Next-Generation Optical Communication Systems

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SSF project mid-term presentation

Outline

- Background, motivation and goal
- Partners and organization
- Results and achievements

MC2
Microtechnology and Nanoscience

FORCE
Fibre Optic Communications Research Centre

Background, Motivation & Goal

- Optical bandwidth is becoming a scarce resource → Need to develop much more spectrally efficient transmission (i.e. non-binary formats) to meet the ever increasing capacity demands
- We can leverage techniques from wireless systems; adopted to much higher (hardware constrained) speed and to a nonlinear transmission channel (the fiber)
- Cross-disciplinary effort involving two Chalmers groups with leading edge research
- We aim to generate essential knowledge & competence for next generations of optical communications systems, covering a wide range of application from < 1km datacom links (very cost sensitive) to Mm trunk multi Tb/s networks
- Co-optimization of optical & electrical hardware and signal processing algorithms. (Ex. optical vs. electronic dispersion compensation).

Partners and Project Organization

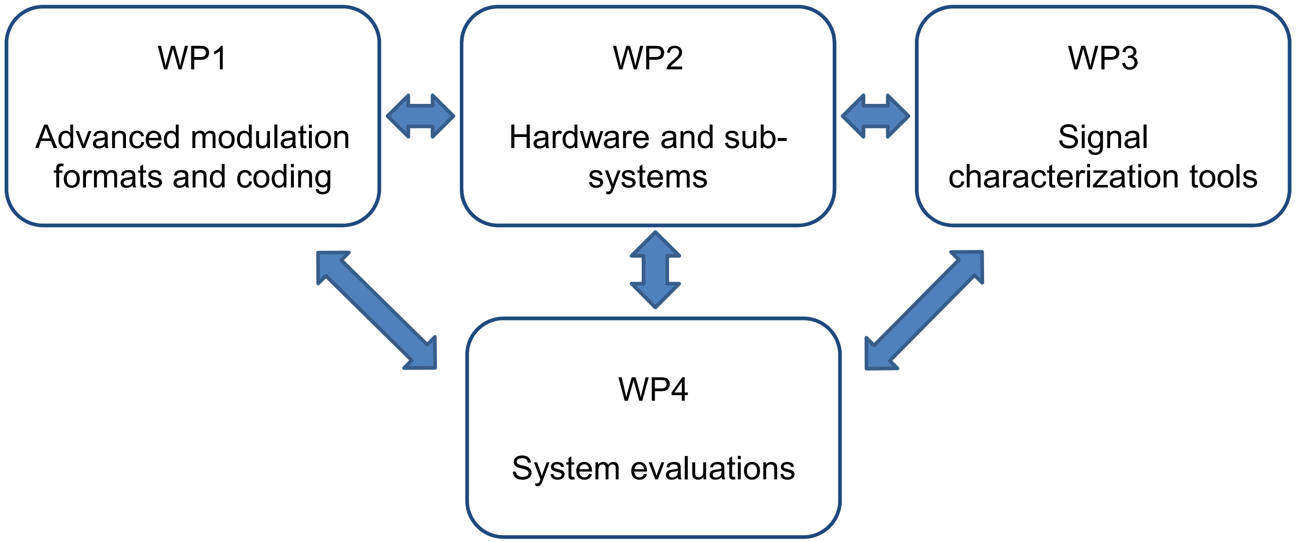
Partners

Optical Communications Group, Microtechnology and Nanoscience, Chalmers (Peter Andrekson)

Communication Systems Group, Signals and Systems, Chalmers (Erik Agrell)

External Swedish industry partners: Ericsson AB, Proximion AB, EXFO Sweden AB

Work packages:



The People

Researchers:

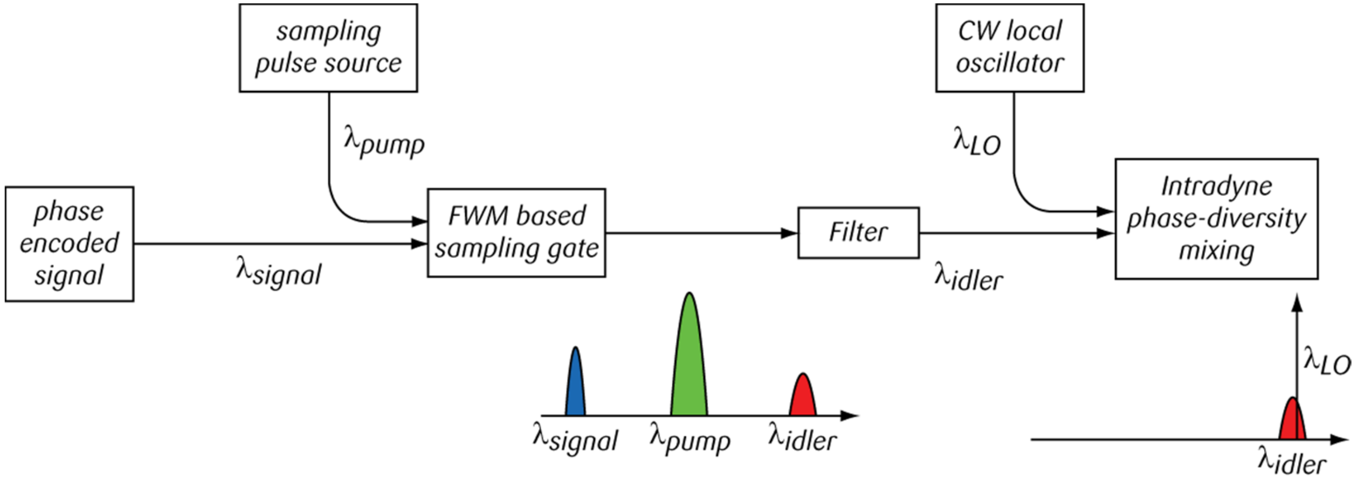
Peter Andrekson
Magnus Karlsson
Erik Agrell
[Guo-Wei Lu]
Henk Wymeersch
Pontus Johannisson
[Serdar Tan]
Debarati Sen
Bill Corcoran

PhD students:

Krzysztof Szczerba
Martin Sjödin
Ekawit Tipsuwannakul
Lotfollah Beygi
Johnny Karout

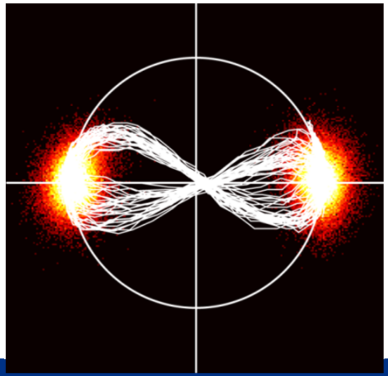
Notable Highlights to-date

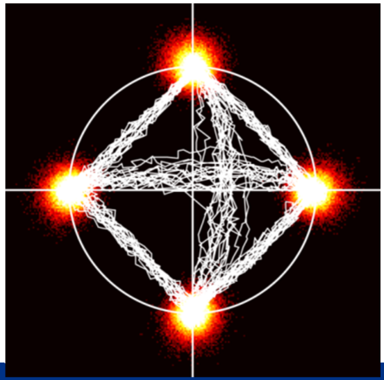
Complex modulation formats need advanced measurement tools: Phase-sensitive all-optical sampling



Pulsed pump in optical-fiber-based four-wave mixing gate and cw LO provides high time resolution measurement capability of the complete optical field.

Examples of constellation diagrams captured with 3 ps resolution





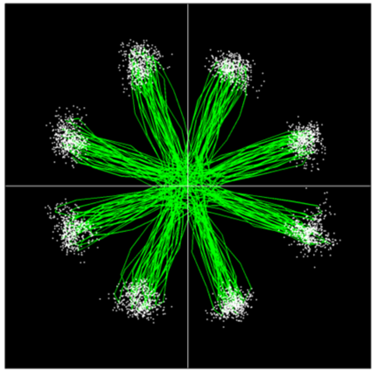
Non-coherent systems

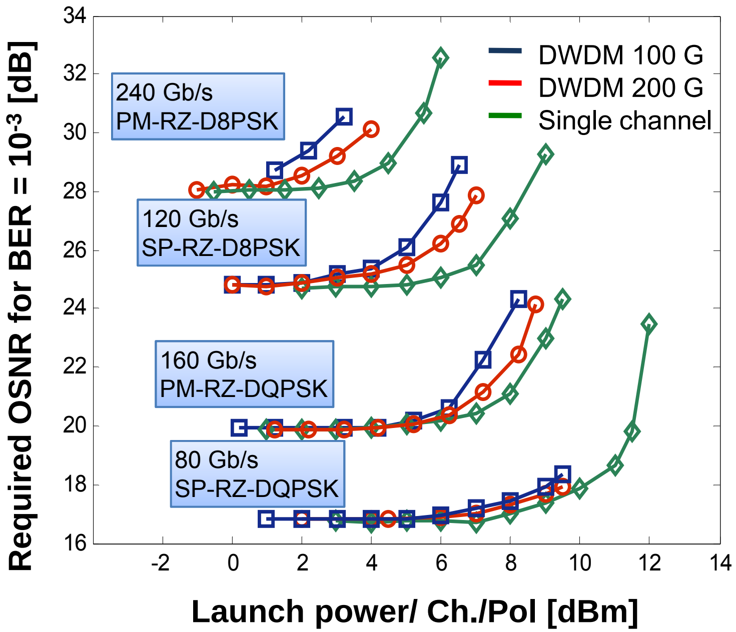
Simpler, less powerful receivers compared with coherent counterpart

Transmission of 240 Gb/s dual-polarization D8PSK over 320 km in a 10 Gb/s DWDM system

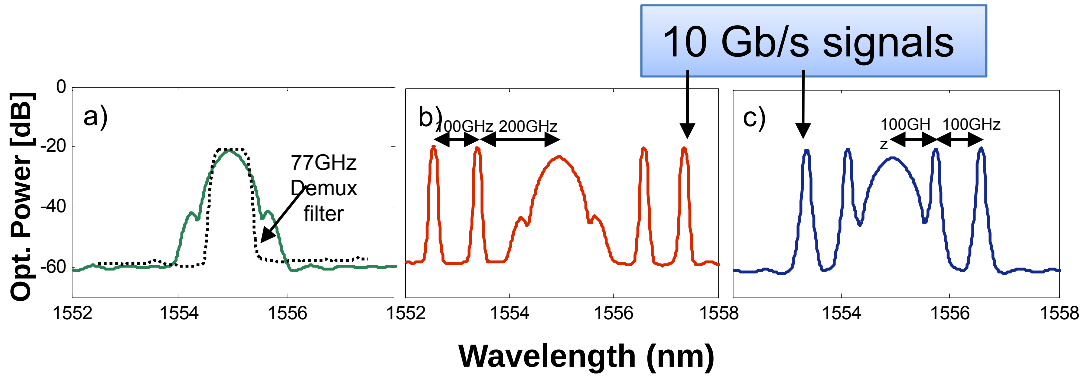
- Demonstration of a record bit-rate (240 Gbit/s) differential format over a single wavelength
- Investigation of nonlinear effects in upgrade scenario

D8PSK constellation



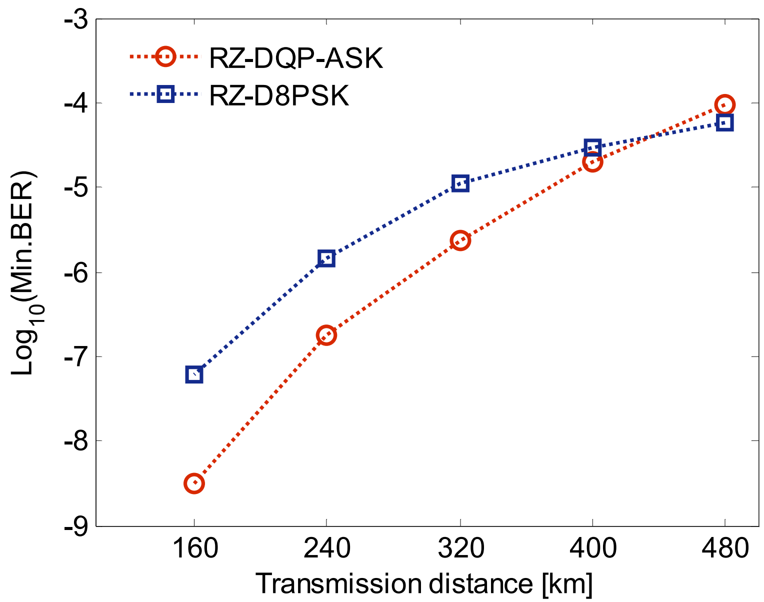


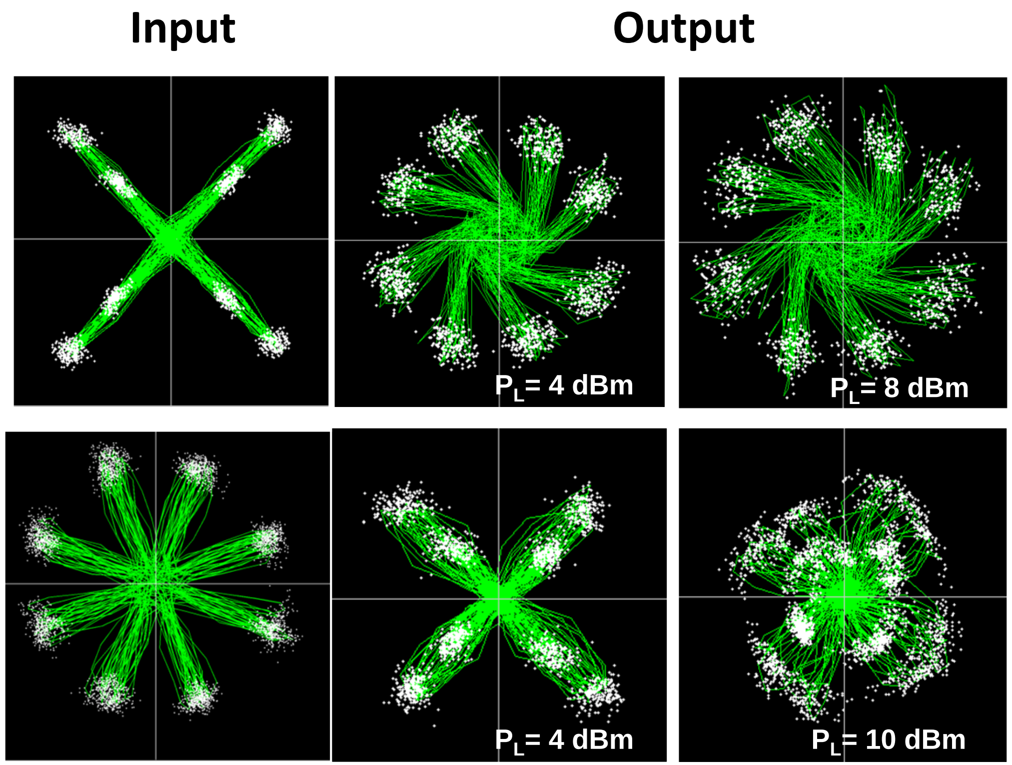
- Three configurations investigated
- D8PSK is less robust against fiber nonlinearities compared to DQPSK



Performance comparison of 120 Gb/s DQPSK-ASK versus D8PSK

- First direct comparison of 8-ary differential formats
- First nonlinear study of DQPSK-ASK
- The compared bit-rate is relevant for the forthcoming 100 GbE



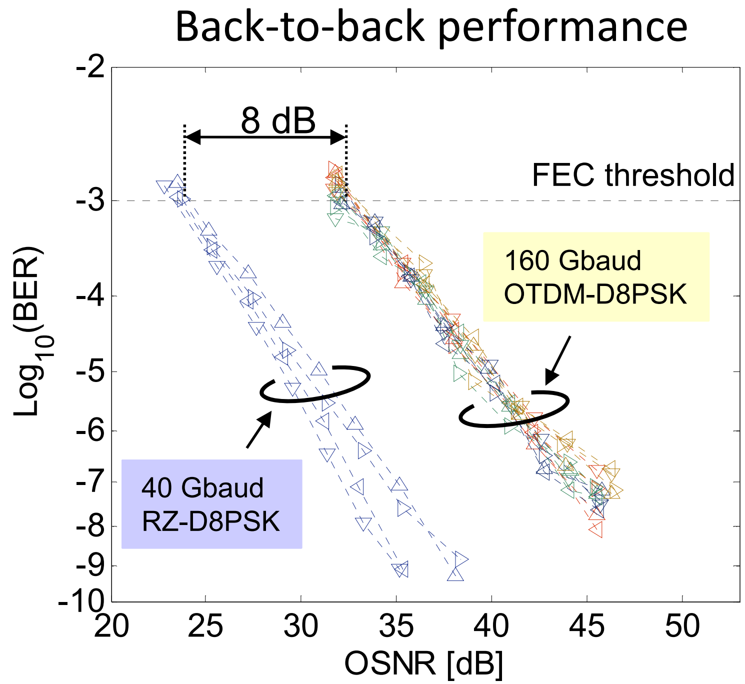


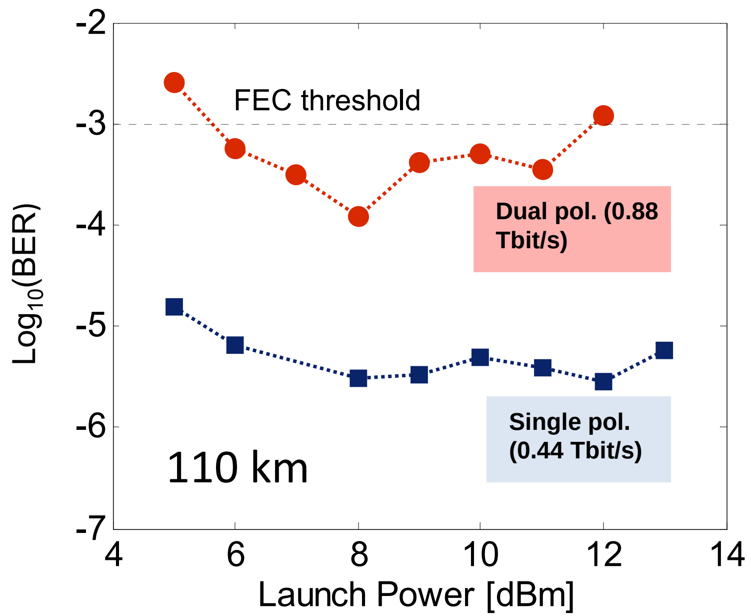
- Either can be better over different reaches
  - < 400 km: DQP-ASK
  - > 400 km: D8PSK

0.9 Tb/s, 160 GBaud PM-D8PSK-OTDM transmission over 110 km

First D8PSK OTDM study

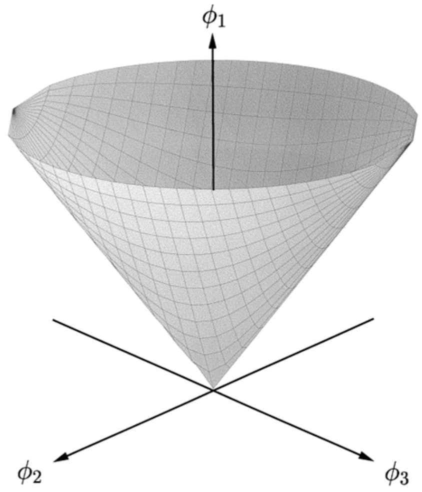
- Highly relevant to anticipated 400 GbE
- Transmission over a conventional link





- Successful transmission (BER $<10^{-3}$) over
  - 220 km (0.44 Tbit/s – single polarization)
  - 110 km (0.88 Tbit/s – dual polarization)
- Performance limited by cross- & self-phase modulation

Sensitivite modulation formats for IMDD applications

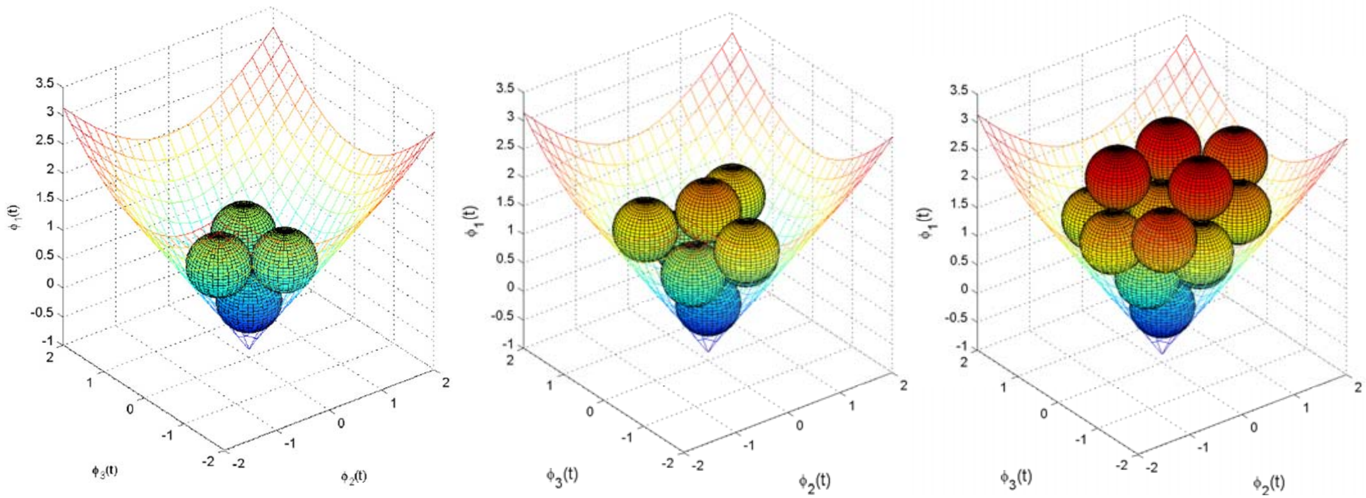


The signal space in IMDD links is a 3-dimensional cone if an electrical subcarrier is used:

- Φ_3 – Cosine component of the subcarrier
- Φ_2 – Sine component of the subcarrier
- Φ_1 – Symbol bias

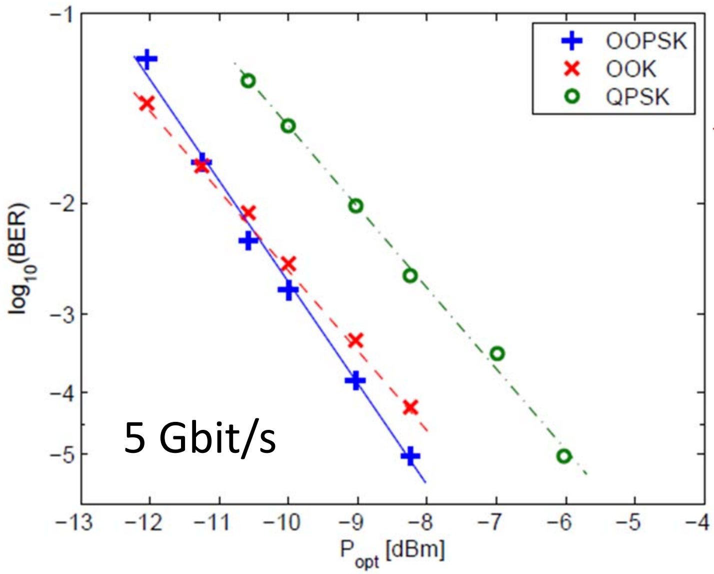
Modulation format optimization in the available signal space:

[Patent pending]



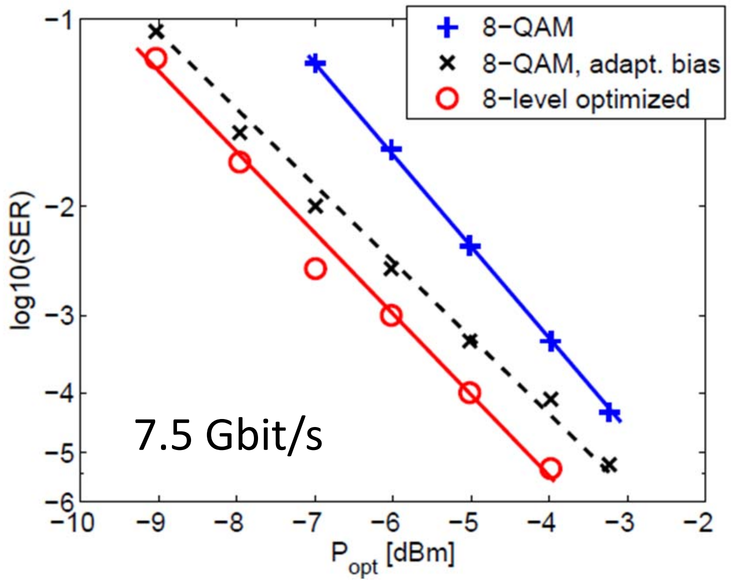
4-level 8-level 16-level

Experimental results for IMDD links

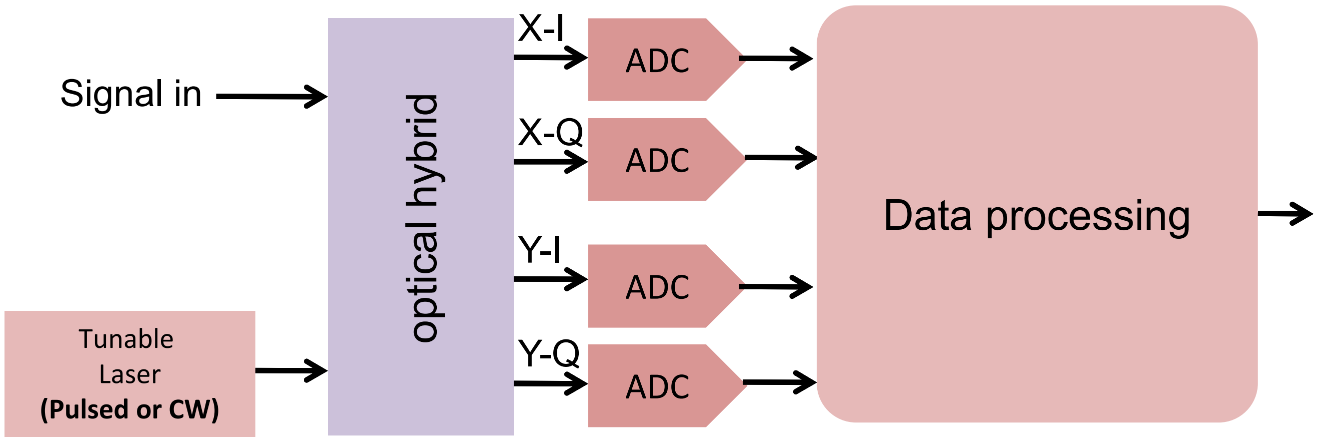


OOPSK (on-off phase shift keying) – a new format with 2 dB improvement over QPSK subcarrier modulation and 0.6 dB over OOK.

Adaptively biased star-shaped 8-QAM and an optimized 8-level format with 1dB and 2 dB improvement over subcarrier 8-QAM, respectively.



Coherent systems and receivers



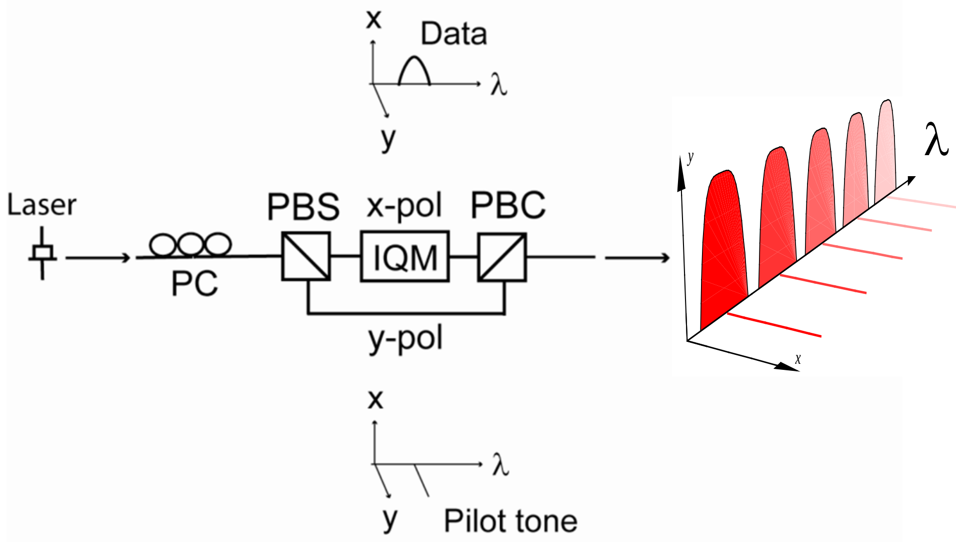
Self-homodyne coherent transmission

In self-homodyne systems, a co-propagating pilot tone in the orthogonal polarization state is used as phase reference in the receiver instead of a local oscillator laser.

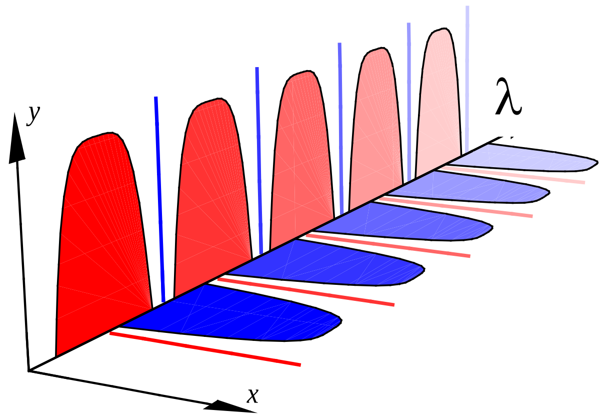
DSP in the receiver not required

Lasers with broad linewidth can be used

Not compatible with pol-multiplexing

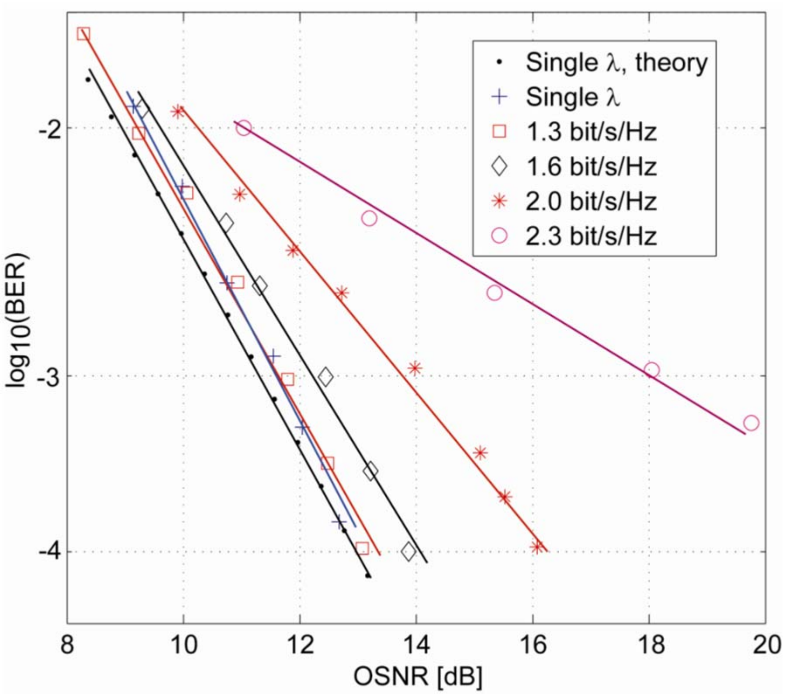


“Zipper multiplexing scheme” can be used to obtain high spectral efficiency in self-homodyne coherent systems, with a very low complexity receiver.
[Patent pending]

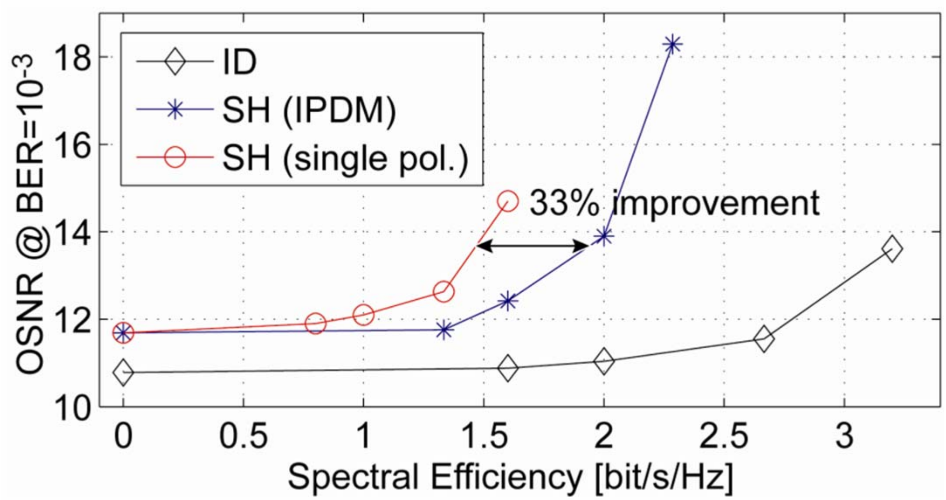


Measured results with 10 GBaud QPSK DWDM signals over 200 km link

Back-to-back BER vs. OSNR



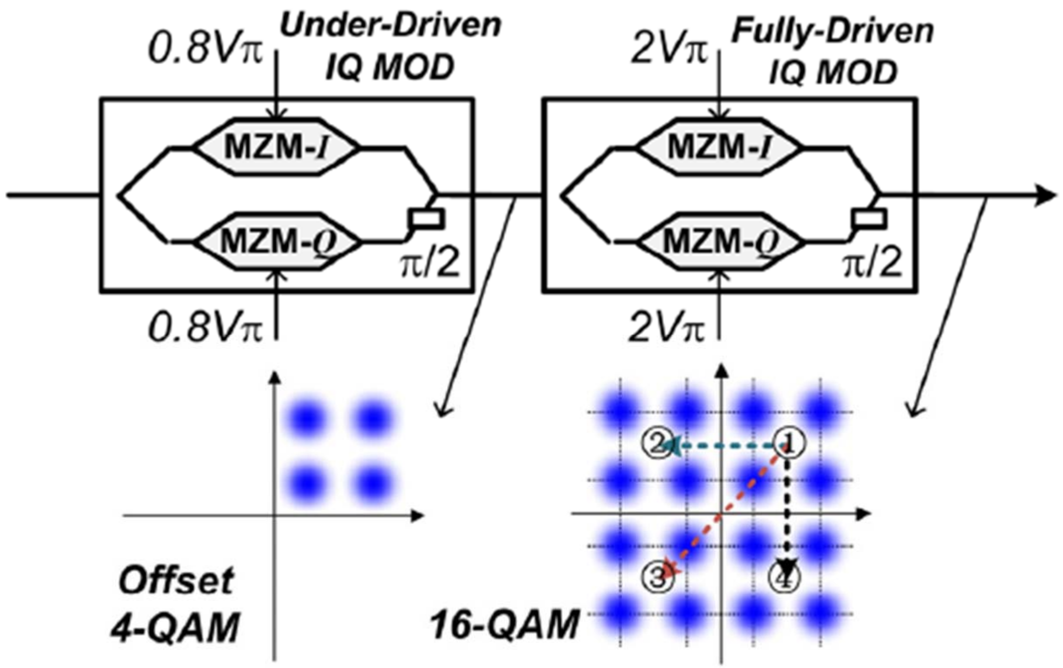
Required OSNR vs. spectral efficiency



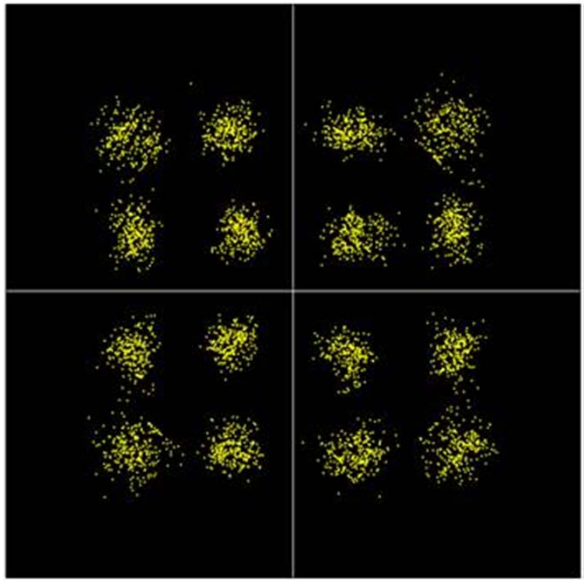
ID: intradyne; SH: self-homodyne

Further improvement expected with adequate pre-filtering od the signals

16-QAM transmitter using cascaded in-phase/quadrature modulators driven by binary electrical signals



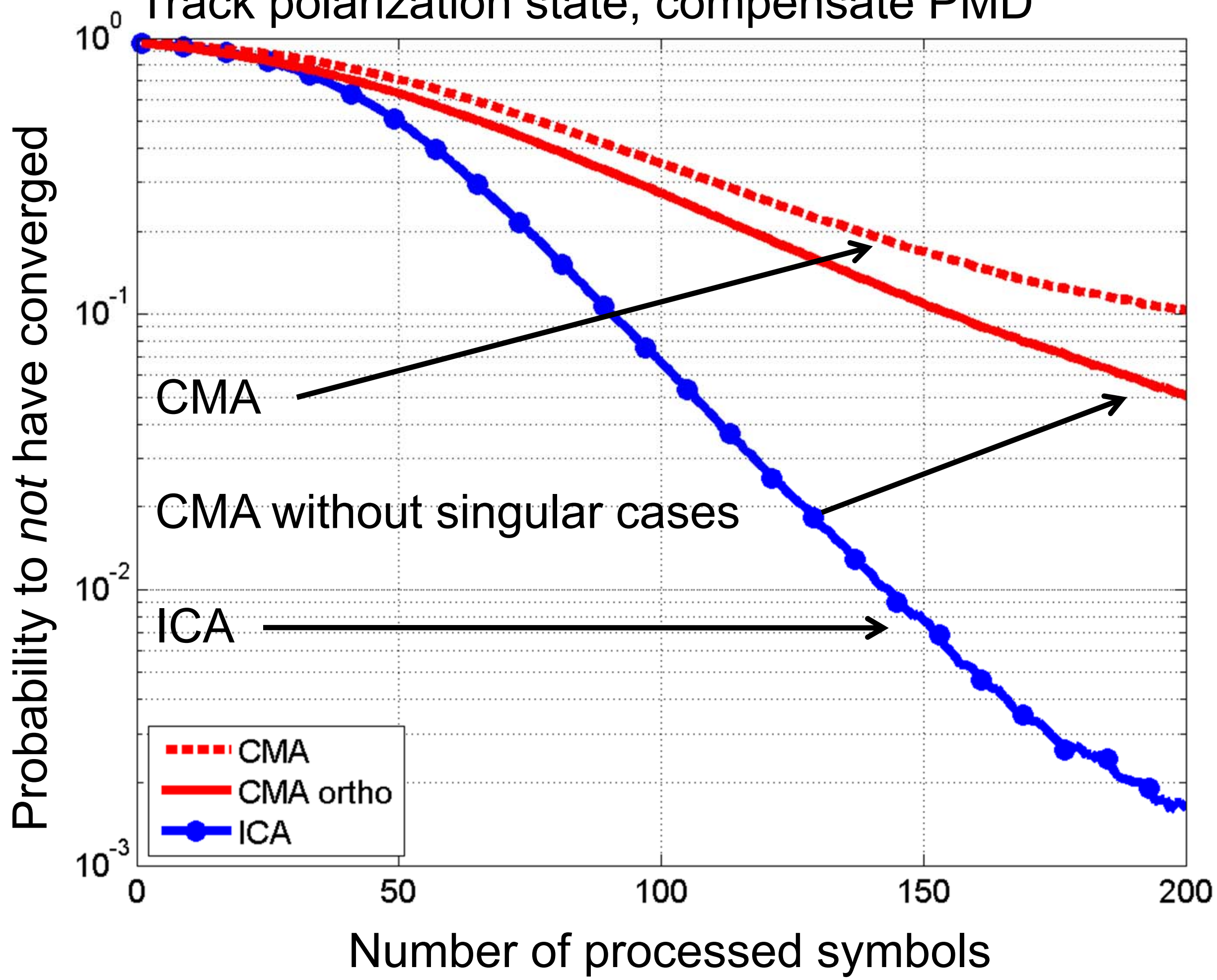
Measured 40 Gbaud 16-QAM signal



Simple approach with existing hardware that can be scaled further

Polarization Demultiplexing using Independent Component Analysis

Track polarization state, compensate PMD



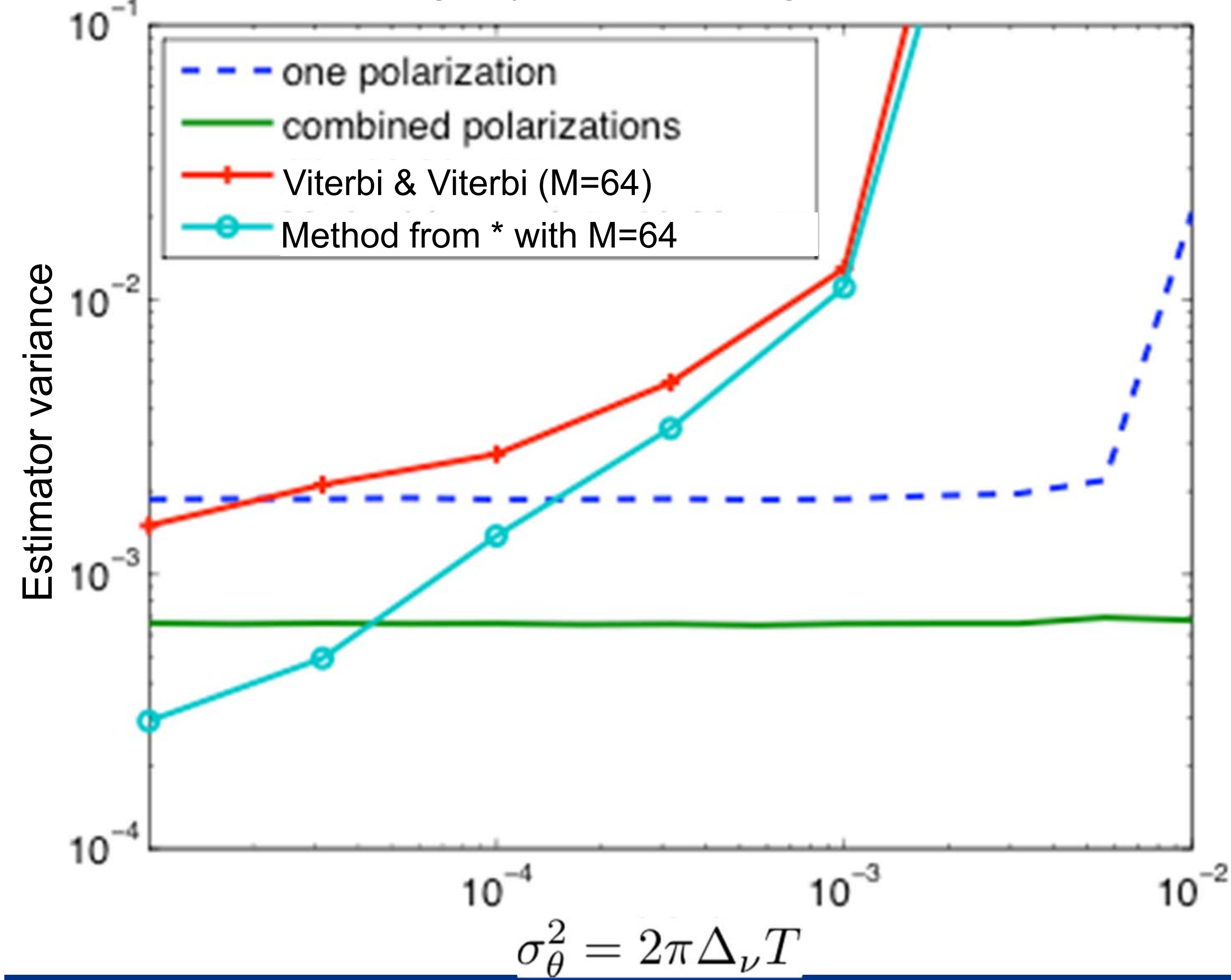
Commonly used algorithm
- Constant Modulus Algorithm (CMA)

Proposed method
- Independent Component Analysis (ICA)

Proposed Method
- Converges always
- Shows faster convergence

Phase Tracking for 16-QAM

Phase Tracking: Synchronize signal and LO phases



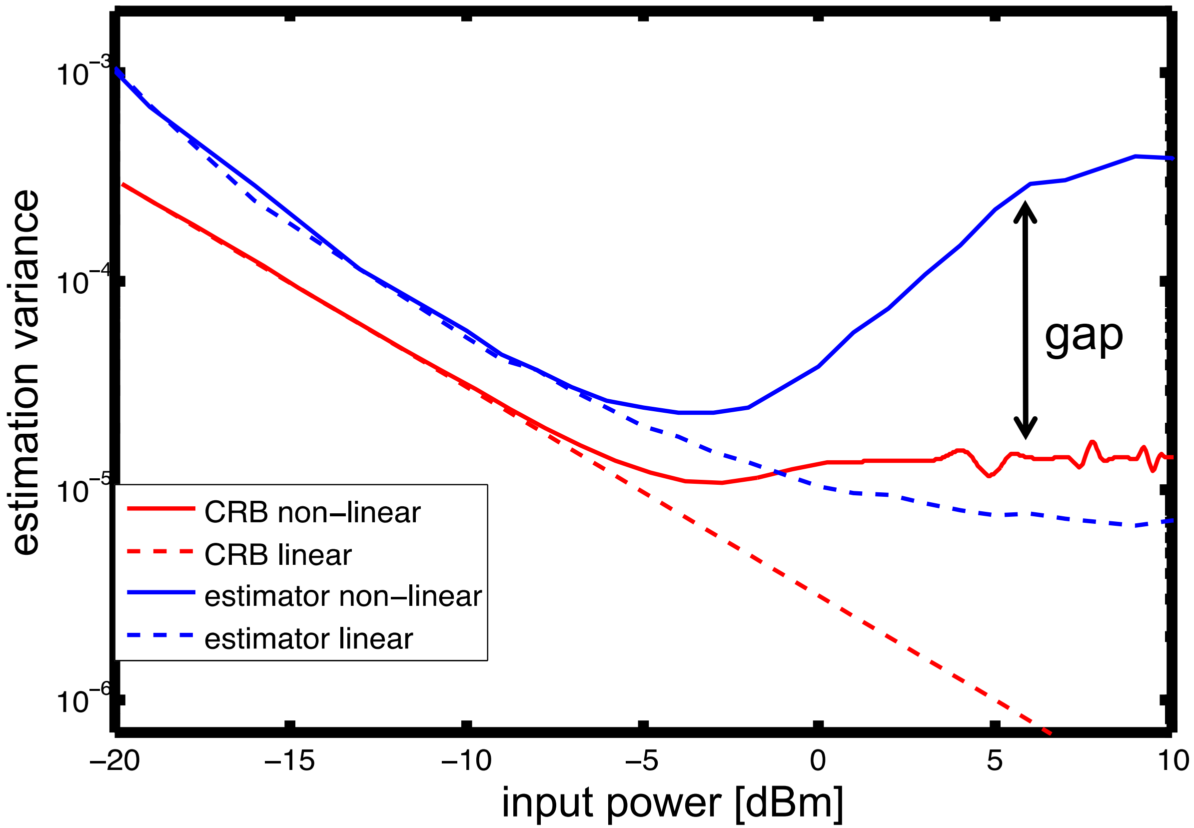
Phase tracking requires:
- Sufficiently high SNR
- Low laser linewidth

Proposed Method
- Tolerates high laser linewidth but requires increased SNR
- Performance improves by using both polmux channels

*M.Seimetz, OFC2008, OTuM2(2008).

Clock recovery in coherent receivers

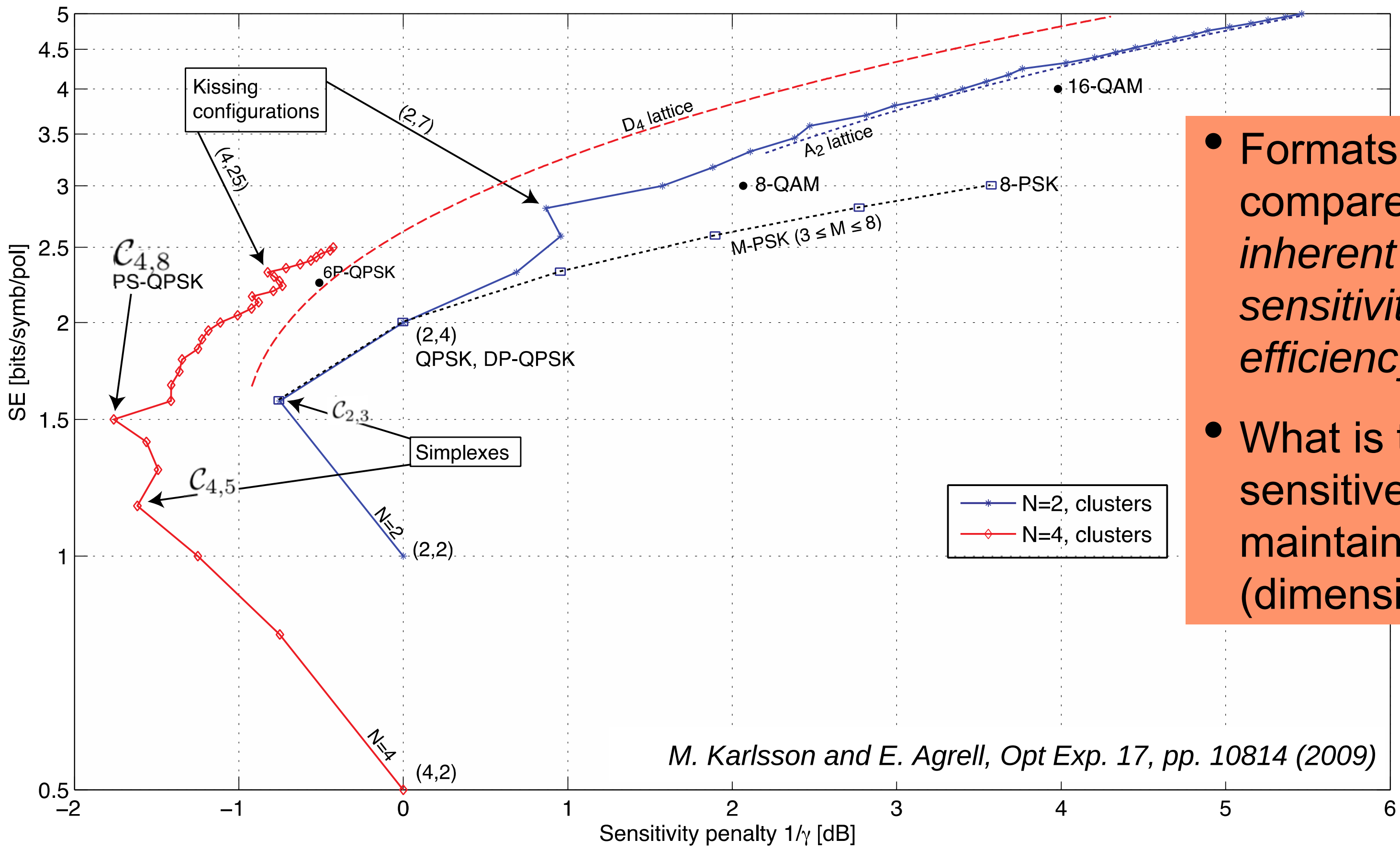
- The goal of clock recovery is to estimate optimal sampling times
- We have investigated the impact of SPM on the accuracy of estimation
- Cramér-Rao Bound (CRB): Lower bound on error variance of any unbiased estimator



- CRB, which shows optimal algorithm performance, derived for first time for optical links.

- There is a large gap in performance: Better algorithms can be developed!

Which modulation format is most sensitive in 2d and 4d?



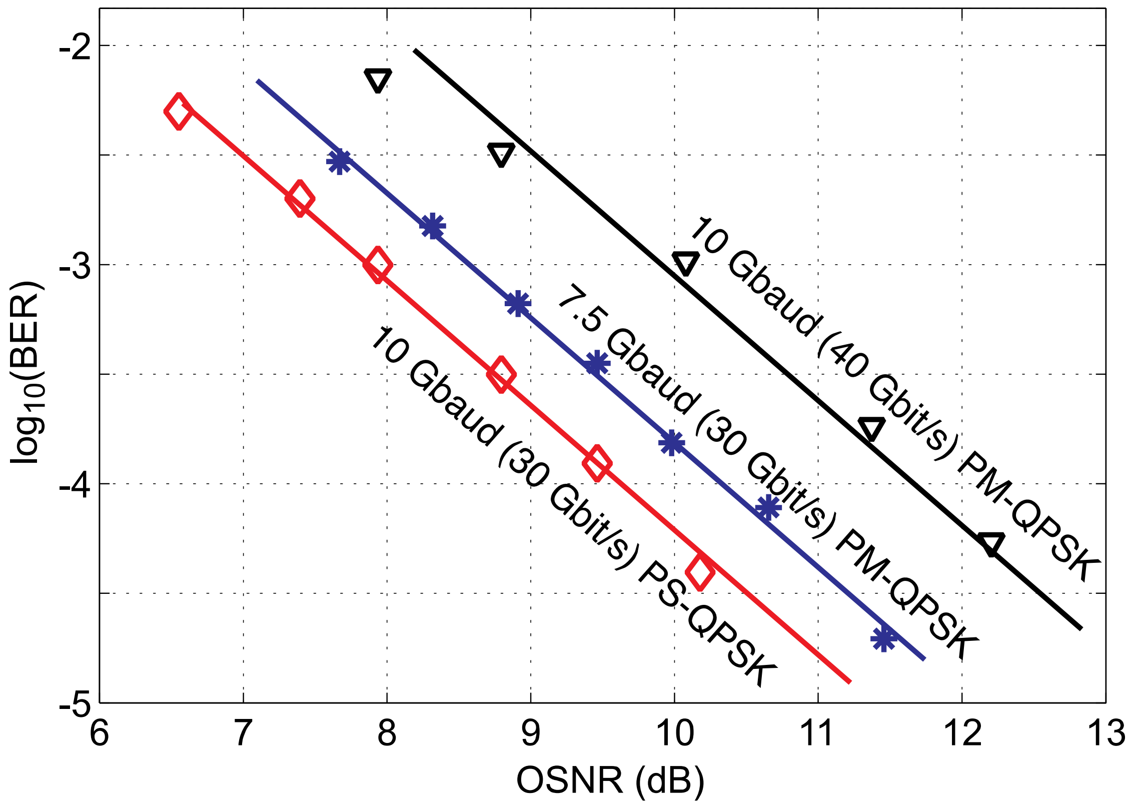
- Formats are usually compared by plotting the *inherent trade off* between *sensitivity* and *spectral efficiency (SE)*.
- What is the best (=most sensitive) we can do with maintained complexity (dimensionality)?

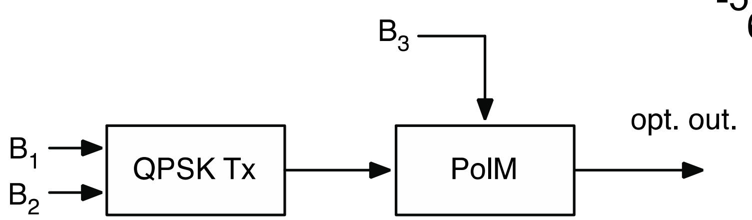
- Simulations of all formats < 32 points in 4d constellation space.
- An 8-point constellation is overall best (1.76 dB better than BPSK) in 4d.
- It is known as polarization-switched QPSK, PS-QPSK.

The PS-QPSK format – experimental verification

M. Sjödin et al, Opt Exp. 19, pp. 7839 (2011)

- PS-QPSK format transmits 3 bits per symbol, and can be generated by QPSK and a polarization selection.
- It gains 1 dB over PM-QPSK @BER=0.001
- First experimental verification!

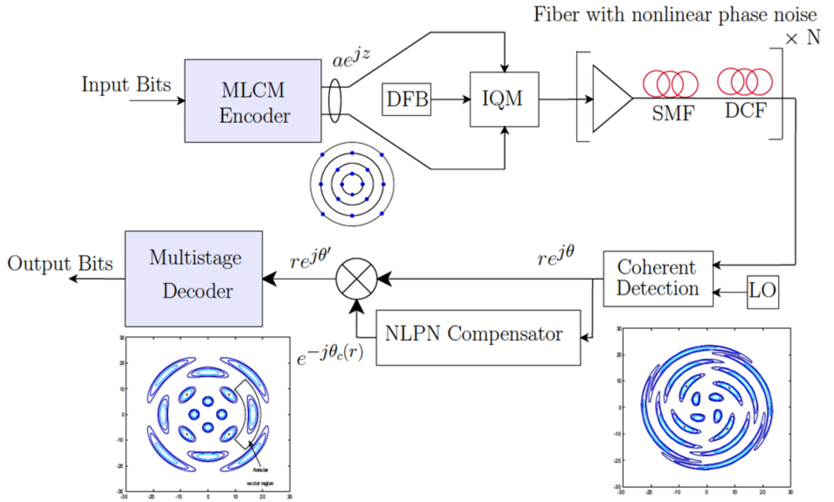




Multilevel coded modulation (MLCM)

By co-optimizing **modulation** and **coding,** one can obtain:

- higher *power efficiency*,
- a simple, flexible *multistage receiver,* and
- *capacity-achieving* systems.

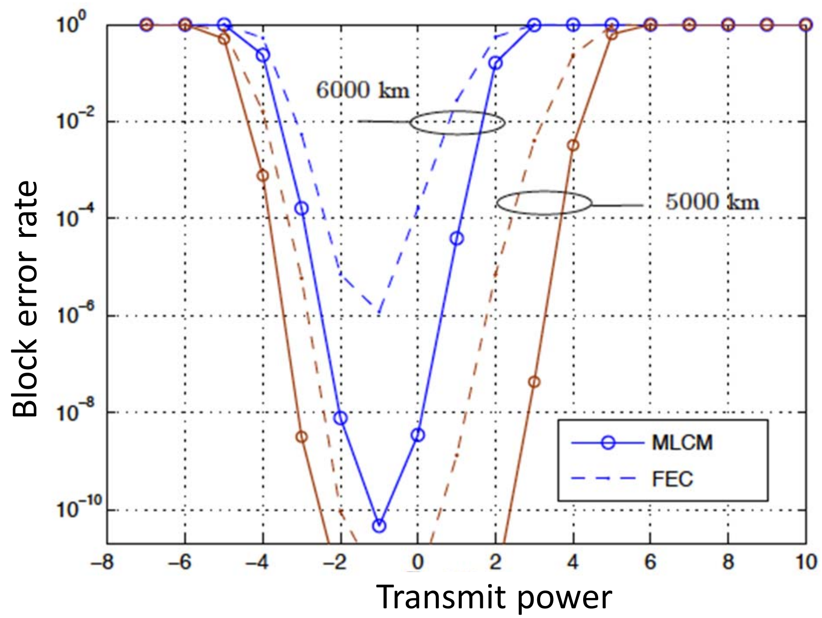


After equalization *After transmission*

Example: 16-QAM penalized by nonlinear impairments over 5-6000 km transmission

Results:

- A new design method for MLCM with Reed-Solomon codes
- An MLCM system for transmission with nonlinear phase noise



Dissemination

- 18 journal papers (1 invited)
- 24 conference presentations (8 invited)
- 1 book chapter
- 3 Licentiate theses (L. Beygi, M. Sjödin, E. Tipsuwannakul)
- 2 patent applications
- Inauguration of the FORCE Center of Excellence at Chalmers along with a workshop in May 2010

FORCE

Future plans

WP1: Advanced modulation and coding
Coded modulation optimized for more realistic fiber transmission systems
Estimation methods based on training sequences for phase/polarization tracking & timing recovery

WP2: Hardware and subsystems
Novel modulation formats, e.g. pulse-position modulation combined with PS-QPSK
Novel concepts for dispersion and nonlinearity mitigation, e.g. so-called factor graphs

WP3: Signal characterization tools
Quantify DSP-based carrier recovery performance (coherence, noise) by benchmarking with self-homodyne method
Parallelized real-time optical sampling for high bandwidth signal characterization

WP4: System evaluations
Evaluation of ultralow noise, phase-sensitive amplifiers in real transmission links
Adaptive optical networks; Channel estimation & optical performance monitoring