Long-distance transmission over space-division multiplexing fibers

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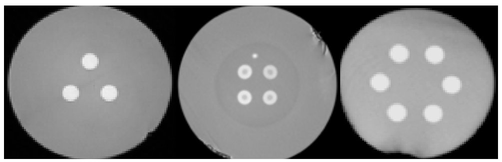
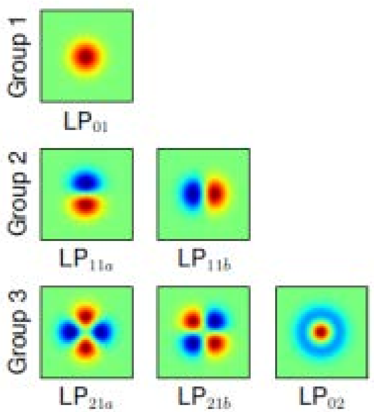
Multiplexing domains in optical fibers:
Wavelength, Polarization, and modes/cores

Cores

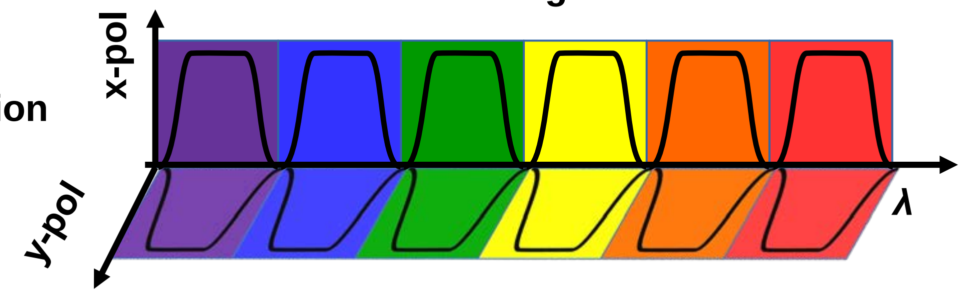


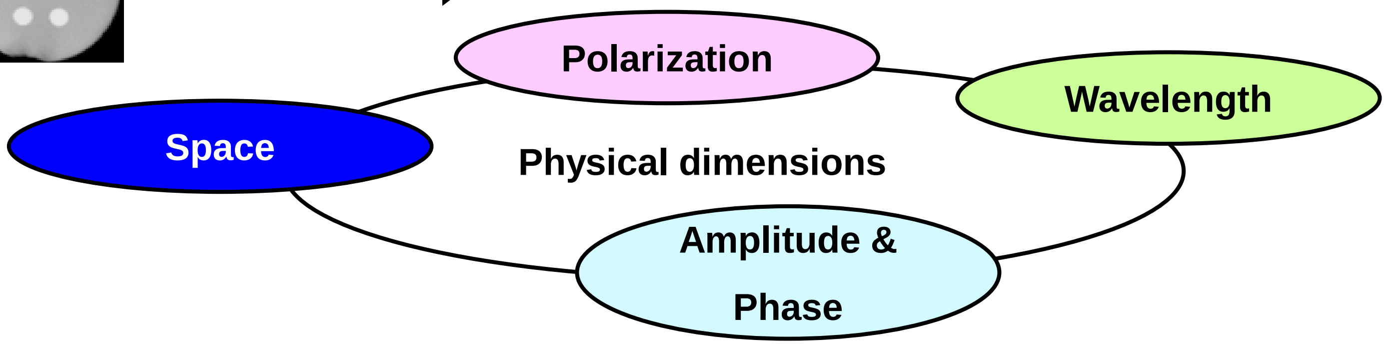
Modes

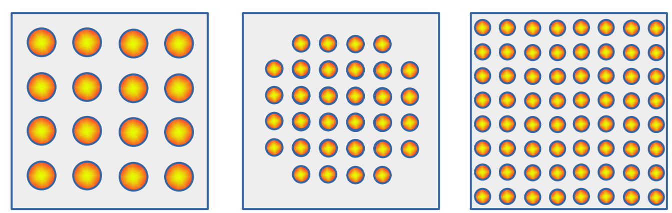


Polarization

Wavelength

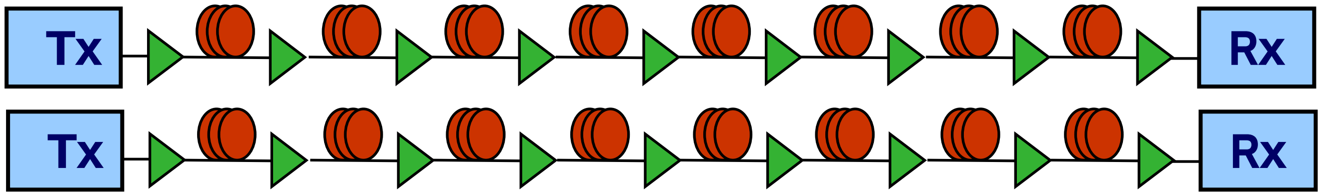


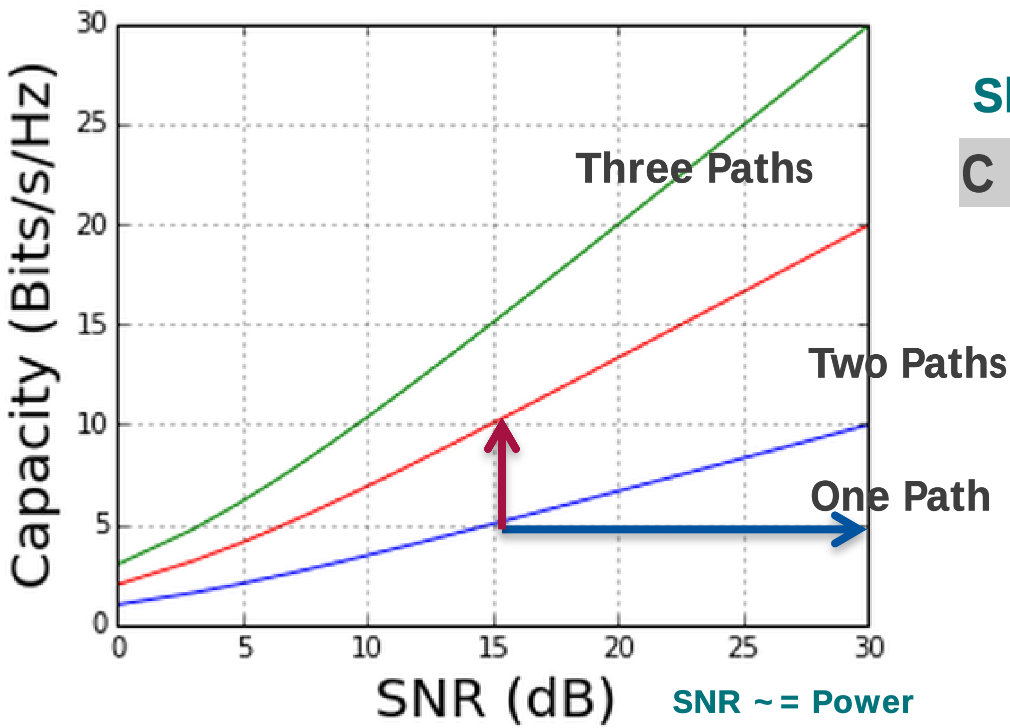




16QAM 32QAM 64QAM

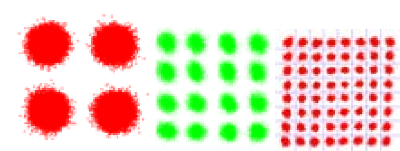
Scale capacity with parallel spatial paths





Shannon's Formula:

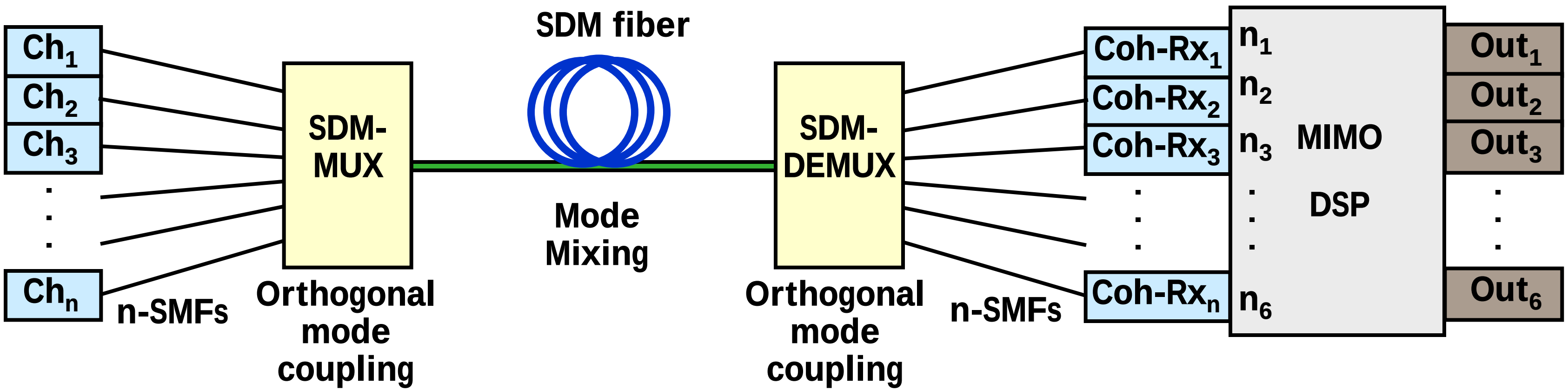
$$C = B \log_2 (1 + SNR)$$



Single Path: Double capacity requires exponential increase in power

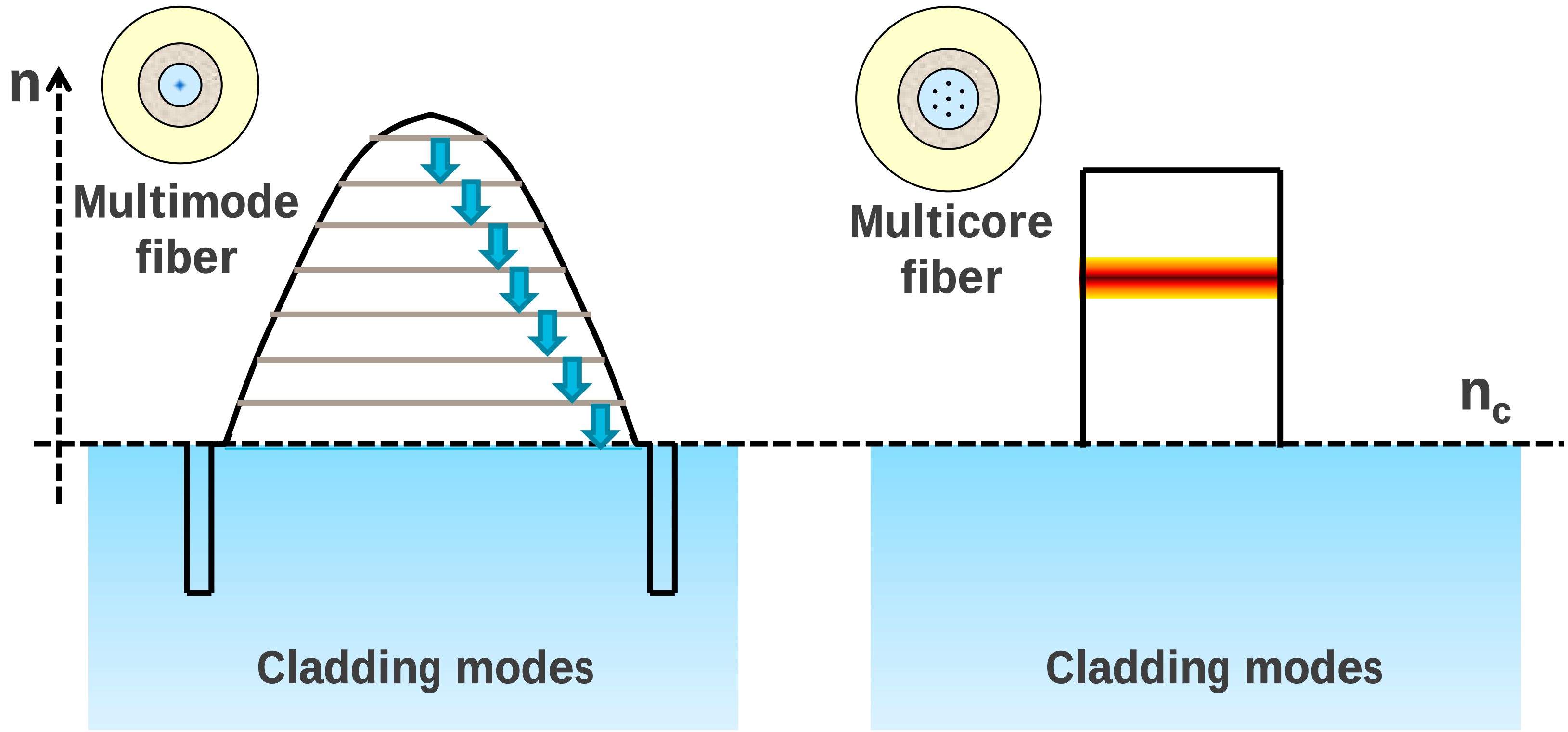
Two Paths: Double capacity requires twice the power

SDM multiple-input multiple-output transmission with coupled channels



- **All *n* guided modes** of the fiber are **selectively launched**
- Modes are strongly coupled during propagation in the fiber
- **All *n* guided modes** are simultaneously **detected with coherent receivers**
- Digital signal processing (DSP) decouples the received signals to recover the transmitted signal (*n* x *n* MIMO)
- This is a generalization of the scheme used for coherent DSP based polarization multiplexed transmission (2 x 2 MIMO)

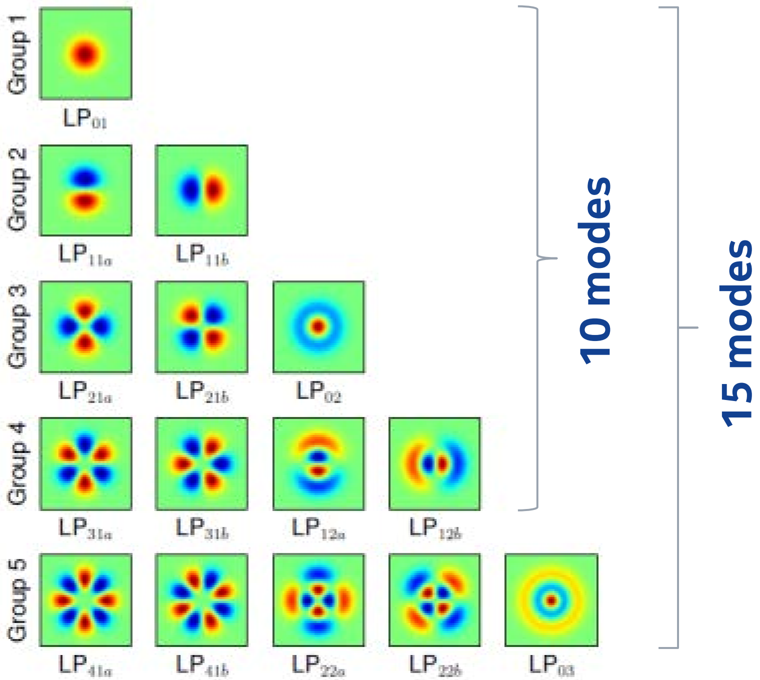
Modes in multimode and coupled-core fibers

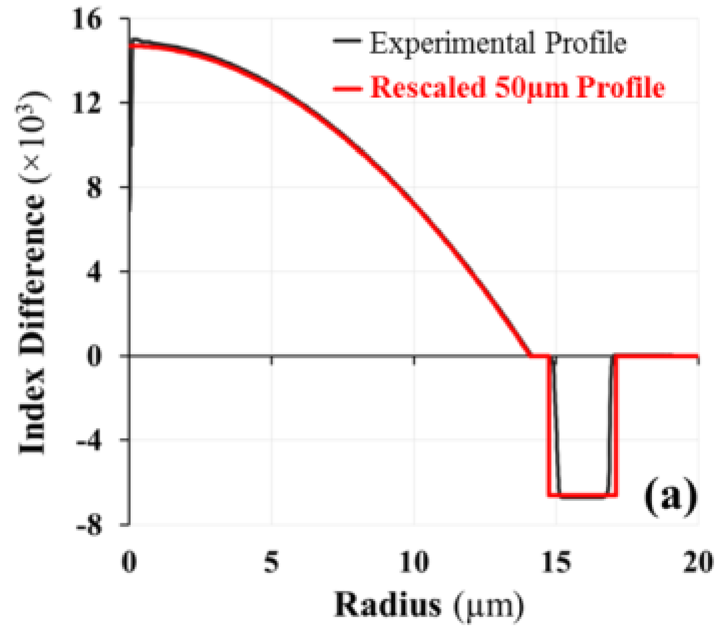


- Graded-index profile required to minimize DGD
- Δn_{eff} similar between mode pairs
- Low DGD enables nonlinear inter-modal effects

- All modes almost degenerate
- Core spacing defines:
  a) Δn_{eff} Splitting between super modes
  b) Amount of coupling between cores
- Strong coupling between cores reduces inter-modal nonlinear effects

Low differential group delay graded-index fibers





P. Sillard, et.al. OFC2015, M2C.2

10 modes (6-LP modes): DGD <120 ps/km, Loss 0.22 dB/km, MDL < 0.02 dB/km,

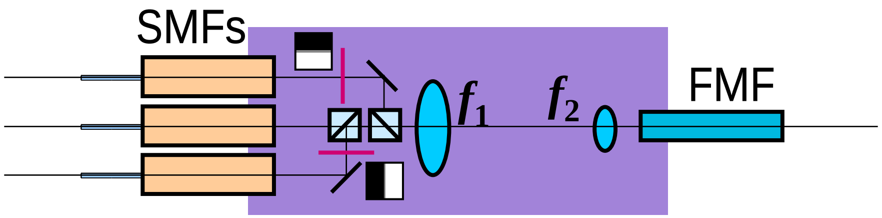
CD 19 and 21 ps/nm/km, Aeff 117 to 270 µm^2

15 modes (9-LP modes): DGD <220 ps/km, Loss 0.22 dB/km, MDL < 0.02 dB/km,

CD 19 and 21 ps/nm/km, Aeff 95 to 215 µm^2

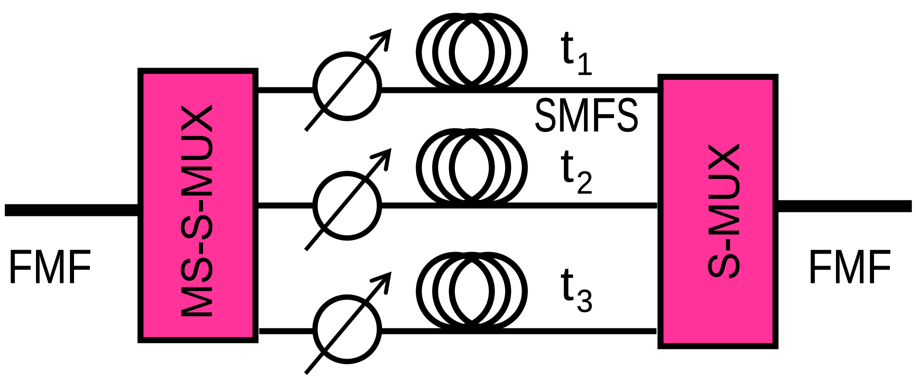
New SDM components

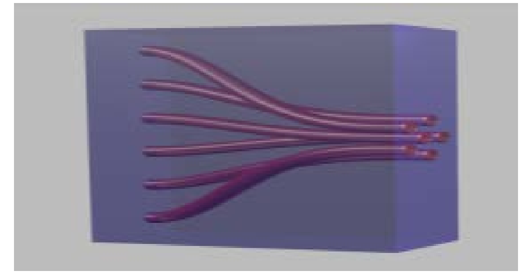
- “Mode” Couplers



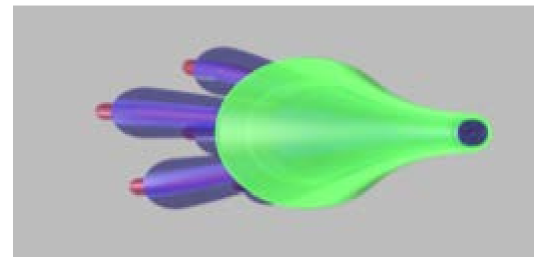
Phase-plate MUX

- MDL and DGD compensators

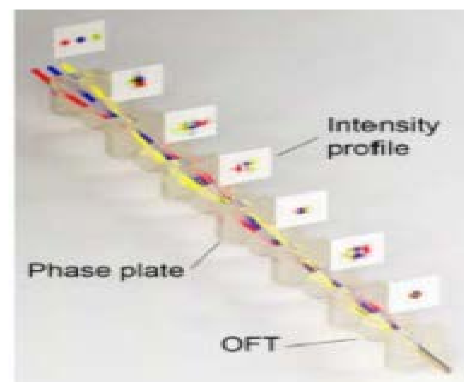




3D-waveguide MUX



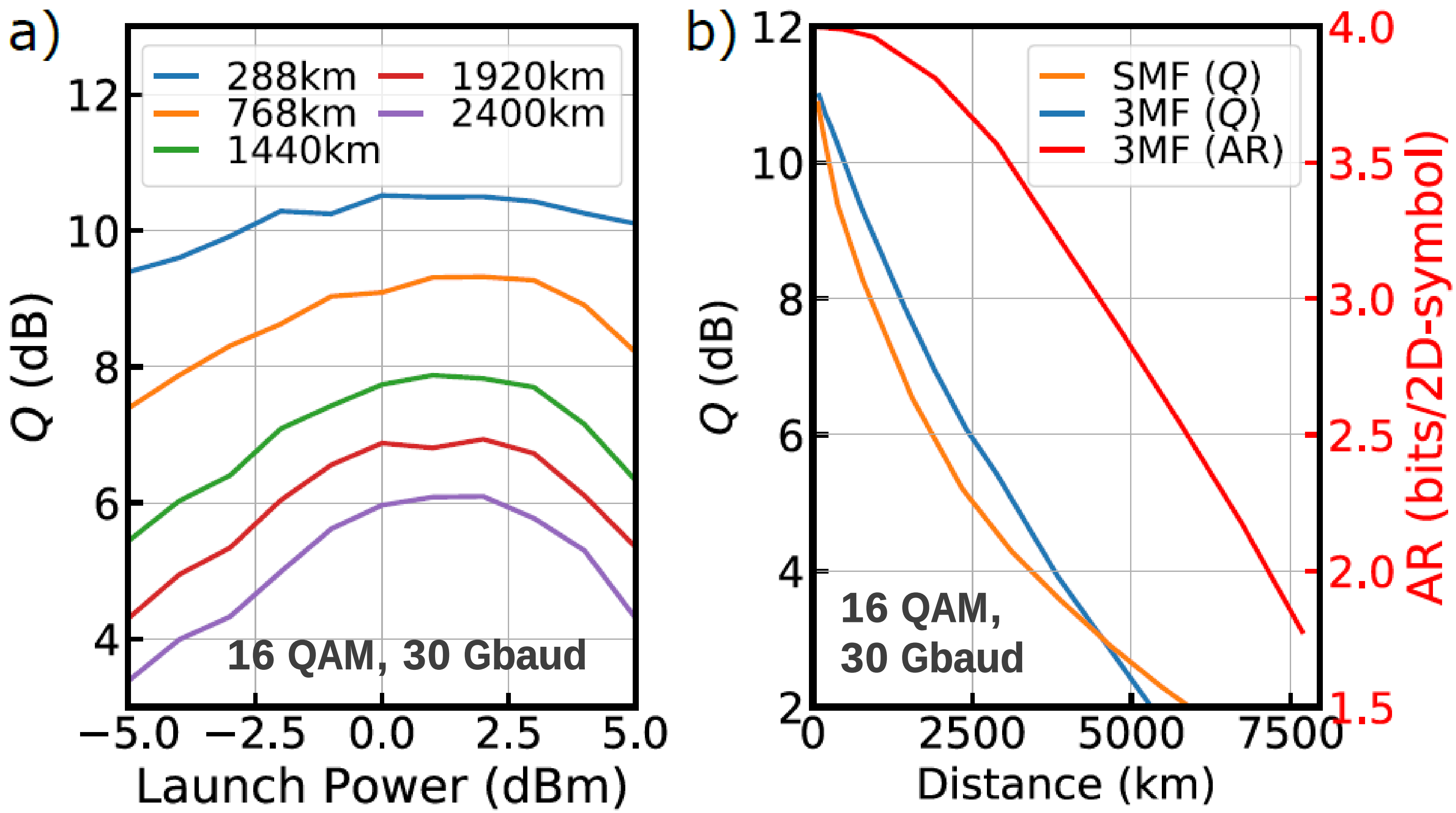
Photonic Lantern MUX



Multi-Plane MUX, see talk Su4J.3

3-Mode transmission experiment

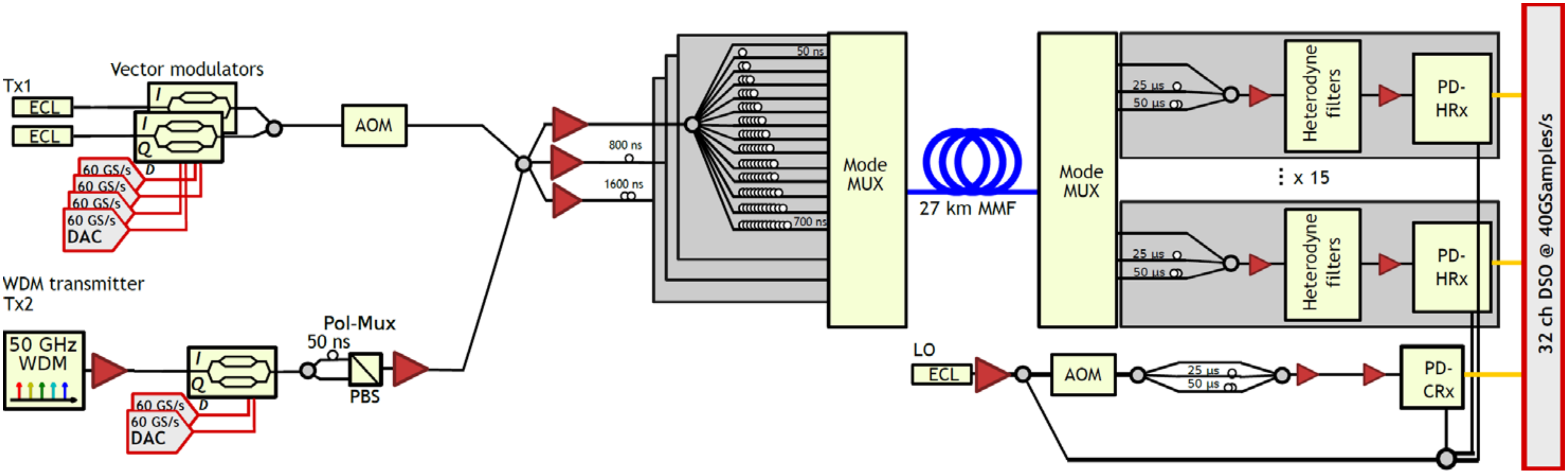
J. van Weerdenburg et al,. OFC2018).



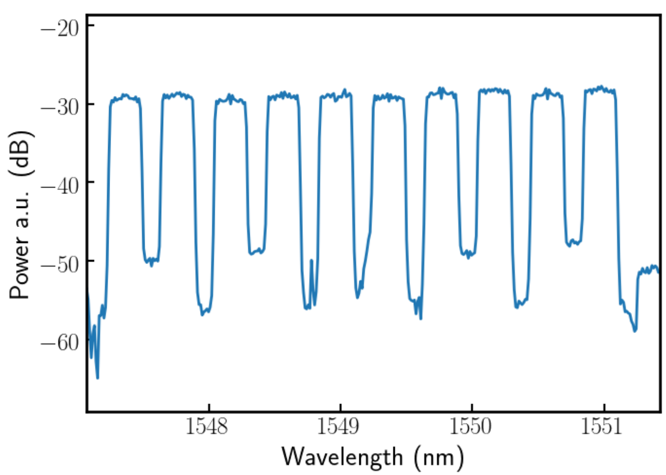
Large effective area 3-mode fiber outperforms standard single-mode fiber

NOKIA

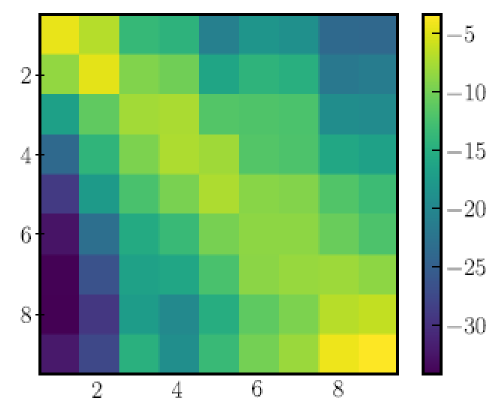
45-Mode transmission experiment



Spectrum



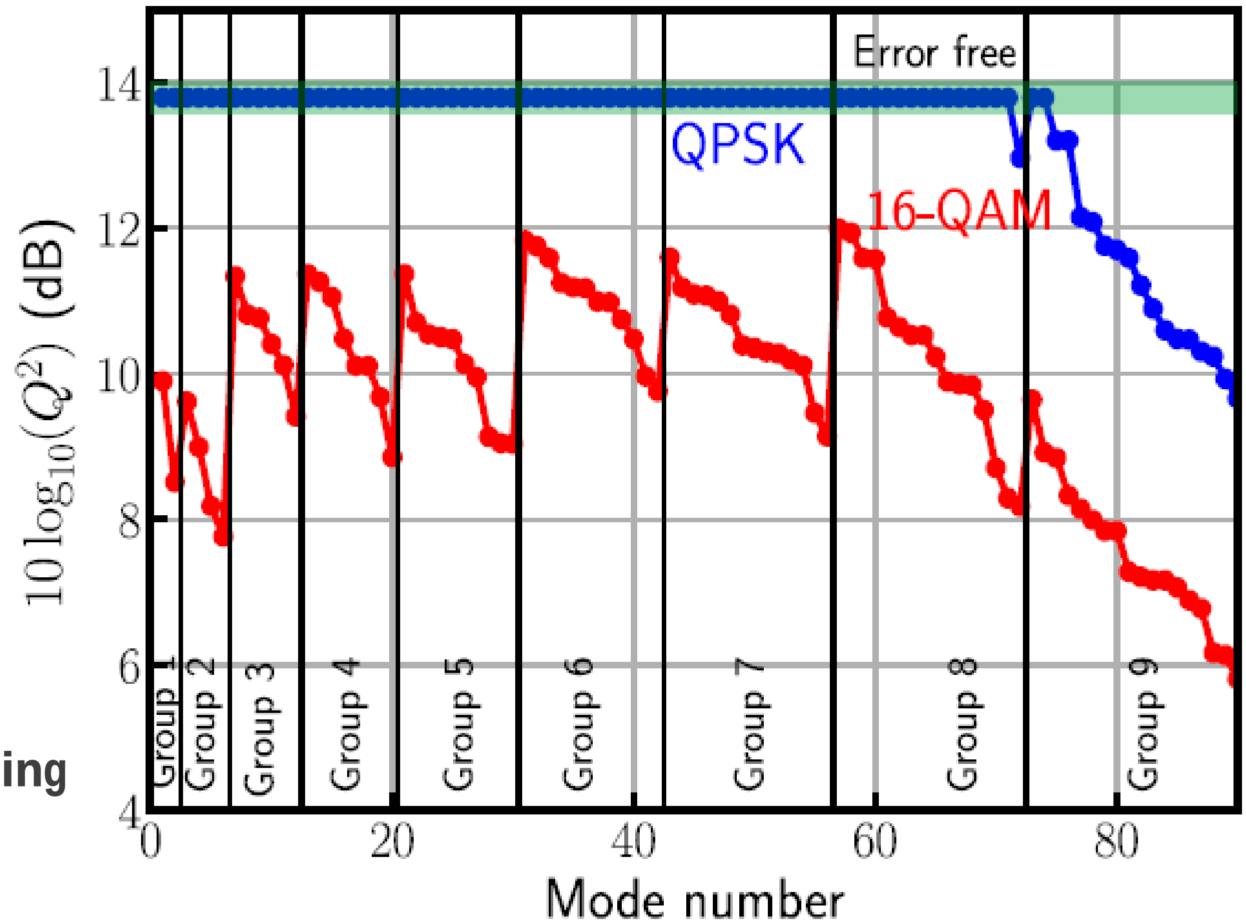
Intensity transfer matrix (from equalizer)



45-Mode transmission experiment

- **Measured at 1549.32 nm with all 2x10 WDM channels present**
- **Transmission signal is 15Gbaud QPSK and 16QAM**
- **all 90 spatial tributary have Q > 5.7 dB for 16QAM**
- **First 7 mode groups are “error free” for QPSK**
- **Spectral efficiency assuming FEC with 7% overhead is**

202 bit/Hz/s



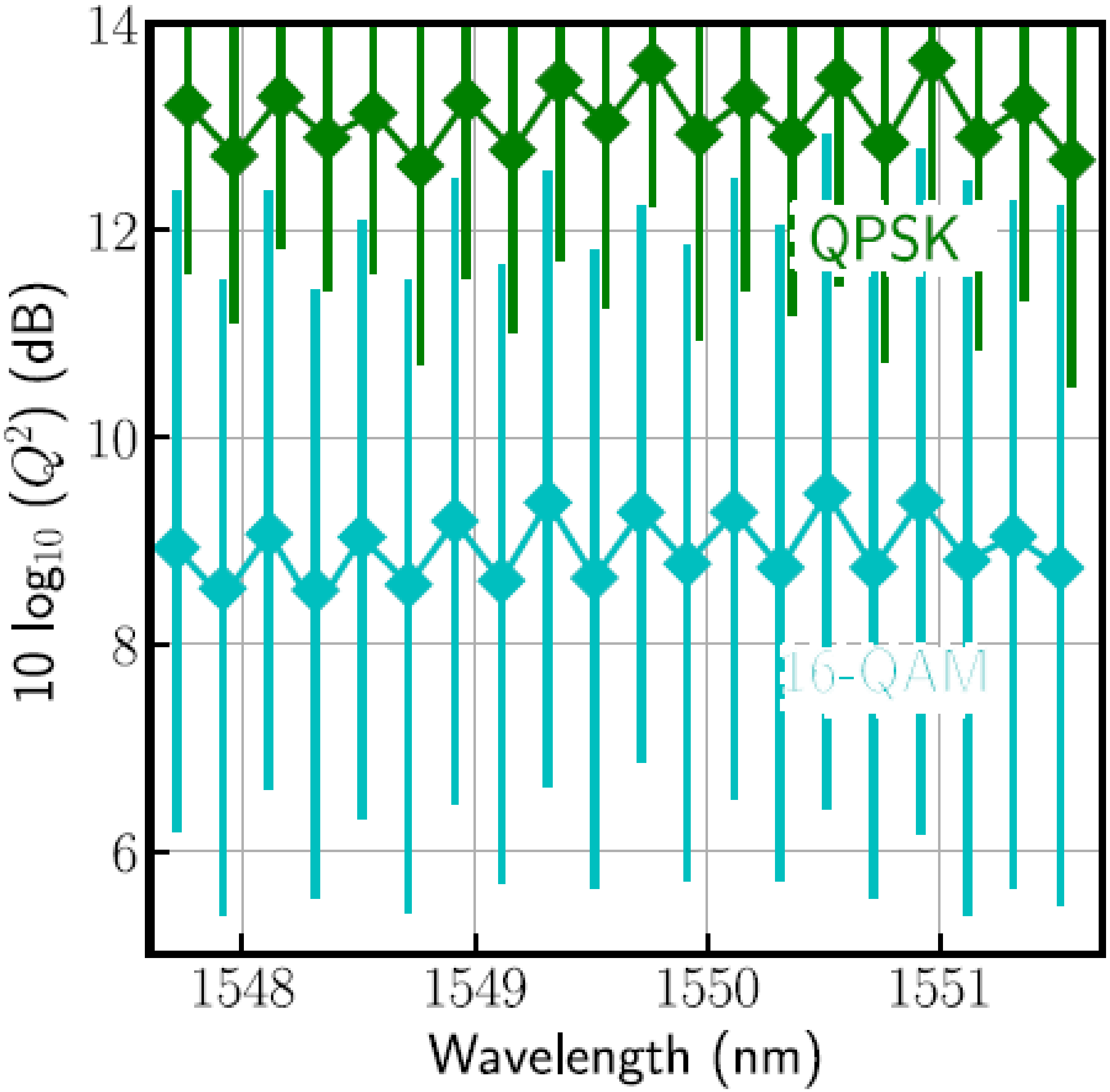
Ryf et.al., ECOC 2018 PD

45-Mode transmission WDM experiment

- **Transmission performance was measured over 500GHz bandwidth for both 15Gbaud QPSK and 16QAM**
- **All 20 WDM channels have an average Q > 8.5 dB**
- **Capacity assuming FEC with 7% overhead is**

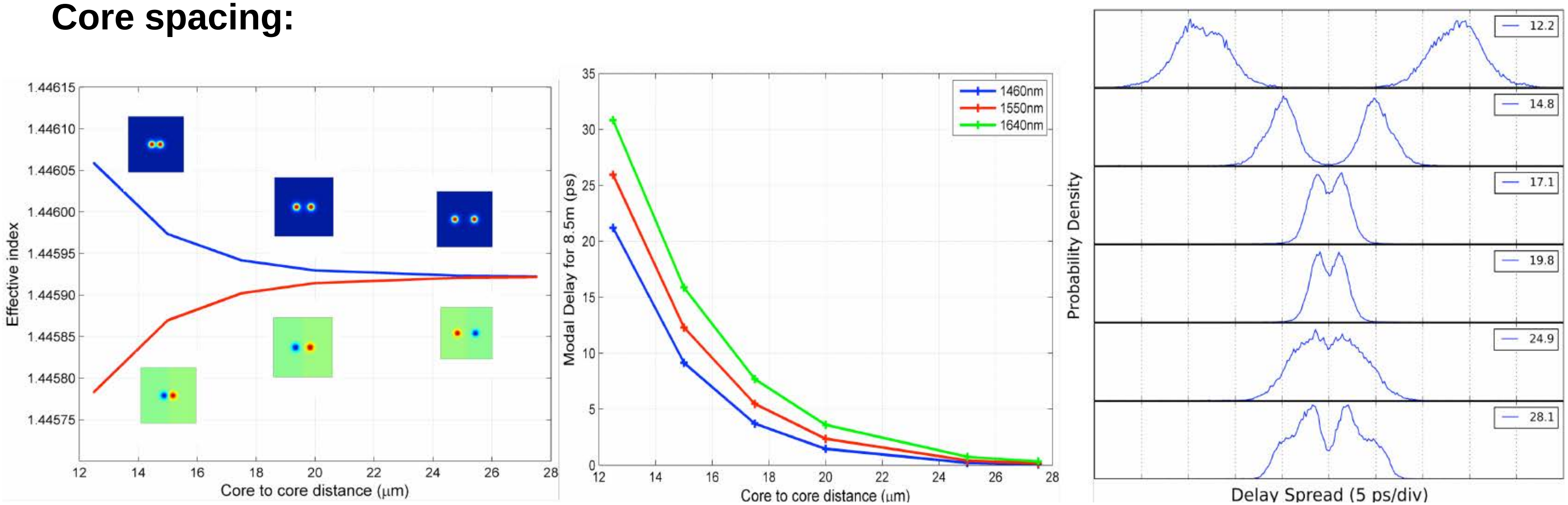
101 Tb/s

Ryf et.al., ECOC 2018 PD



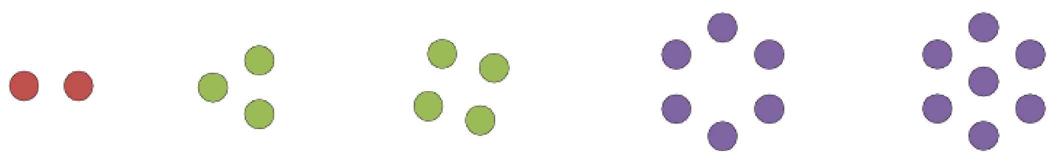
Coupled-Core Multicore Fiber: Optimum core spacing and geometry

Core spacing:



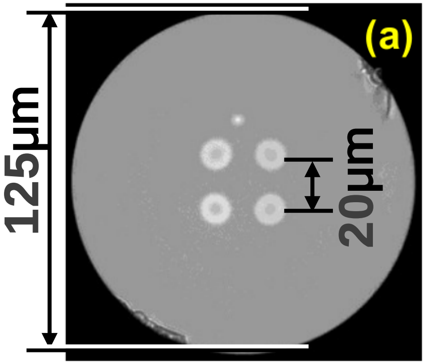
Huang, et.al., CLEO 2016, STu1F.3

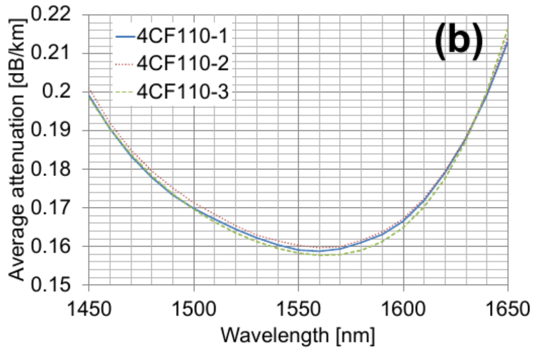
Geometry
:

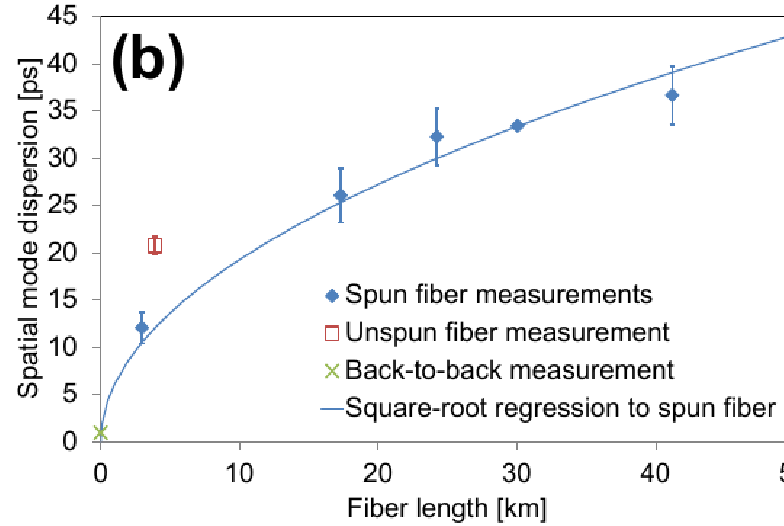


Hayashi, et.al., " Effects of Core Count/Layout and Twisting Condition on Spatial Mode Dispersion in Coupled Multi-Core Fibers", ECOC 2016

4-core coupled-core fiber







- **Aeff =112 µm^2**
- **Cutoff wavelengths: 1470 nm**
- **Loss: 0.158-0.161 dB/km at 1550 nm**
- **Spatial mode dispersion: 5.7-6.6 ps/√km between 1520 and 1580 nm**
- **Chromatic dispersions: 20.0-20.1 ps/(nm km)**
- **Dispersion slope: 0.060-0.063 ps/(nm2 km)**

Hayashi, et.al., OFC 2016, PD Th5A.1

Single mode fiber with nominal identical core:

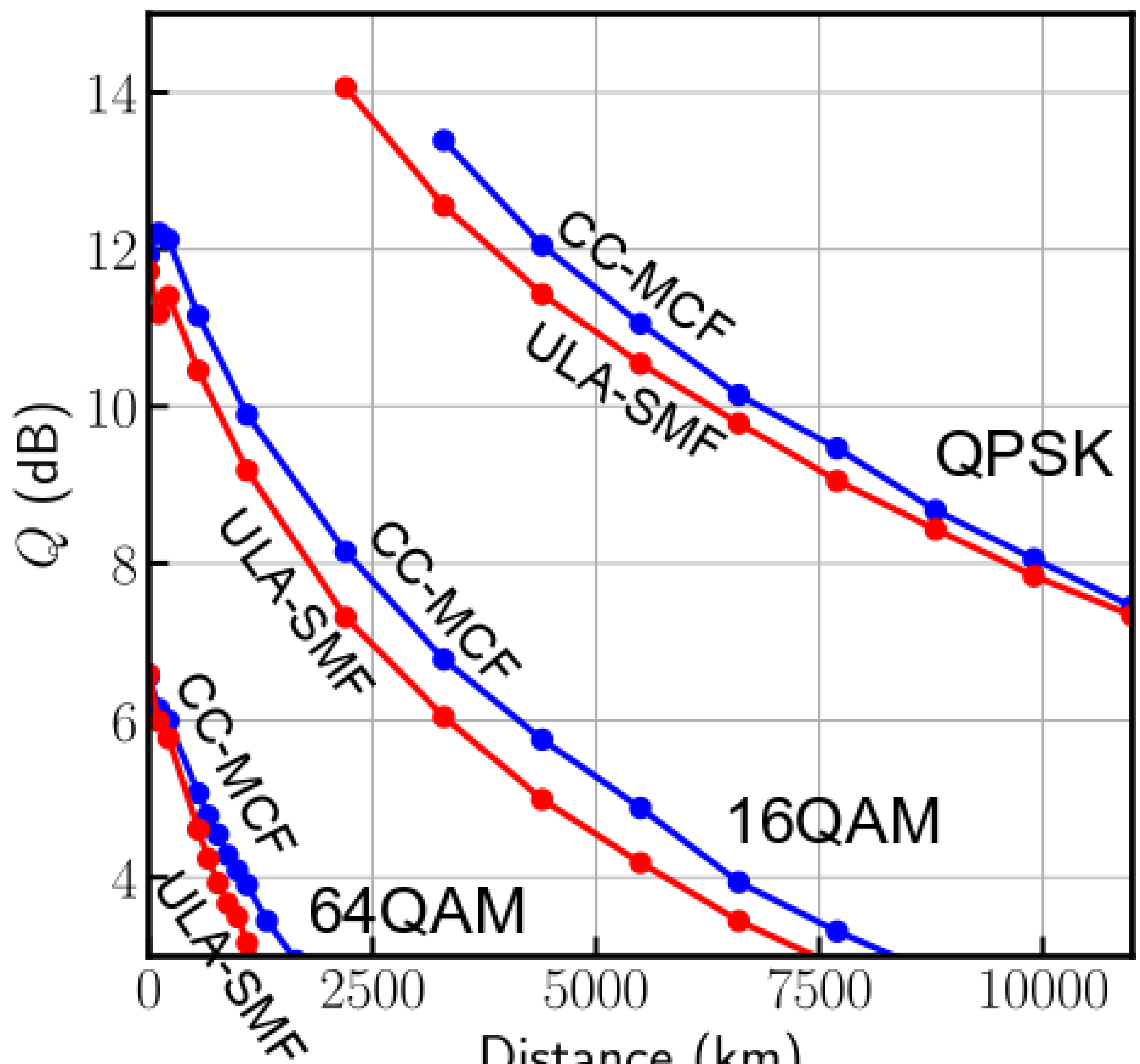
- **Aeff =112-116 µm^2**
- **Cutoff wavelengths: 1470 nm**
- **Loss: 0.160 dB/km at 1550 nm**
- **Ploarization mode dispersion: 0.039 ps/√km between 1520 and 1580 nm**
- **Chromatic dispersions: 20.4-20.6 ps/(nm km)**
- **Dispersion slope: 0.060 ps/(nm2 km)**

M. Hirano, et.al OFC 2013, PDP5A.7

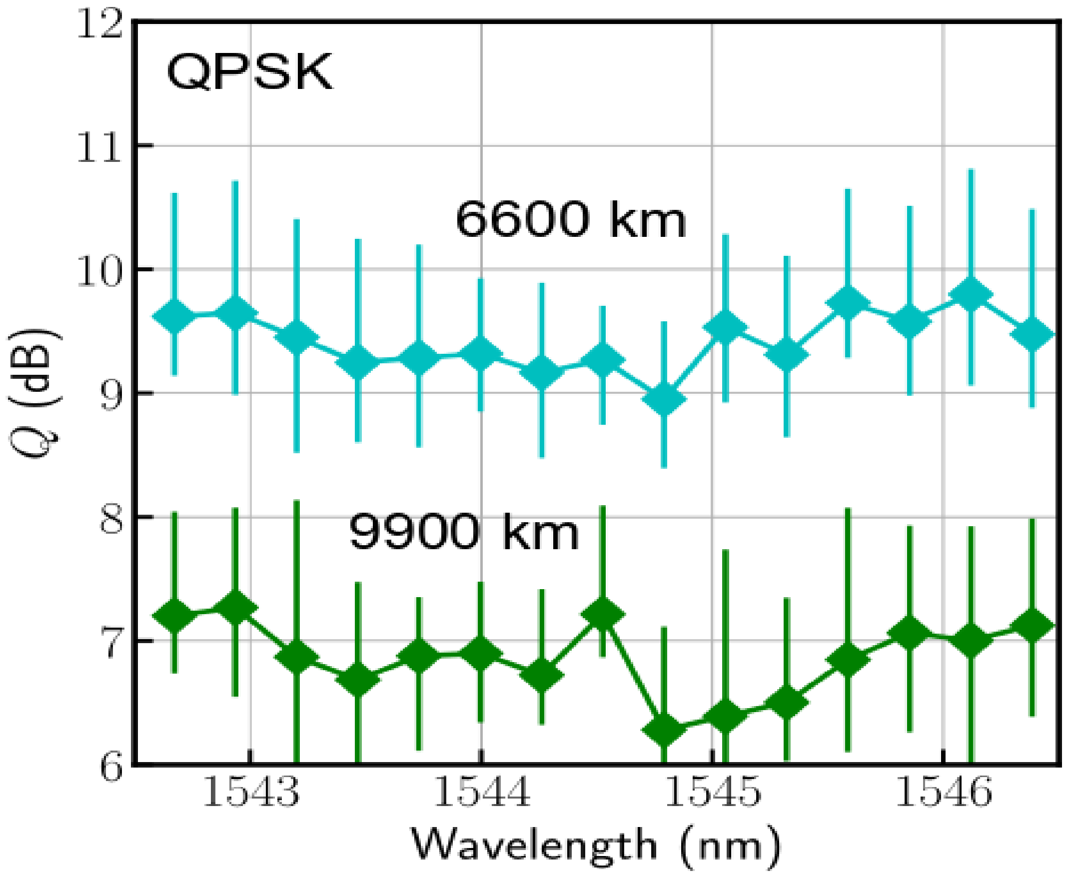
Comparison to SMF for different modulation formats

- **Measured at 1549.32 nm with all 15 WDM channel present**
- **Input power: -8 to -1 dB/ch**

- **4-core fiber has consistently better performance than SMF**
- **Improvement is as large as 0.8 dB**



4 core fiber: WDM results



Ryf, et.al., ECOC 2017

Transmission distances up to 9900 km can be achieved with 15 WDM channels with 20% FEC overhead resulting in a spectral efficiency of 11.53 bit/s/Hz, and a spectral efficiency of distance product of 114'150 bit/s/Hz km

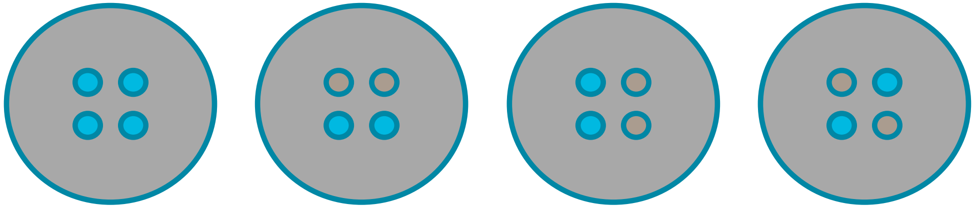
Nonlinear performance of coupled-core fiber

The coupled-core multicore fiber has the potential to outperform the performance of an equivalent single mode fiber while providing N times the capacity

[1] S. Mumtaz, et.al., “Reduction of nonlinear impairments in coupled-core multicore…”, IEEE Summer Topical 2012

[2] C. Antonelli, et.al., “Scaling of inter-channel nonlinear interference noise and capacity…”, OFC 2016, W4I.2

Supermodes:



Qualitative reason:

1) Strong coupling spreads the signal across N cores and the signals are effectively transmitted over the supermodes, which have N times the effective area

2) Intermodal nonlinearity between the supermodes are reduced by the continuous strong coupling

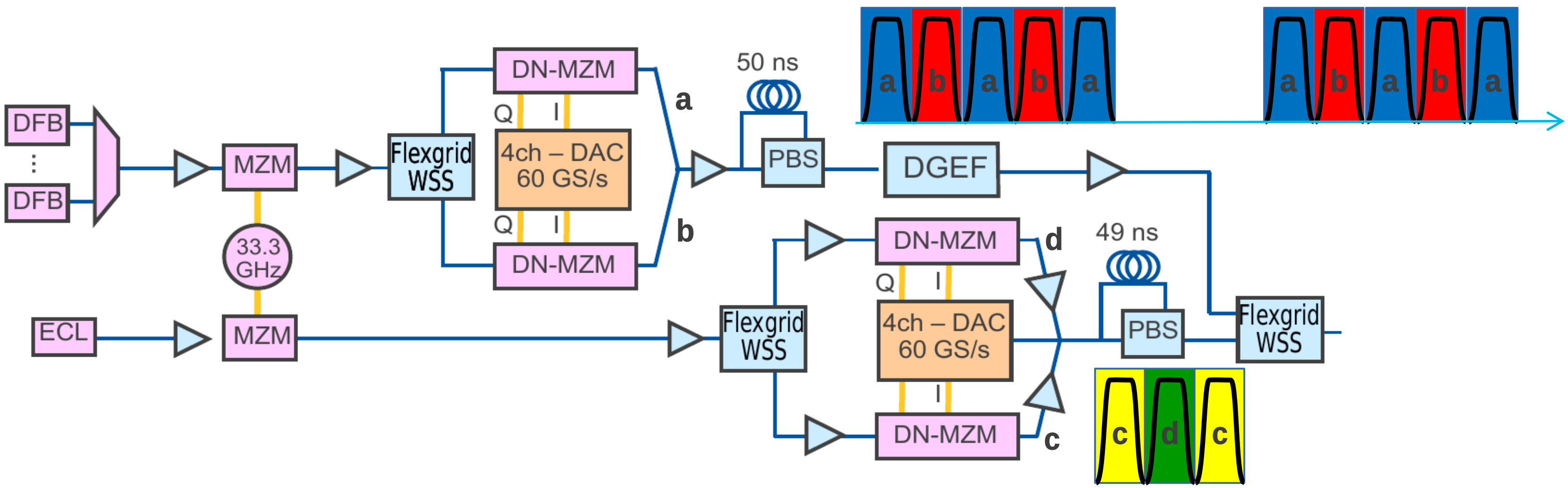
High performance test signals for optical transmission systems

High performance test signals for coherent long distance transmission have evolved over the years:

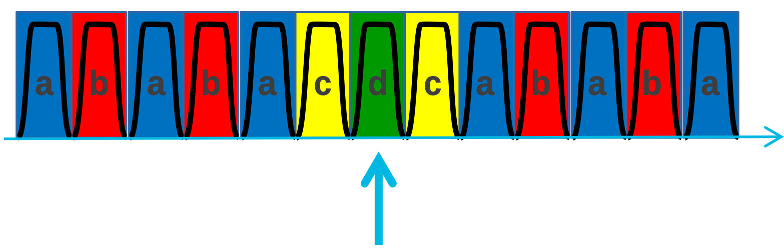
- **Nyquist WDM**
- **Higher order constellation**
- **Probabilistic shaping**

Which makes the signals look more and more like to white Gaussian noise (WGN).

Transmitter for PDM-QPSK, 16QAM, and 64QAM



- 24, 16, 8 independent DeBruijn sequences of the length of 2^{16} are used to generate 64QAM, 16QAM, and QPSK, respectively
- 30 Gbaud, DACs running at 60 GS/s
- 90 WDM channels spaced at 33.3GHz
- Pulse shaping with raised cosine (α=0.01)
- Polarization emulator with 49 ns delay

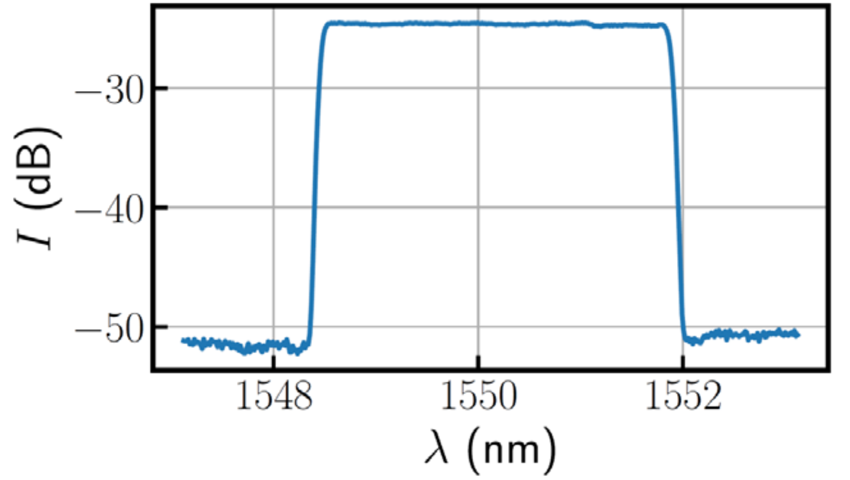


Channel under test

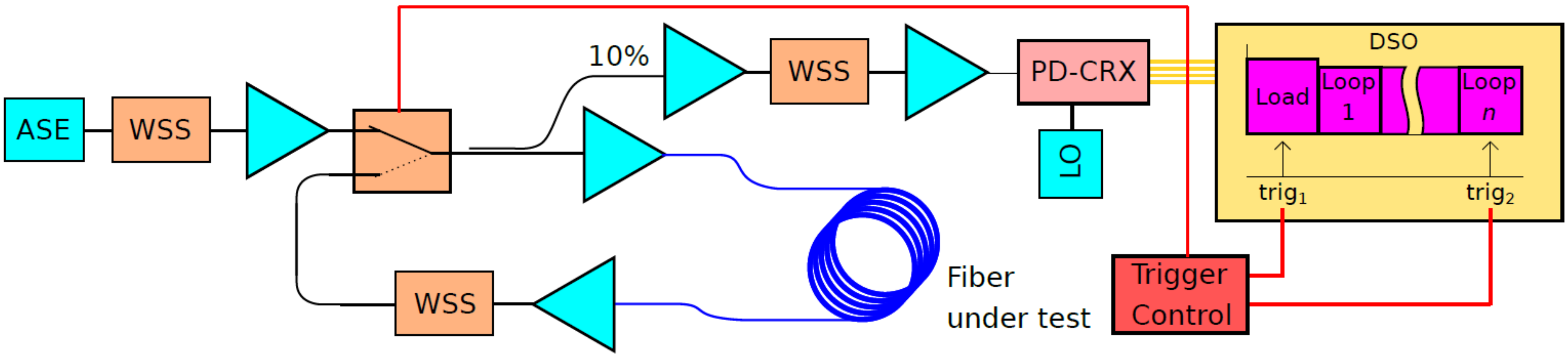
The main idea:

Use white Gaussian noise as test signal to characterize transmission links

WGN transmitter:

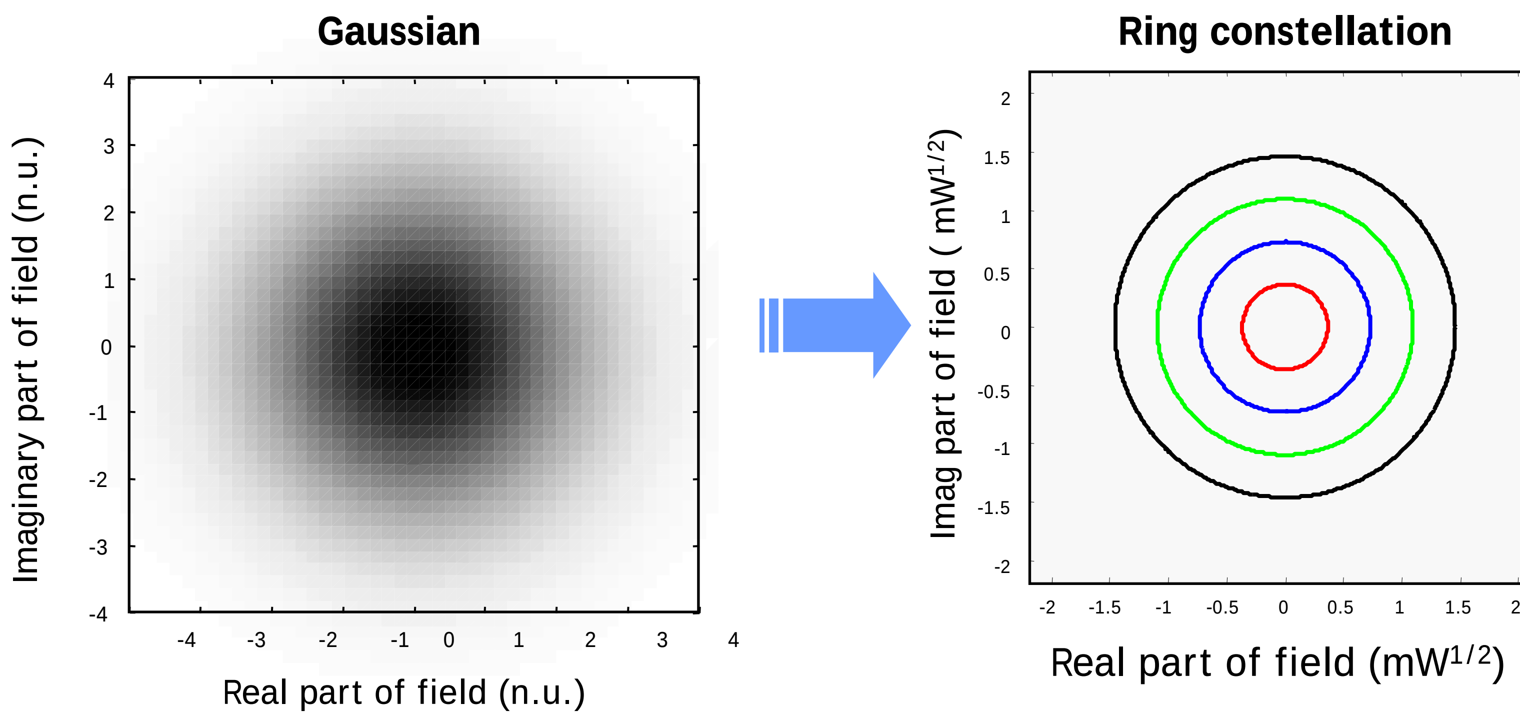


Experimental arrangement for WGN based link characterization



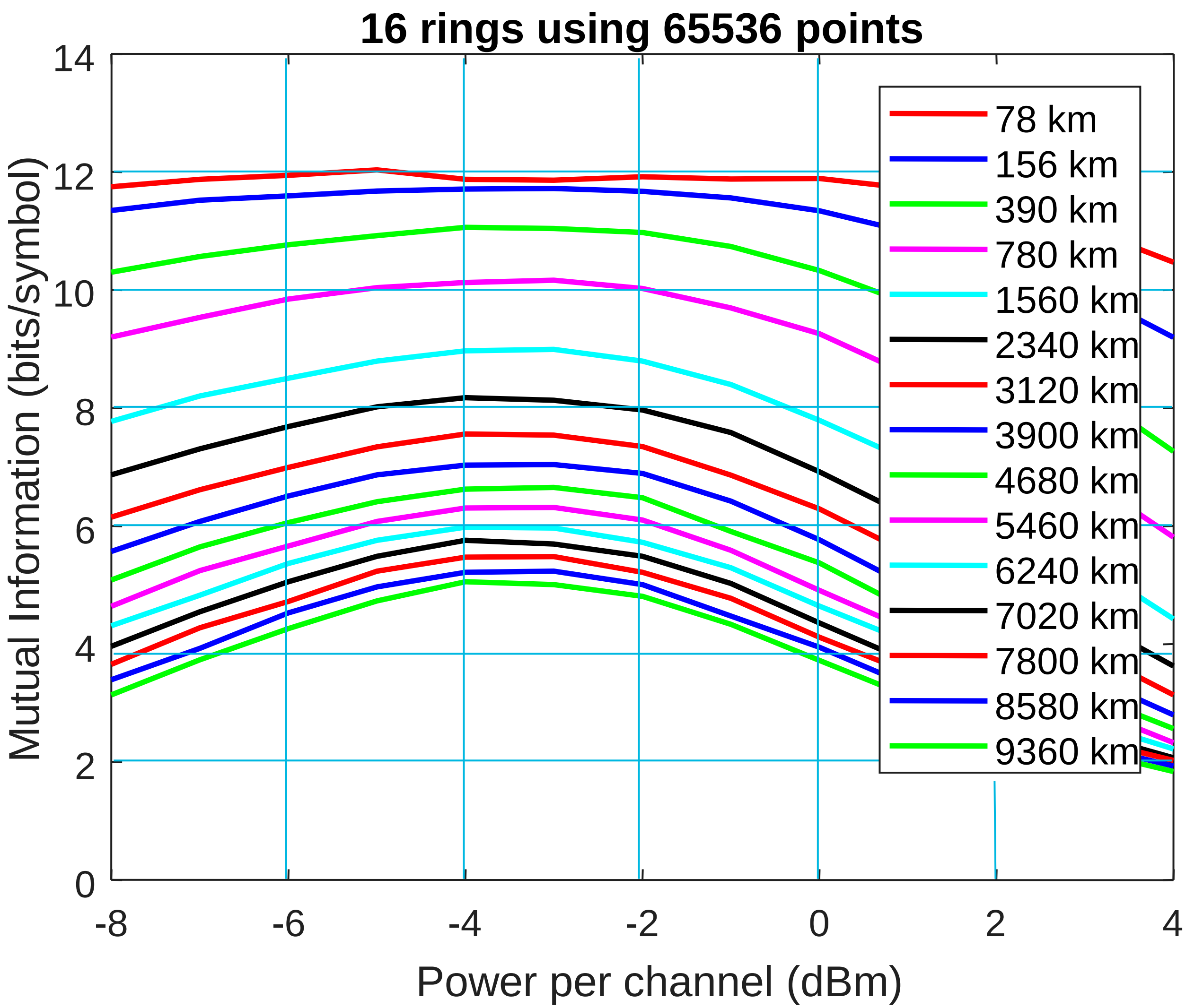
The oscilloscope is used in "sequence mode" to allow the single-shot capture of subsequent trigger events

Ring Constellations for Mutual Information Calculations



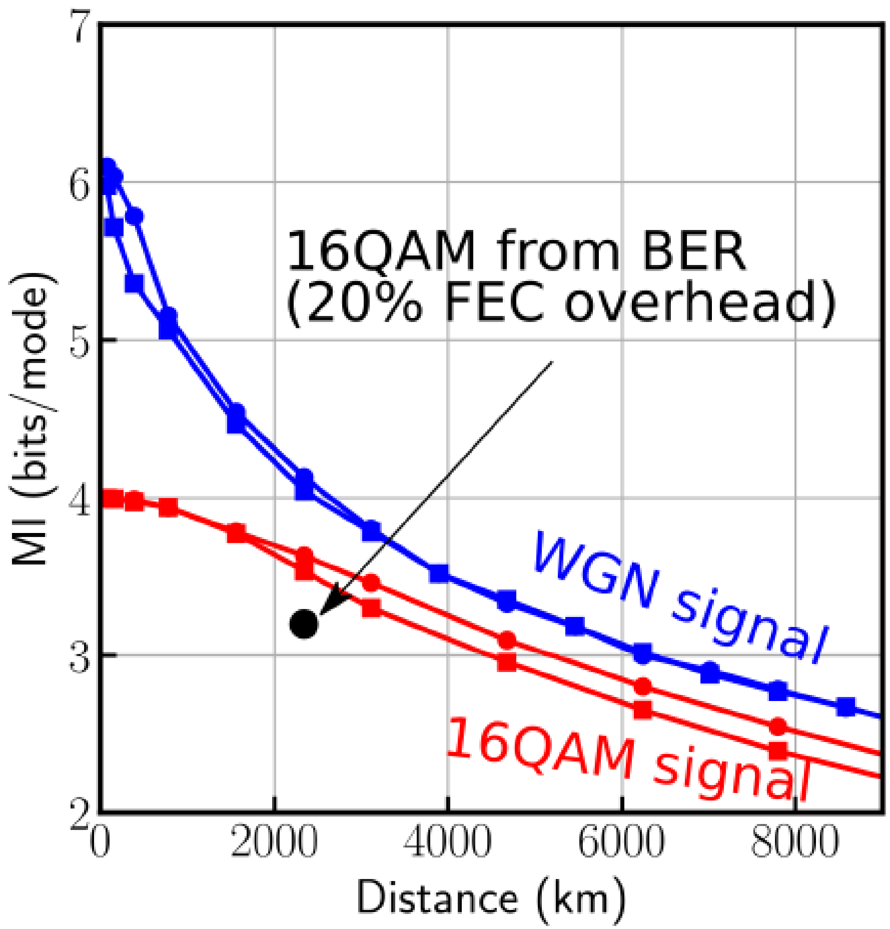
- Ring radii are multiples of the inner ring radius **and e**qual frequency of occupation
- **Probability density function (PDF) of points on each ring are fitted to Gaussian cloud**
- **Mutual information is calculated from conditional and joint PDF between rings**

Example 78km SMF span

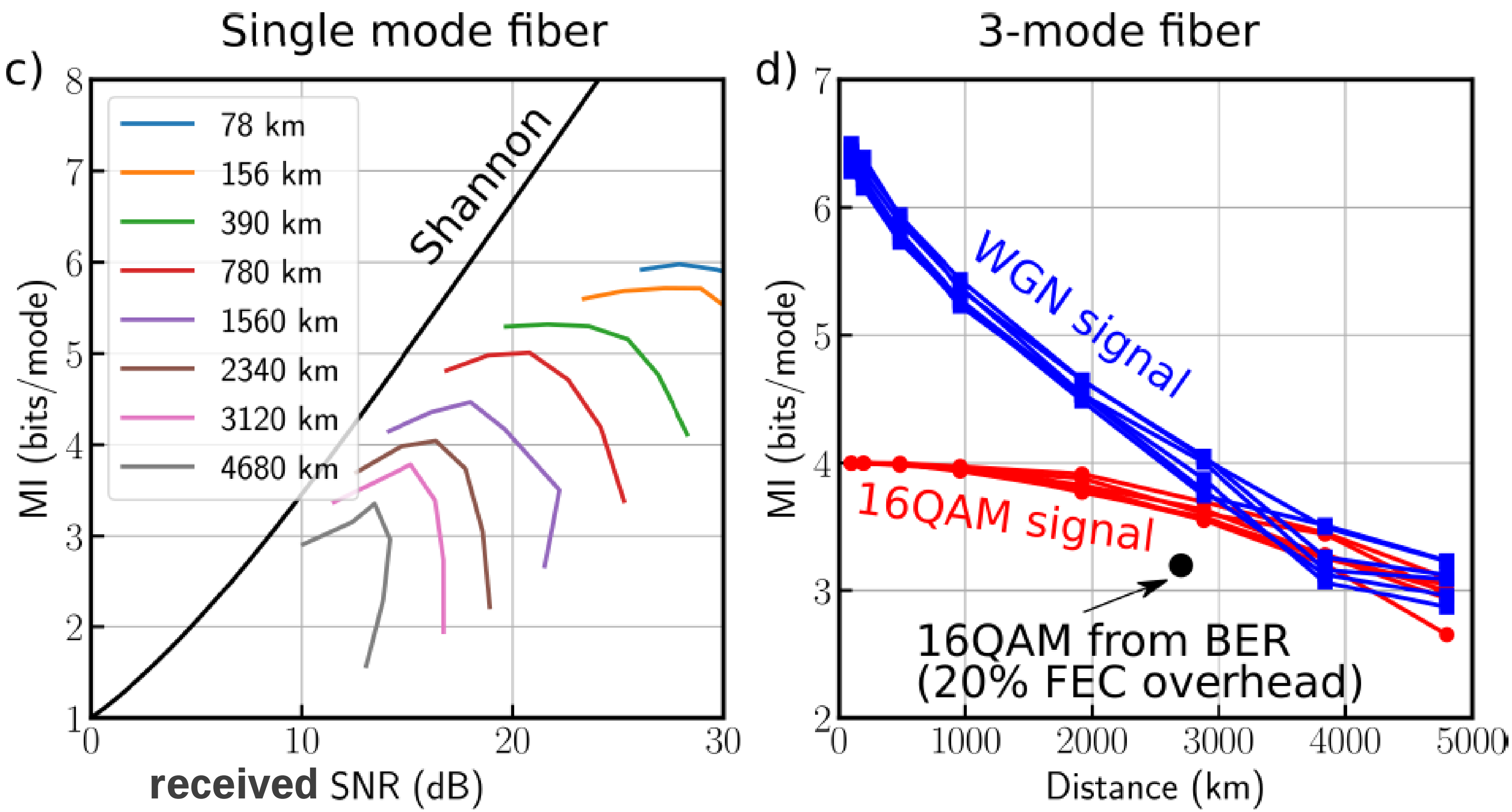


Example 78km SMF span

The MI measured with the WGN signal is compared to the MI measured with a traditional pulse-shaped 30Gbaud 16QAM 33.3GHz spaced WDM signal, where a gap of ~0.3 bits/mode is observed.



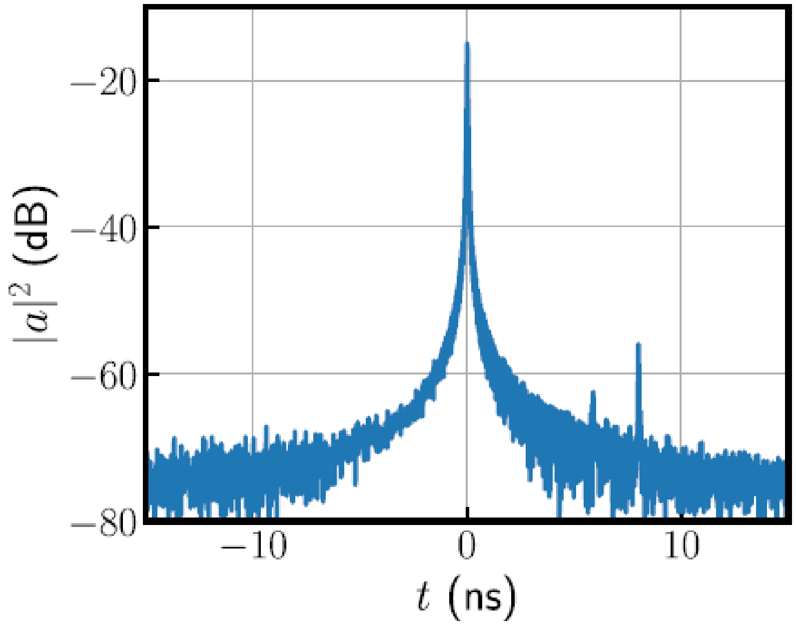
More examples including MDM



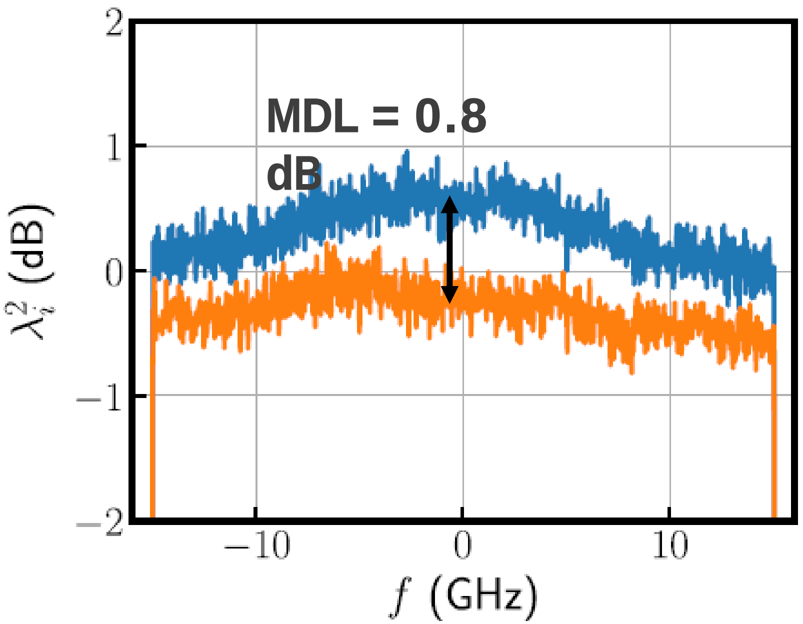
J. Van Weerdenburg et.al. W4C.2

Example 78km SMF span after 1560km transmission

Impulse response



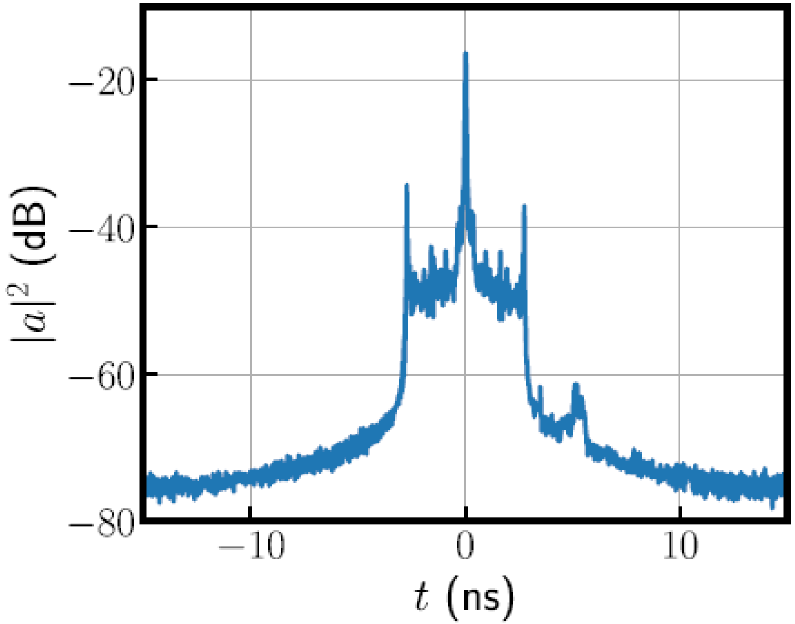
Singular values



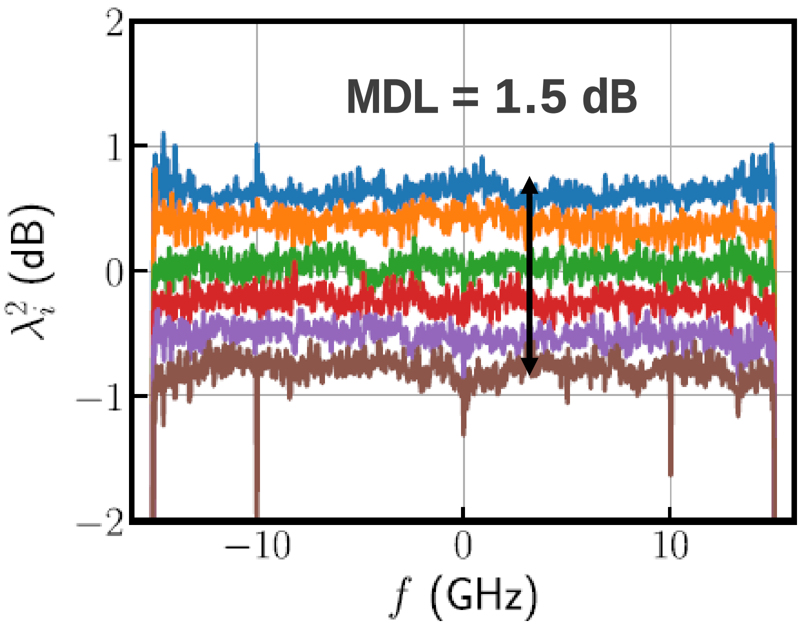
- Impulse response with > 60dB dynamic range
- Wavelength dependence of polarization effects can be detected

Example 96km 3-mode span

Intensity averaged Impulse response



Singular values as function of frequency



- Impulse response with > 60dB dynamic range
- Wavelength dependence of modal effects can be detected

Conclusions

- **MIMO** based digital signal processing enables **space-division multiplexed transmission** at full capacity gain even in the presence of **large crosstalk**
- Mode-multiplexed transmission of up to 45 modes and up to **5000 km multimode fibers and 10000 km coupled-core fiber** has been demonstrated
- Coupled-core fibers can outperform an equivalent single-mode fiber

- We show that white Gaussian noise can be advantageously used as test signal for optical communication link.
- The proposed method is accurate and provides a full channel characterization and capacity estimate requiring a minimal amount of test equipment.