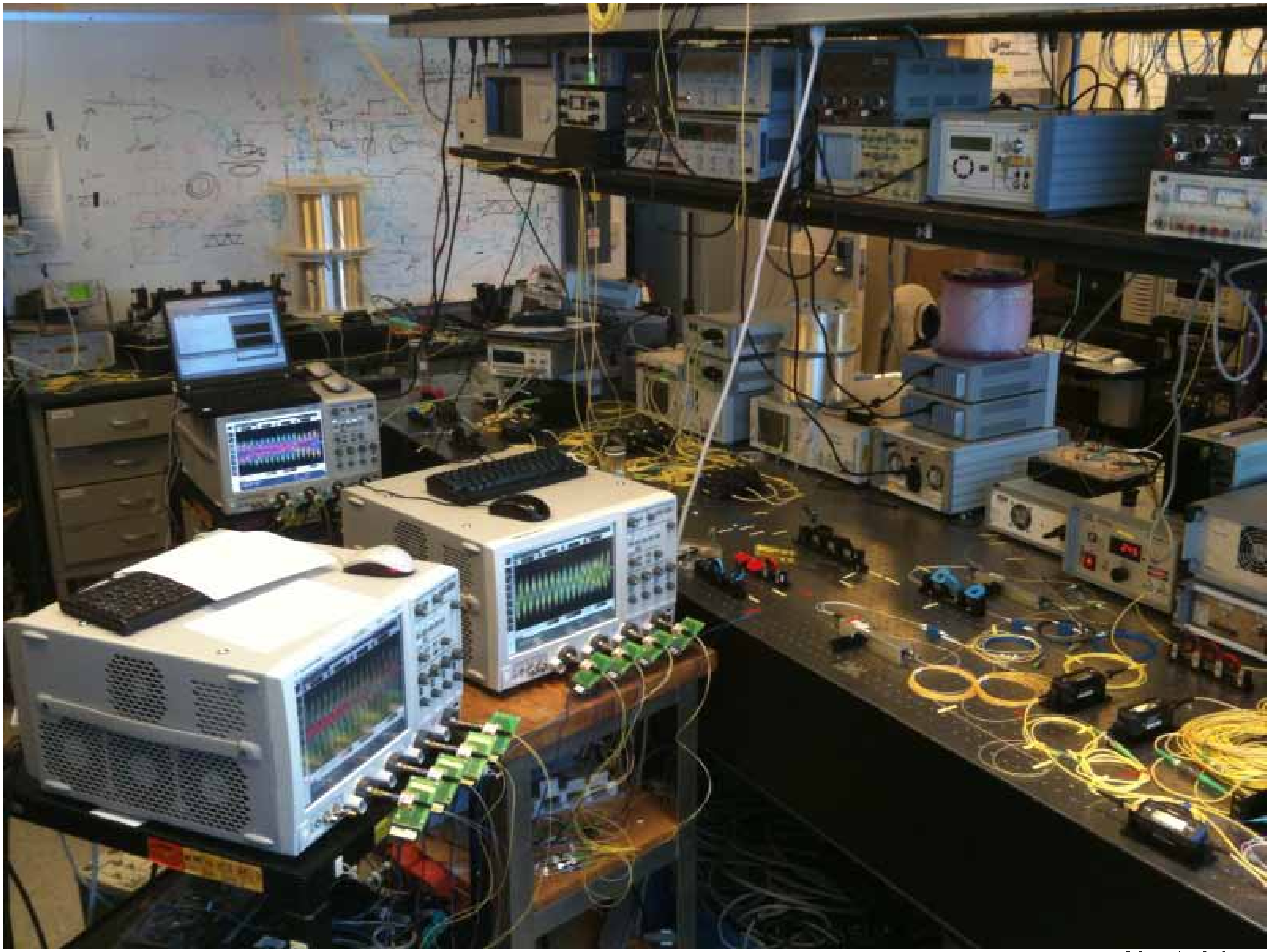
A GLIMPSE INTO AN OPTICAL MIMO-SDM LAB



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SOME FURTHER READING

Single-mode fiber capacity limit

- R.-J. Essiambre et al., "Capacity Limits of Optical Fiber Networks," J. Lightwave Technol. **28**, 662 (2010).

MIMO-SDM capacity scaling

- P. J. Winzer and G. J. Foschini, "MIMO Capacities and Outage Probabilities in Spatially Multiplexed Optical Transport Systems," Optics Express (2011).
- P. J. Winzer "Energy-efficient optical transport capacity scaling through spatial multiplexing," Photon. Technol. Lett. **23**, 851 (2011).

First MIMO-SDM experiments

- R. Ryf et al., "Mode-division multiplexing over 96 km of few-mode fiber using coherent 6x6 MIMO processing," J. Lightwave Technol. **30**, 521 (2012).
- S. Randel et al., "6 x 56-Gb/s Mode-Division Multiplexed Transmission over 33-km Few-Mode Fiber Enabled by 66 MIMO Equalization," Optics Express (2011).

Overview on globally ongoing optical MIMO efforts

- G. Li, X. Liu, "Focus Issue: Space Multiplexed Optical Transmission," Opt. Ex. **19** 16574 (2011).
- T. Morioka et al. "Enhancing optical communications with brand new fibers," IEEE Comm. Mag. **50**, s31 (2012).
- P. J. Winzer, "Optical Networking Beyond WDM," IEEE Photon. J. (2012).

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