DIGITAL SIGNAL PROCESSING TECHNIQUES FOR HIGH-SPEED OPTICAL COMMUNICATIONS LINKS

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PHD CANDIDATE - ELECTRICAL, ELECTRONIC AND COMMUNICATIONS ENGINEERING – XXXI CYCLE

FINAL PHD DEFENSE

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STRUCTURE OF THE TALK

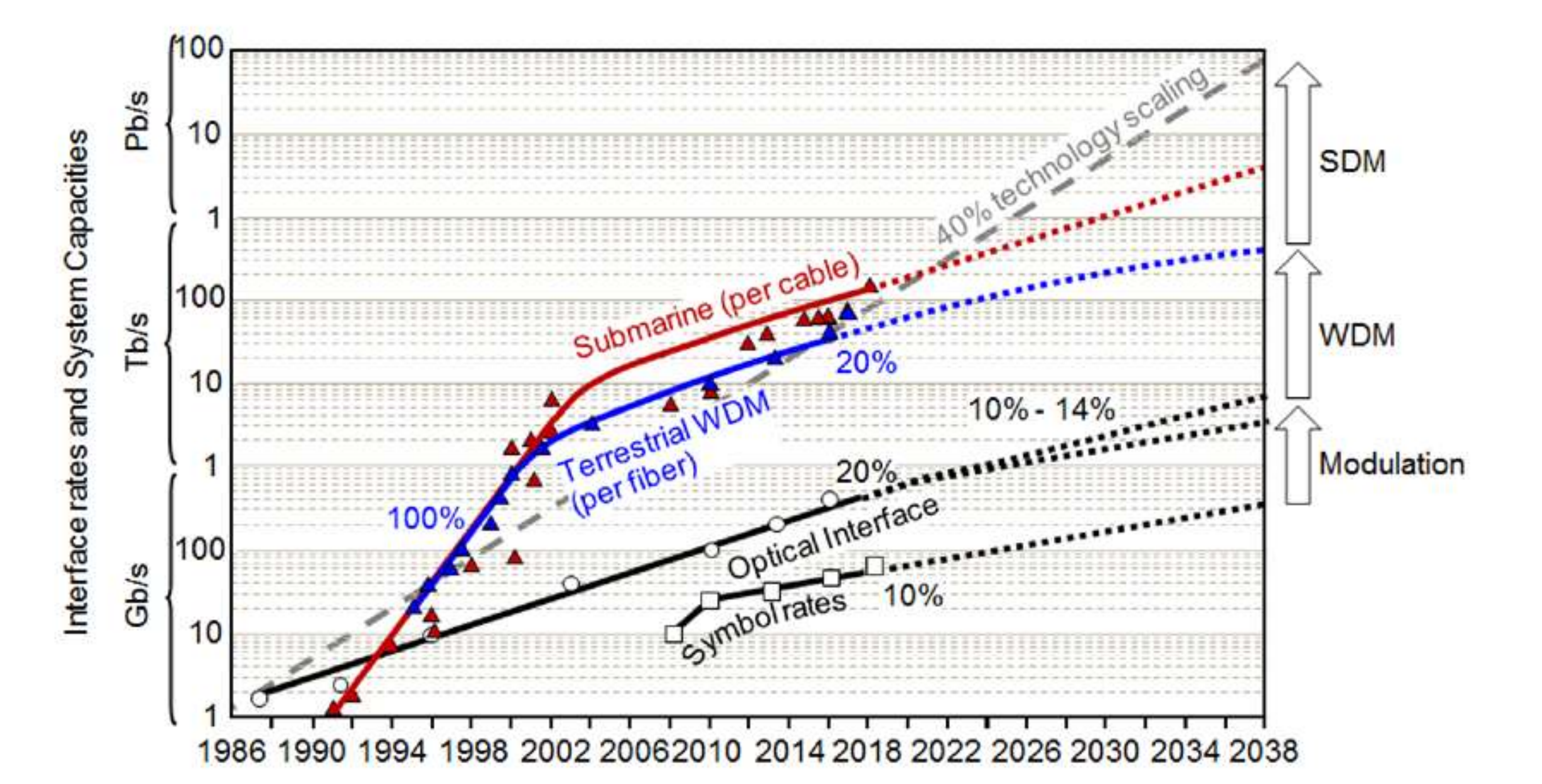
- **Part I:** Direct-Detection Systems
  - Bi-directional PAM-4 architecture for intra-data-center links
  - Self-coherent systems for data-center interconnections

- **Part II:** Coherent Systems
  - Probabilistic constellation shaping: basics over a pure AWGN channel
  - Interaction between PS and fiber non-linear effects: generation and compensation of non-linear phase noise

COLLABORATIONS

- Part of the work presented here has been done in collaboration with CISCO Photonics Italy S.r.l. and LINKS Foundation

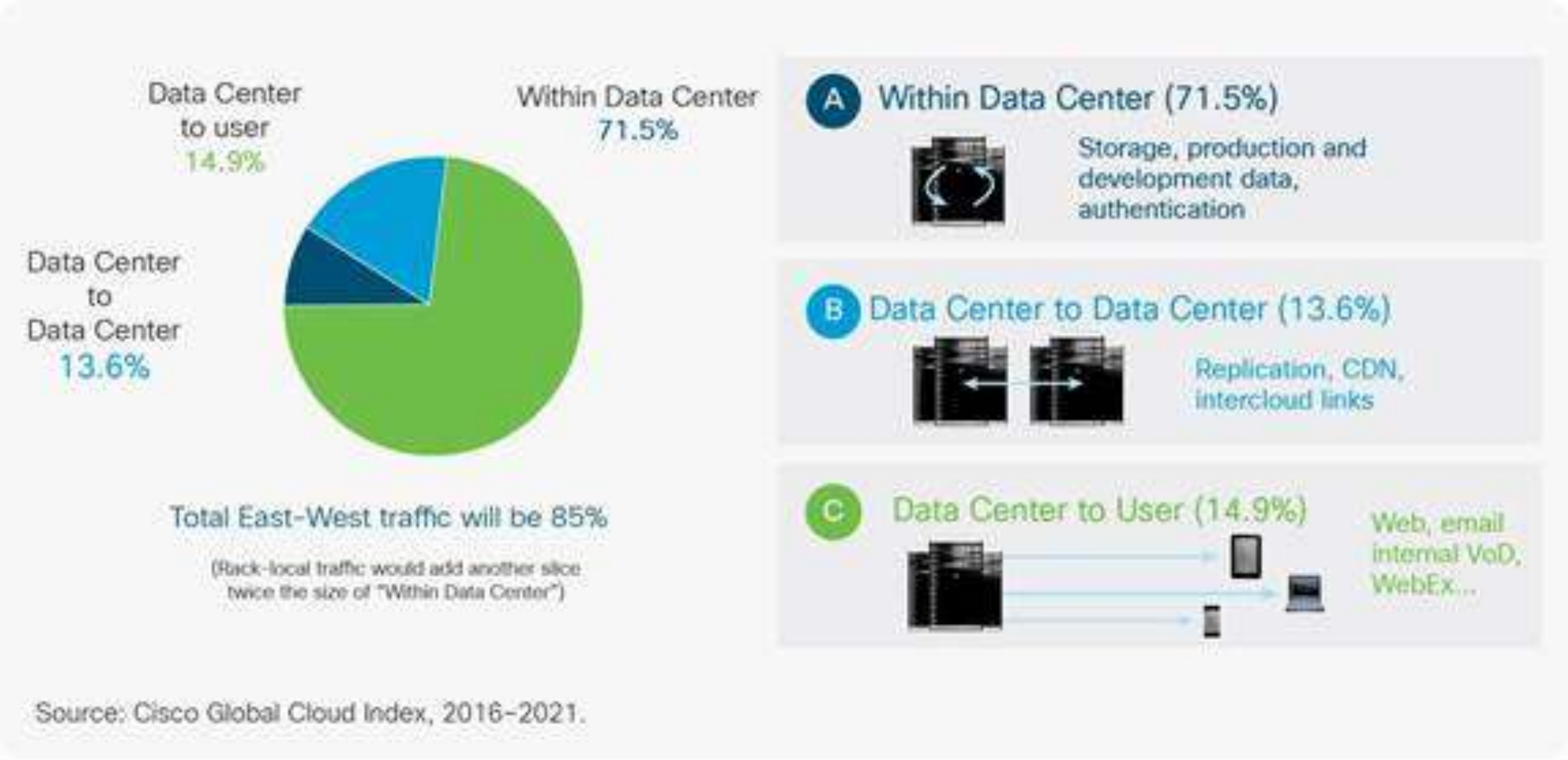
MOTIVATION: LINE RATES INCREASE



Peter J. Winzer, David T. Neilson, Andrew R. Chraplyvy, "*Fiber-optic transmission and networking: the previous 20 and the next 20 years* [Invited]," Opt. Express **26,** 24190-24239 (2018);

DIRECT-DETECTION SYSTEMS

DATA-CENTER LINKS



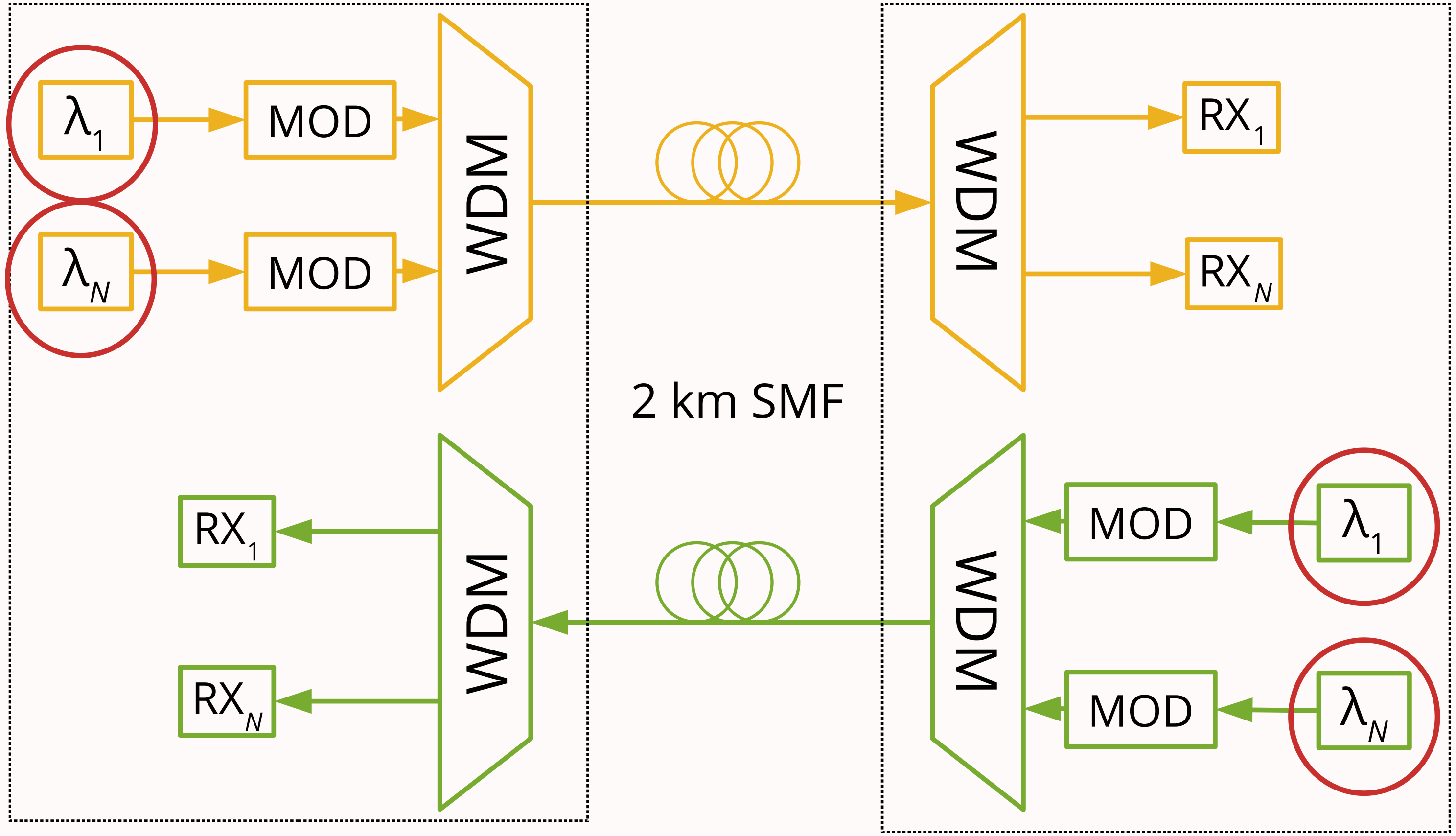
INTRA-DC CONNECTIONS

A “SPATIAL MULTIPLEXING” PROPOSAL

REQUIREMENTS FOR FUTURE INTRA-DC LINKS

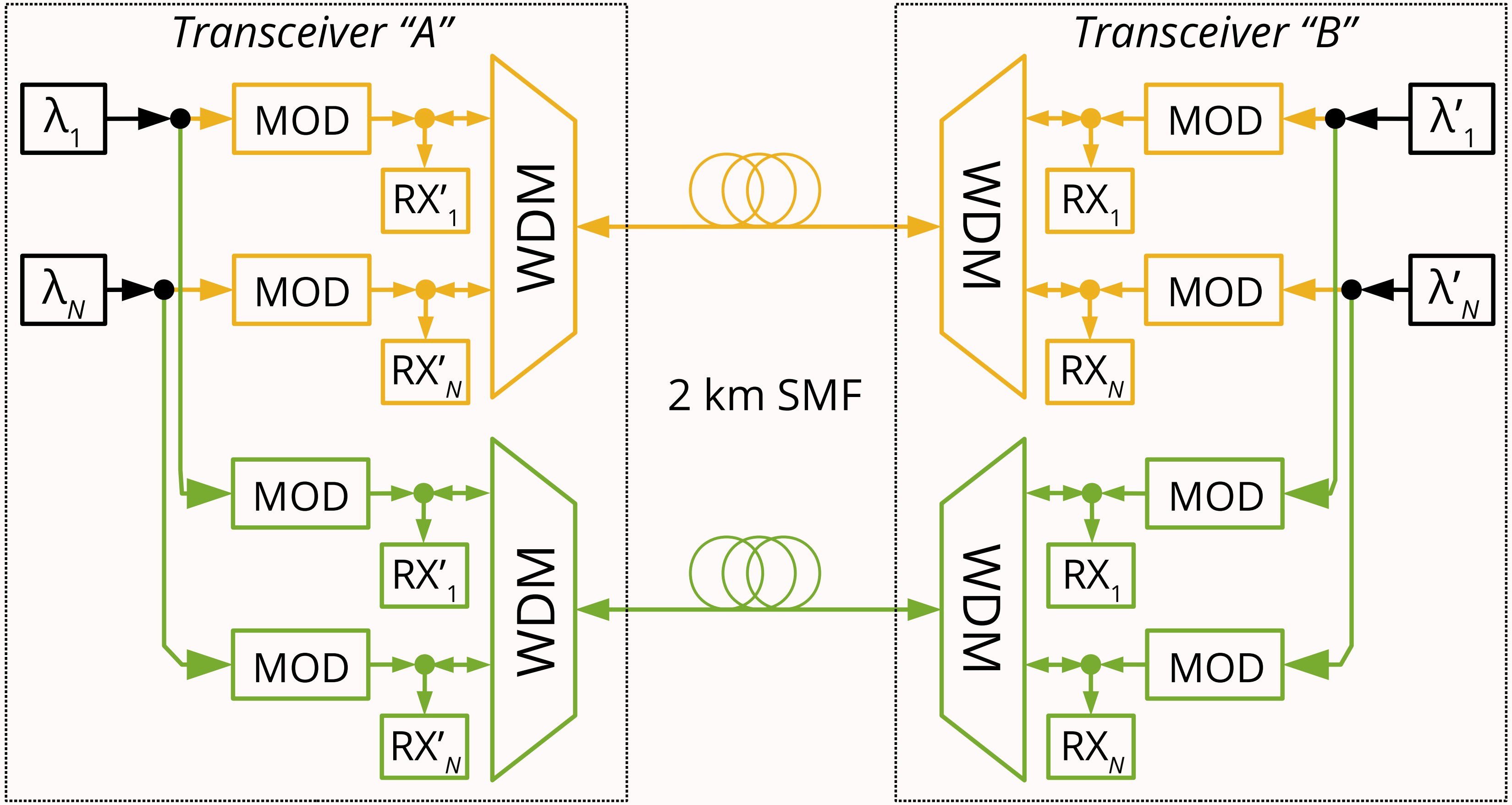
- Speed
- Cost
- Size
- Power consumption

400GBASE-FR8 STANDARD



- 8 WDM channels, 800 GHz spacing
- 50 Gbit/s per channel
- Two transceivers, duplex SMF cable
  - *How to reduce power consumption?*

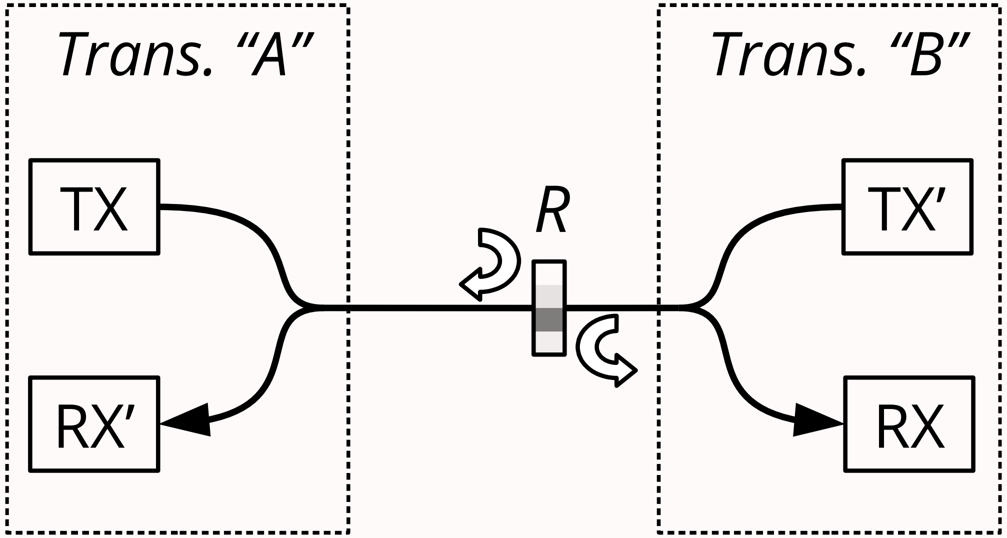
PROPOSED ARCHITECTURE



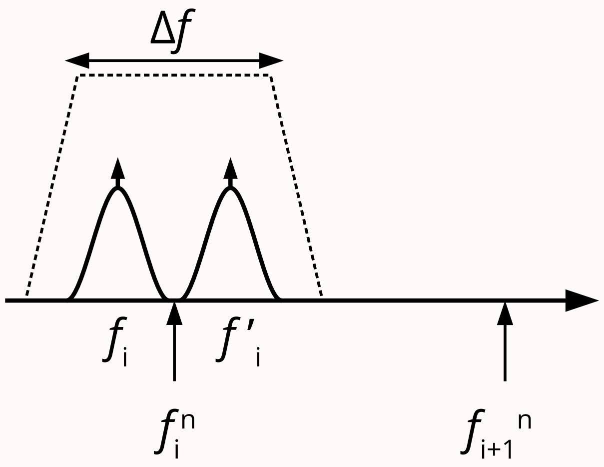
- Lasers are shared inside each transceiver (like MPO)
  - Duplex cable used simultaneously in both directions, like in PONs
- **Double** *per-laser* capacity
  - Unavoidable link-budget loss due to 3-dB splitters

D. Pilori et al., "*Bidirectional 4-PAM to Double Per-Fiber Capacity in 2-km Intra-Datacenter Links*", IEEE Photonics Journal 10.2, pp. 1-10 (2018)

MAIN ISSUE: BACK-REFLECTIONS



- Back-reflections cause coherent crosstalk
- PONs use completely different wavelength (in O- and C-bands)
- Proposal: *slight* detuning, staying in the same WDM channel



D. Pilori et al., "*Bidirectional 4-PAM to Double Per-Fiber Capacity in 2-km Intra-Datacenter Links*", IEEE Photonics Journal 10.2, pp. 1-10 (2018)

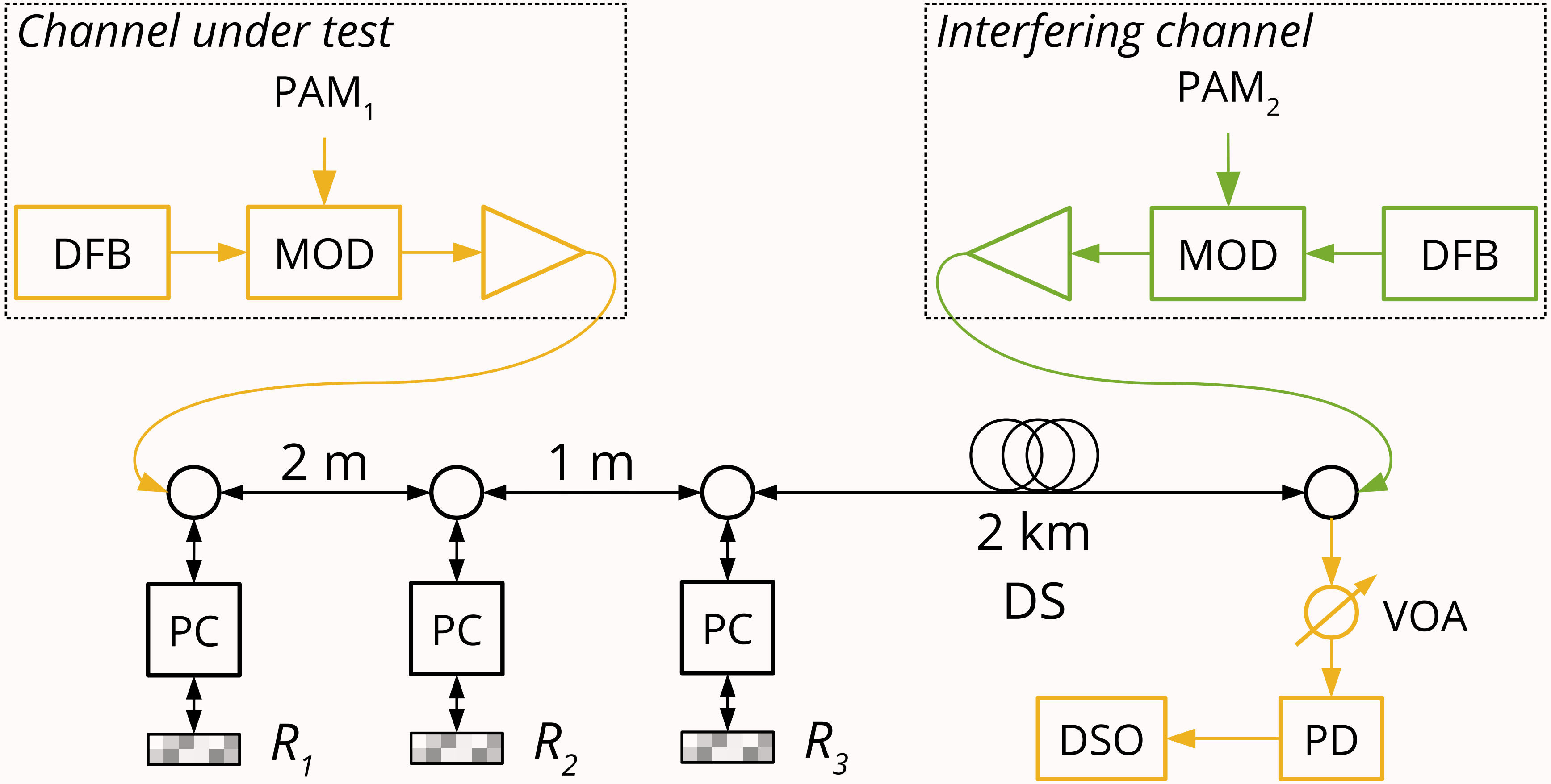
GOAL OF THIS WORK

- **Back-reflection penalty** as a function of **laser frequency separation** for 2-km PAM-4 links

- Demonstrate that a *small* separation is sufficient to keep penalty *low* (<0.5 dB) for "standard" reflections

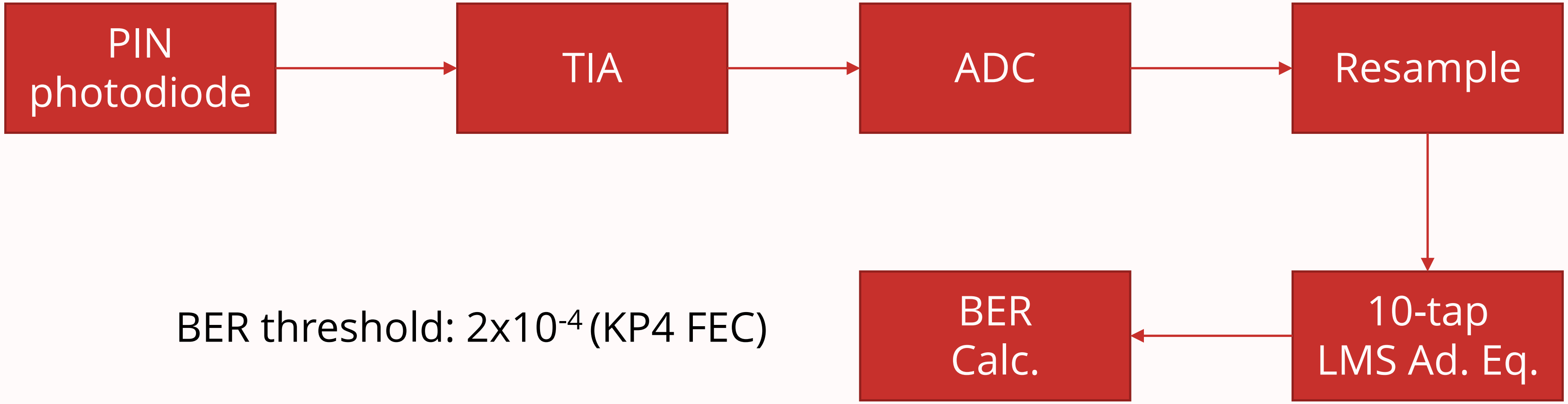
  - For instance, legacy TIA-568 LC connectors have a maximum back-reflection of -26 dB

EXPERIMENTAL SETUP



- 1550-nm transmission using DS fiber to emulate 1310-nm
- 53 GBaud or 28 GBaud PAM-4

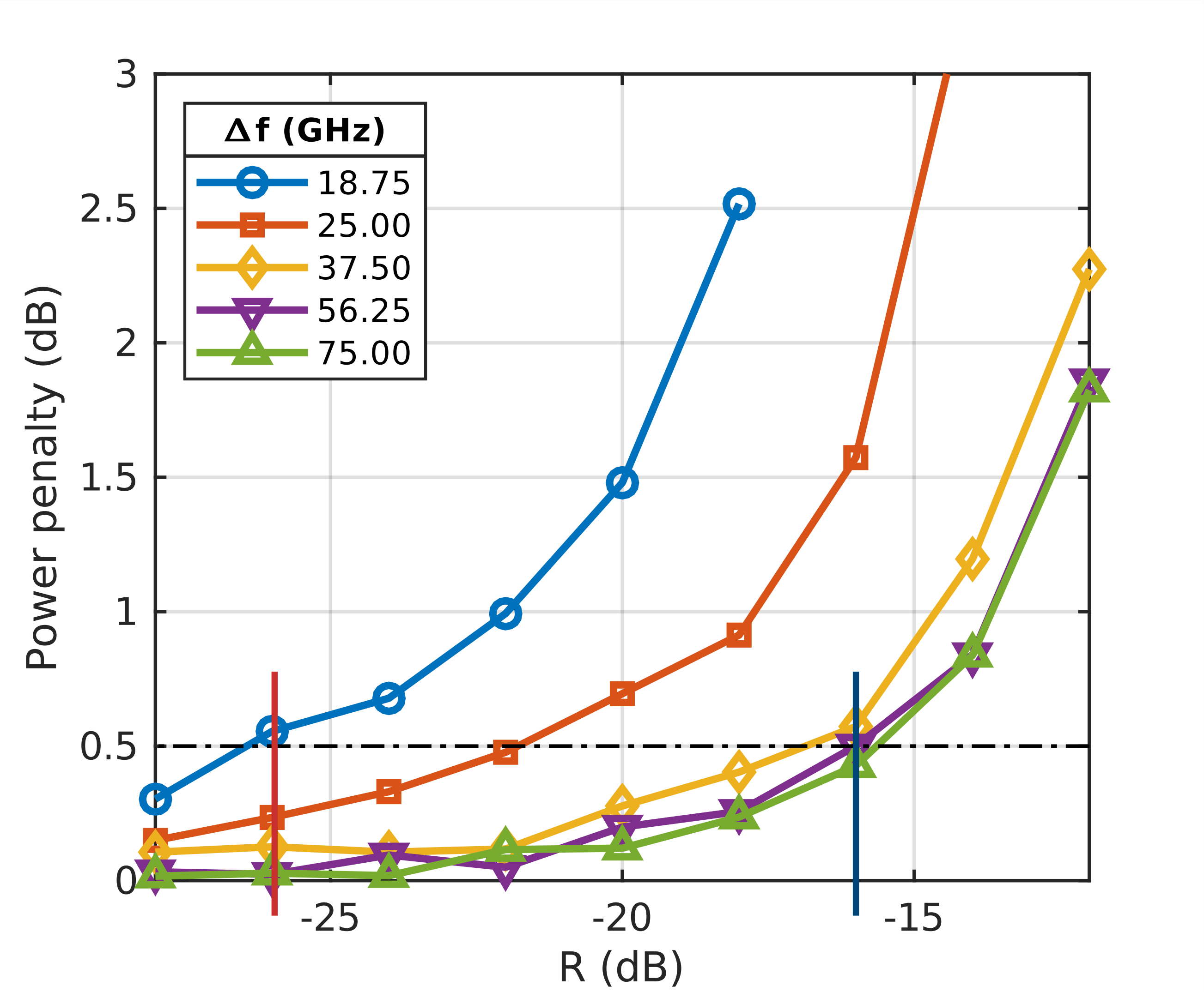
RECEIVER STRUCTURE AND DSP



BER threshold: $2x10^{-4}$ (KP4 FEC)

D. Pilori et al., “*Bidirectional 4-PAM to Double Per-Fiber Capacity in 2-km Intra-Datacenter Links*”, IEEE Photonics Journal 10.2, pp. 1-10 (2018)

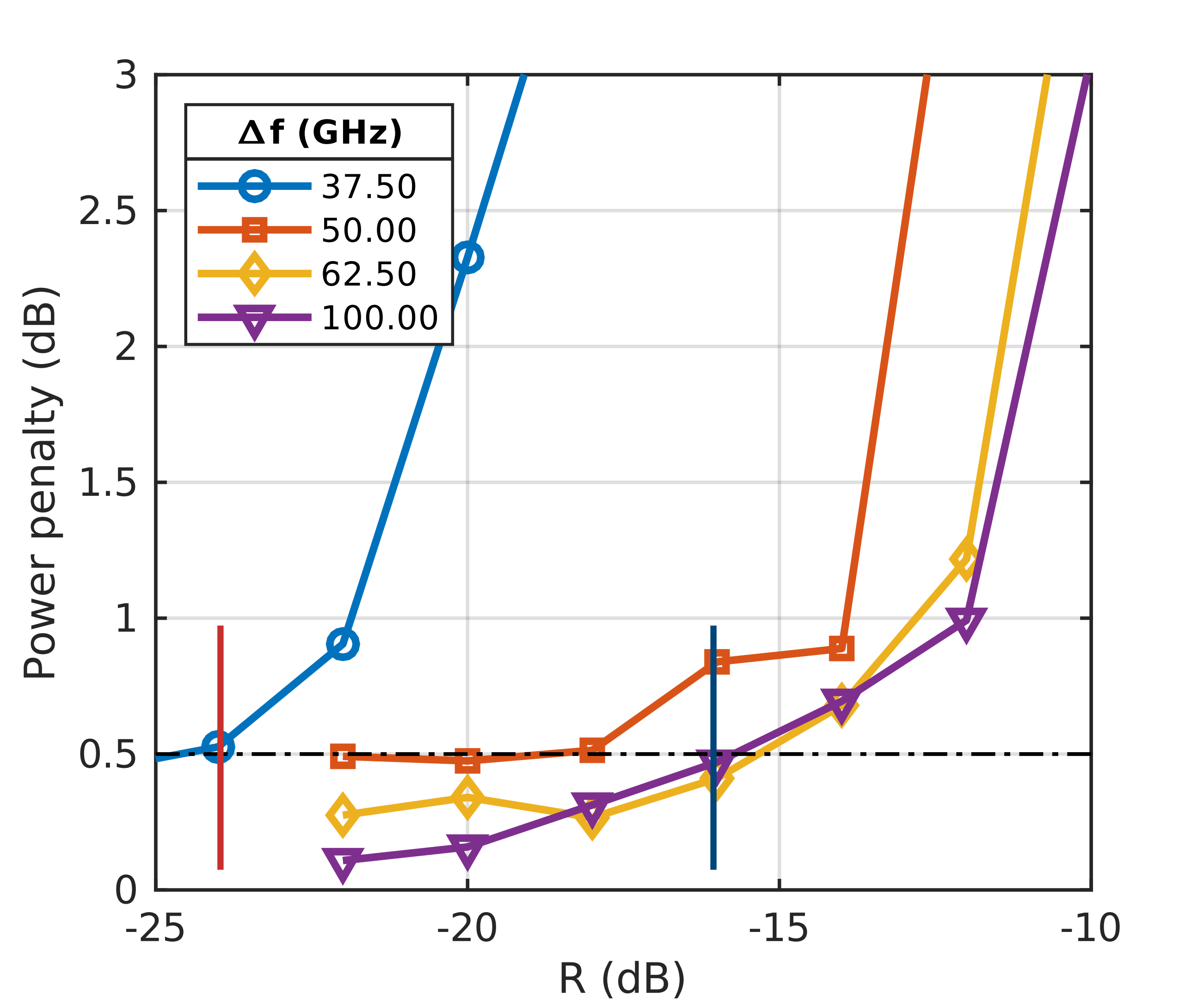
SINGLE REFLECTION RESULTS – 28 GBAUD



- Rule of thumb: **Δf>R_s**
- Feasible in the LAN-WDM grid (800-GHz spacing)

D. Pilori et al., “*Bidirectional 4-PAM to Double Per-Fiber Capacity in 2-km Intra-Datacenter Links*”, IEEE Photonics Journal 10.2, pp. 1-10 (2018)

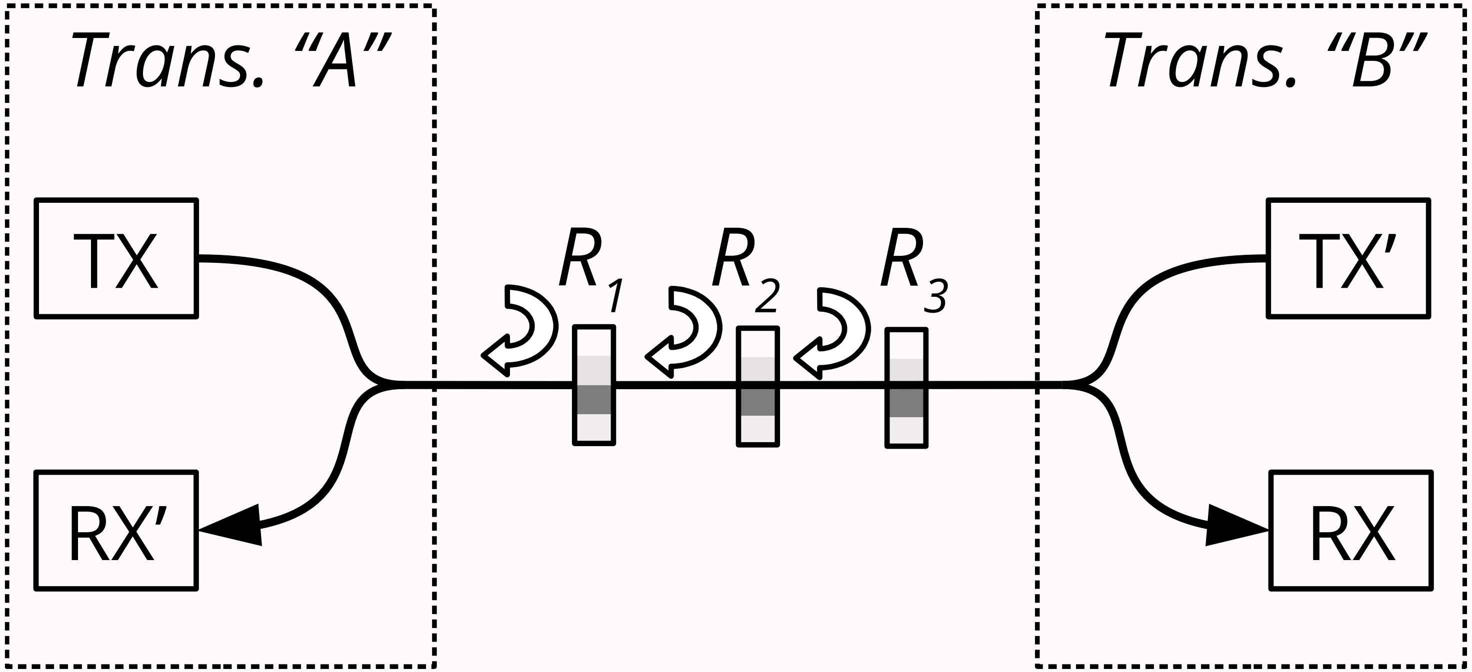
SINGLE REFLECTION RESULTS – 53 GBAUD



- Rule of thumb:
  Δf>R_s

D. Pilori et al., "*Bidirectional 4-PAM to Double Per-Fiber Capacity in 2-km Intra-Datacenter Links*", IEEE Photonics Journal 10.2, pp. 1-10 (2018)

MULTIPLE REFLECTIONS

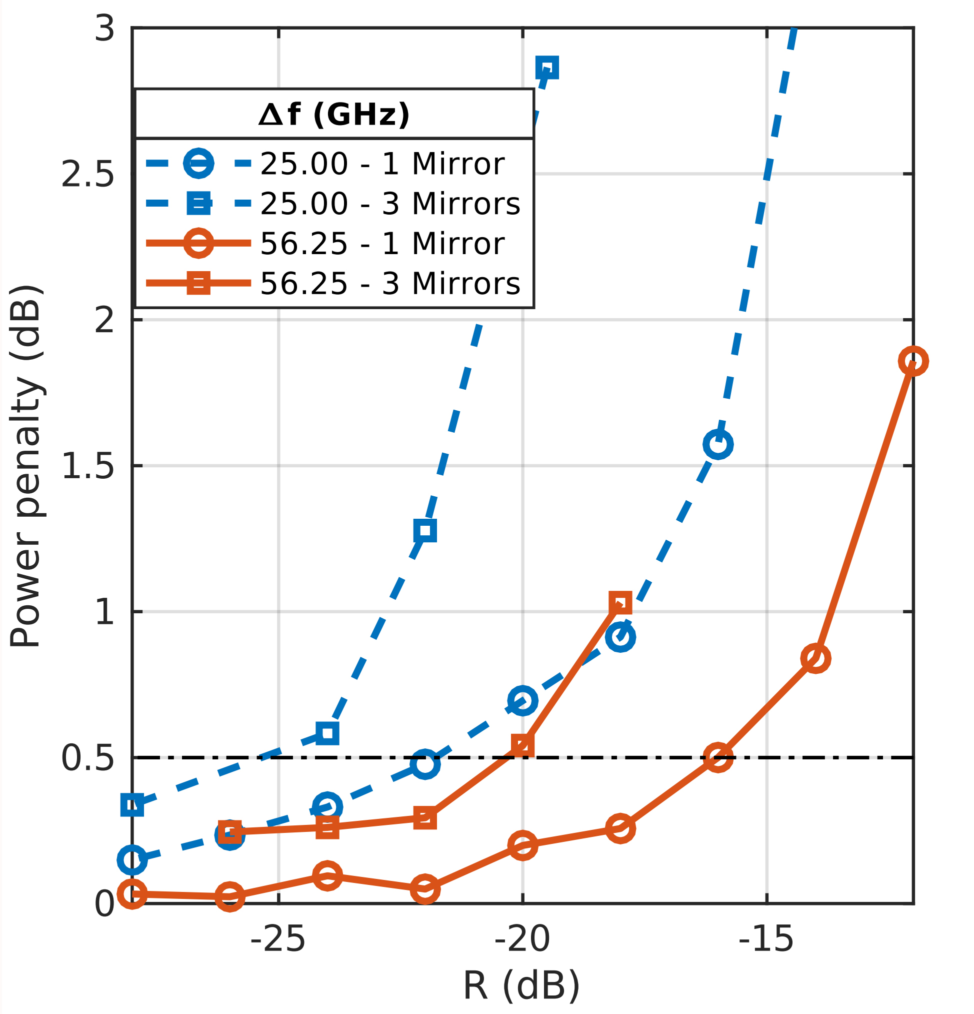


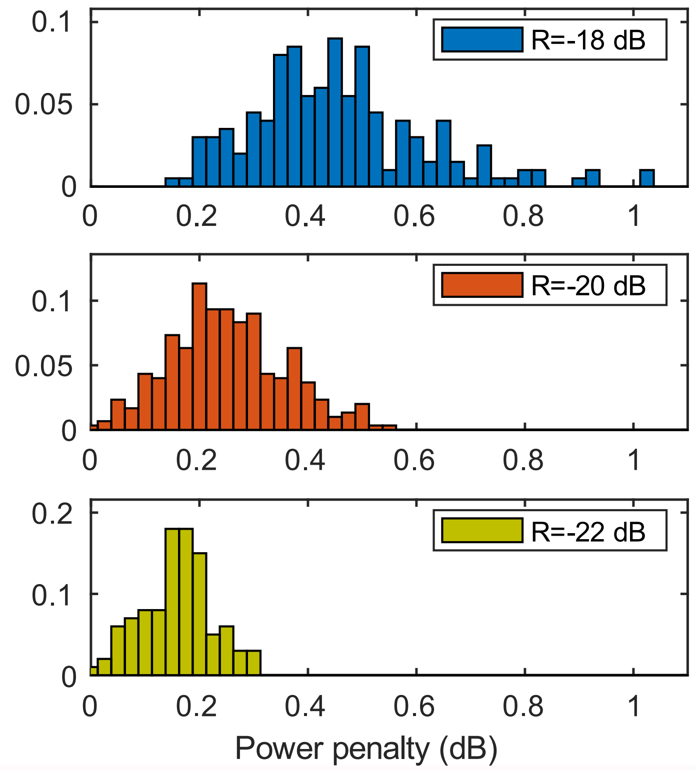
$$P_{\text{refl}} \propto \left| R_1 e^{j\phi_1} + R_2 e^{j\phi_2} + R_3 e^{j\phi_3} \right|^2$$

OPTCOM

D. Pilori et al., "*Bidirectional 4-PAM to Double Per-Fiber Capacity in 2-km Intra-Datacenter Links*", IEEE Photonics Journal 10.2, pp. 1-10 (2018)

THREE REFLECTIONS RESULTS – 28 GBAUD





R is normalized to have the same reflected power at the receiver

- Multiple-reflection penalty is random
  - Worst-case over 100 measurements
- **Rule of thumb: Δf>2R_s**

CONCLUSIONS ON THIS ARCHITECTURE

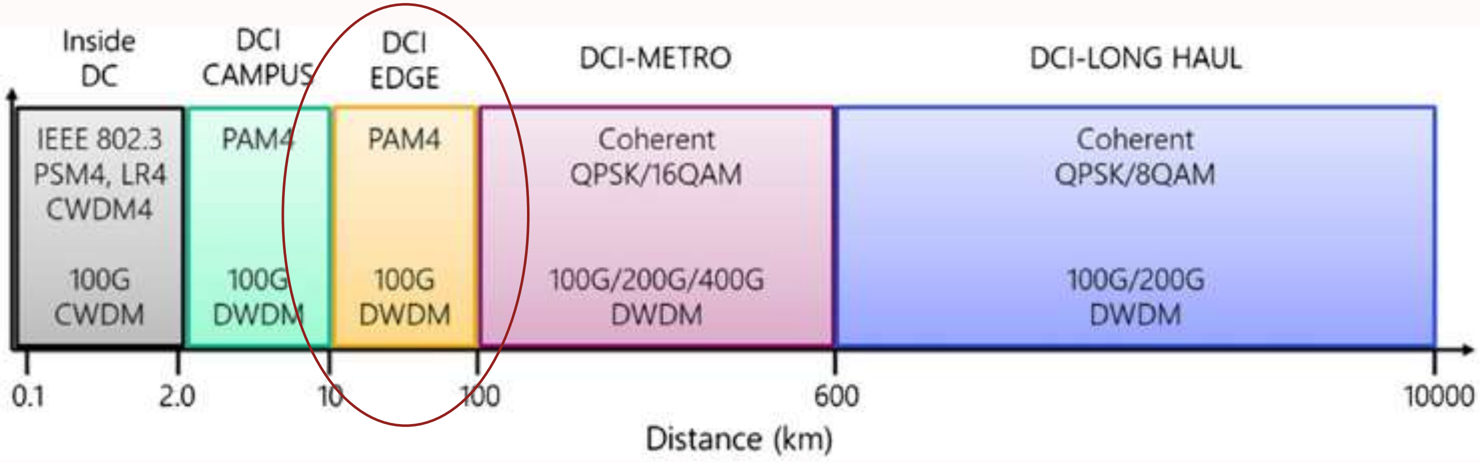
- A **bi-directional** architecture can potentially double *per-laser* capacity over standard duplex SMF cables
  - There are still several issues to be solved: power budget due to 3-dB splitters, laser wavelength control, …
- Back-reflection penalties can be *avoided* if lasers in one transceiver are *slightly* detuned
  - Rule of thumb: $\mathbf{\Delta f > 2R_s}$
  - Keeps same nominal channel in WDM grid

D. Pilori et al., "*Bidirectional 4-PAM to Double Per-Fiber Capacity in 2-km Intra-Datacenter Links*", IEEE Photonics Journal 10.2, pp. 1-10 (2018)

INTER-DC CONNECTIONS

COHERENT OR DIRECT DETECTION?

WHICH MODULATION FORMAT FOR DCI?



Source: R. Nagarajan et al., J. Opt. Commun. Netw. 10, B25-B36 (2018)

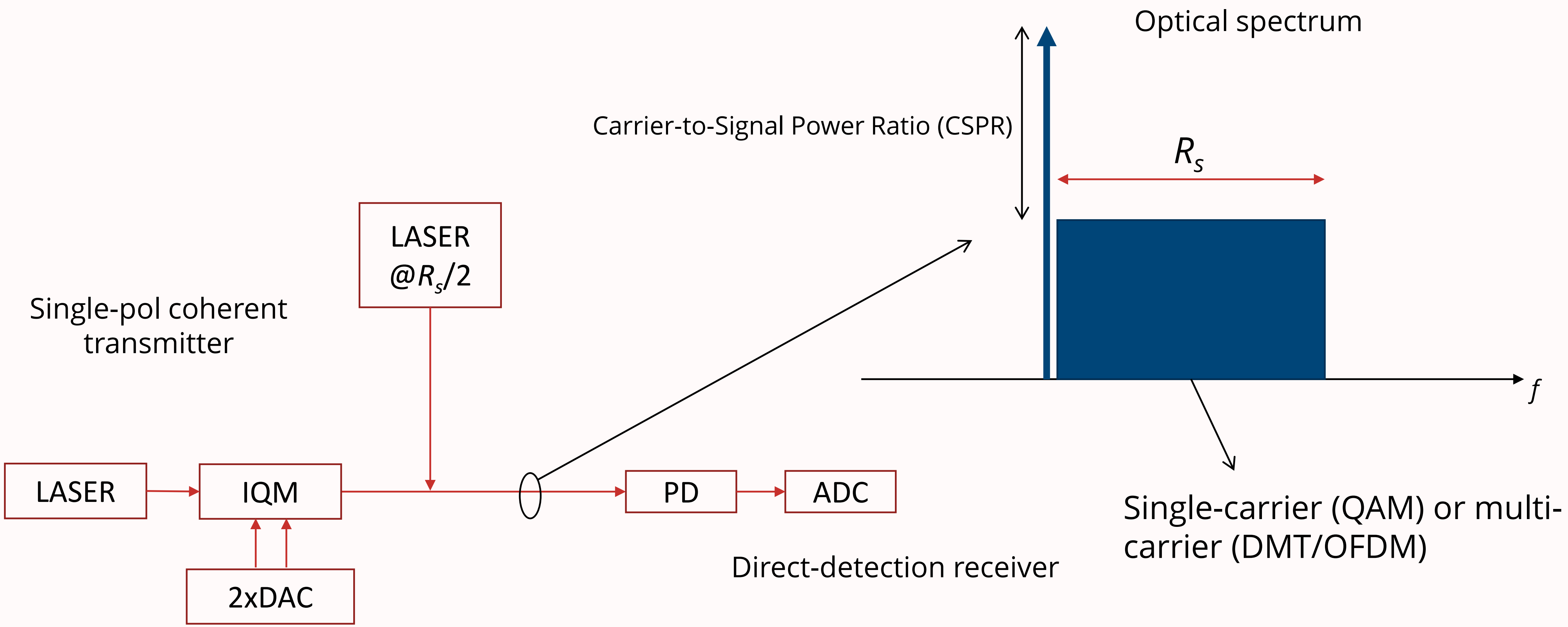
Inphi and Microsoft: PAM-4 (current), PM-16QAM (future)

Main characteristics for this scenario

- Standard single-mode fiber (SSMF) up to 100km
- C-band (EDFAs required at TX and RX)
  - Dispersion must be compensated
- High spectral efficiency not required
- Low cost and power consumption

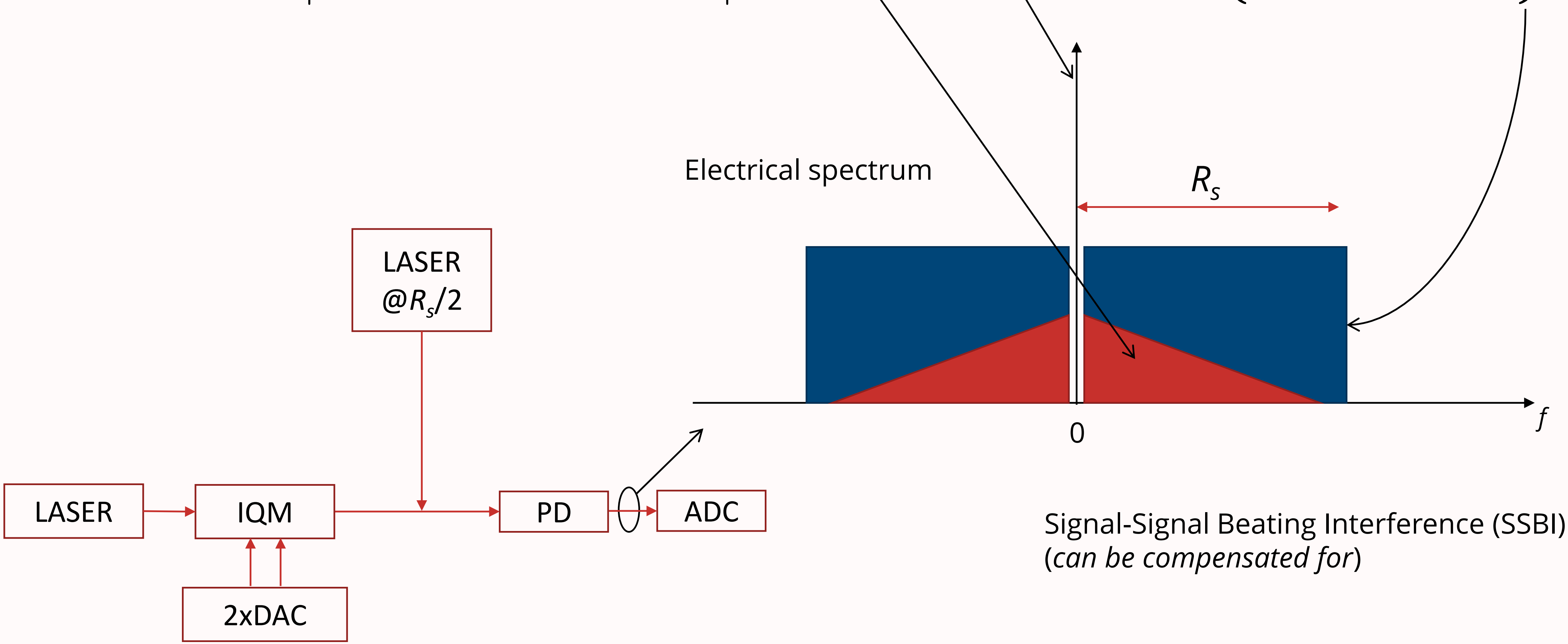
Coherent or direct detection?

SINGLE-SIDEBAND SELF-COHERENT TRANSMITTER



SINGLE-SIDEBAND SELF-COHERENT RECEIVER

$$\left|x(t) + c \cdot e^{-j2\pi t R_s/2}\right|^2 = |x(t)|^2 + c^2 + 2c \cdot \Re\left\{x(t)e^{j2\pi t R_s/2}\right\}$$



Signal-Signal Beating Interference (SSBI)
(*can be compensated for*)

SSB TRANSMISSION: PROS AND CONS

1. Direct detection ✓
2. Higher spectral efficiency ✓
3. Electronic dispersion compensation ✓

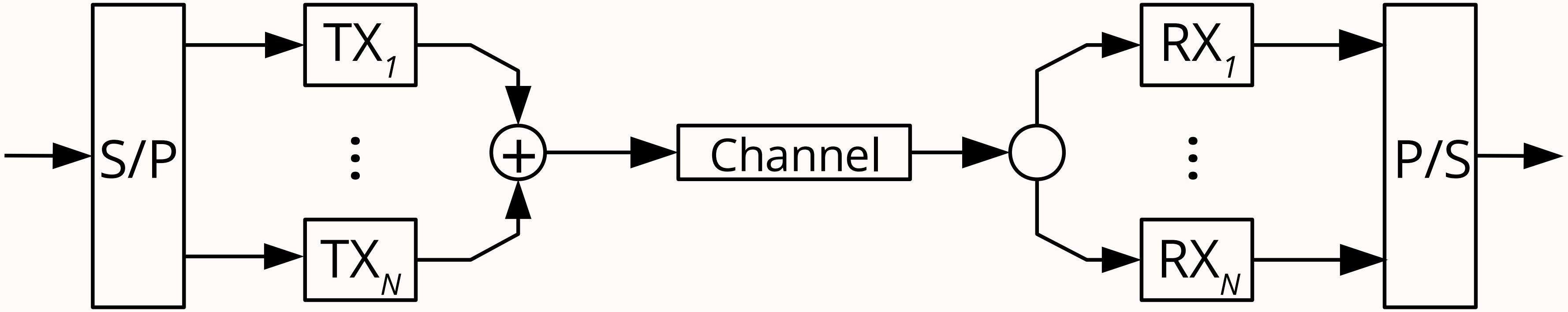
1. Complex transmitter structure ✗
2. High receiver analog bandwidth ✗
3. Reduced OSNR sensitivity ✗

D. Pilori and R. Gaudino, "*Direct-Detection Single-Sideband Systems: Performance Comparison and Practical Implementation Penalties*" [invited], ICTON conference 2018, Bucharest (Romania)

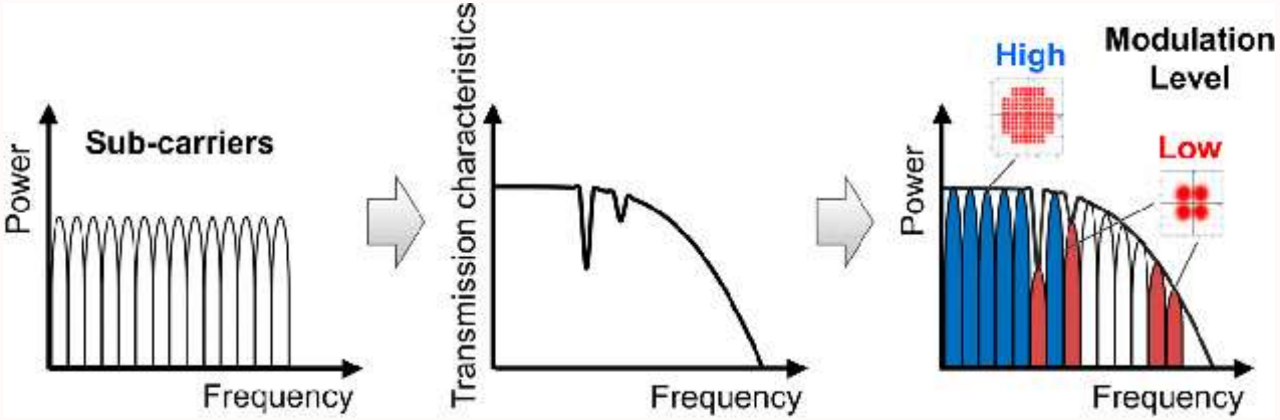
AN EXAMPLE

DMT MODULATION: INTENSITY MODULATION OR SINGLE SIDE-BAND?

DISCRETE-MULTITONE MODULATION (DMT)

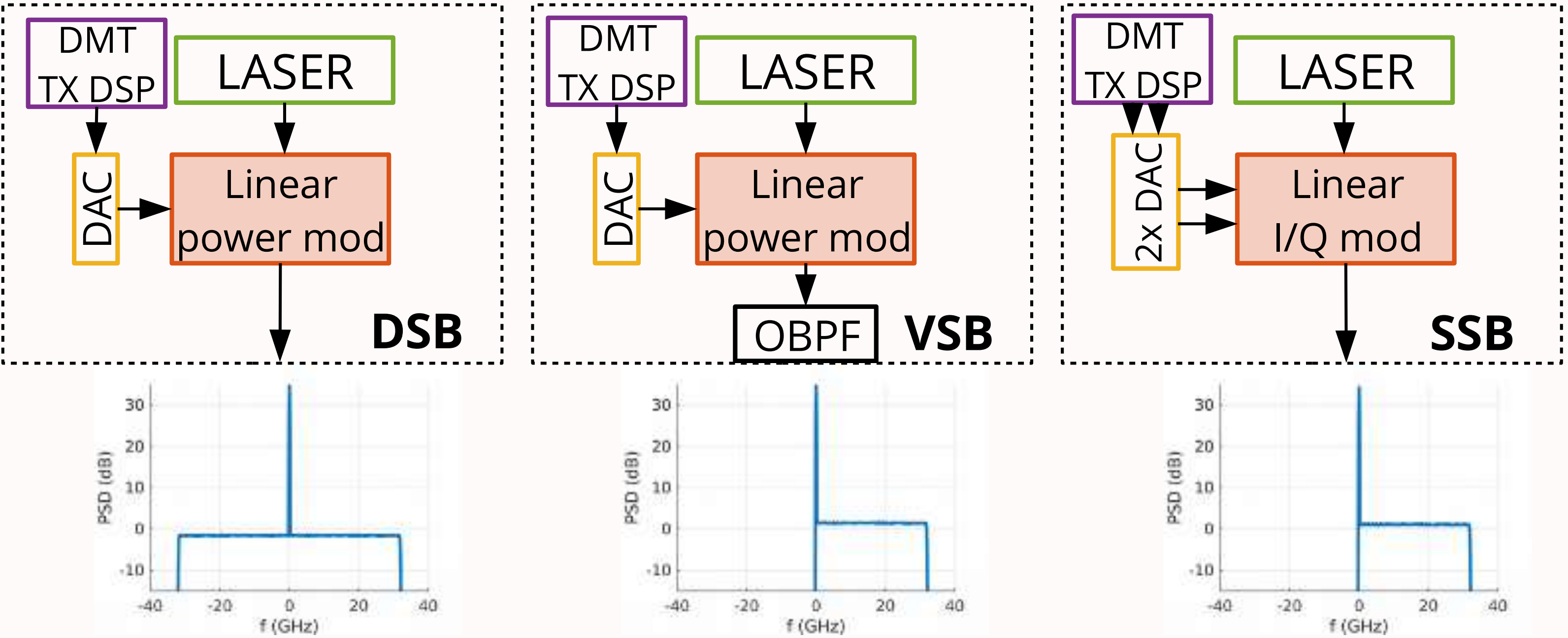


- Partial compensation of the frequency response of a dispersion-uncompensated IM/DD link

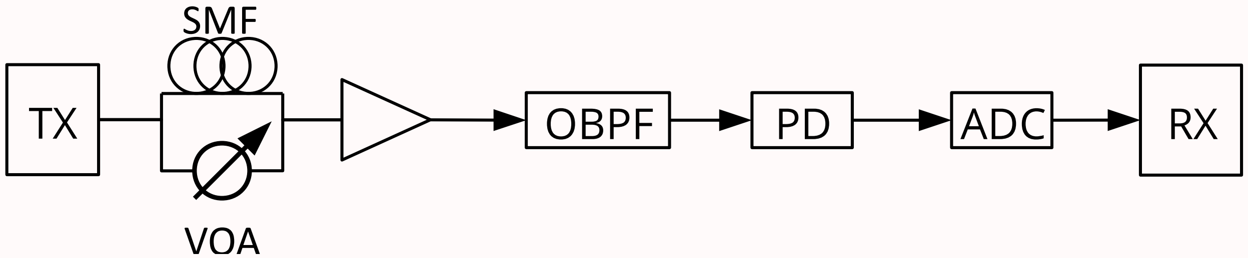


Source: T. Takahara et al., Proc. OFC 2014, M2I.1

SIMULATION SETUP



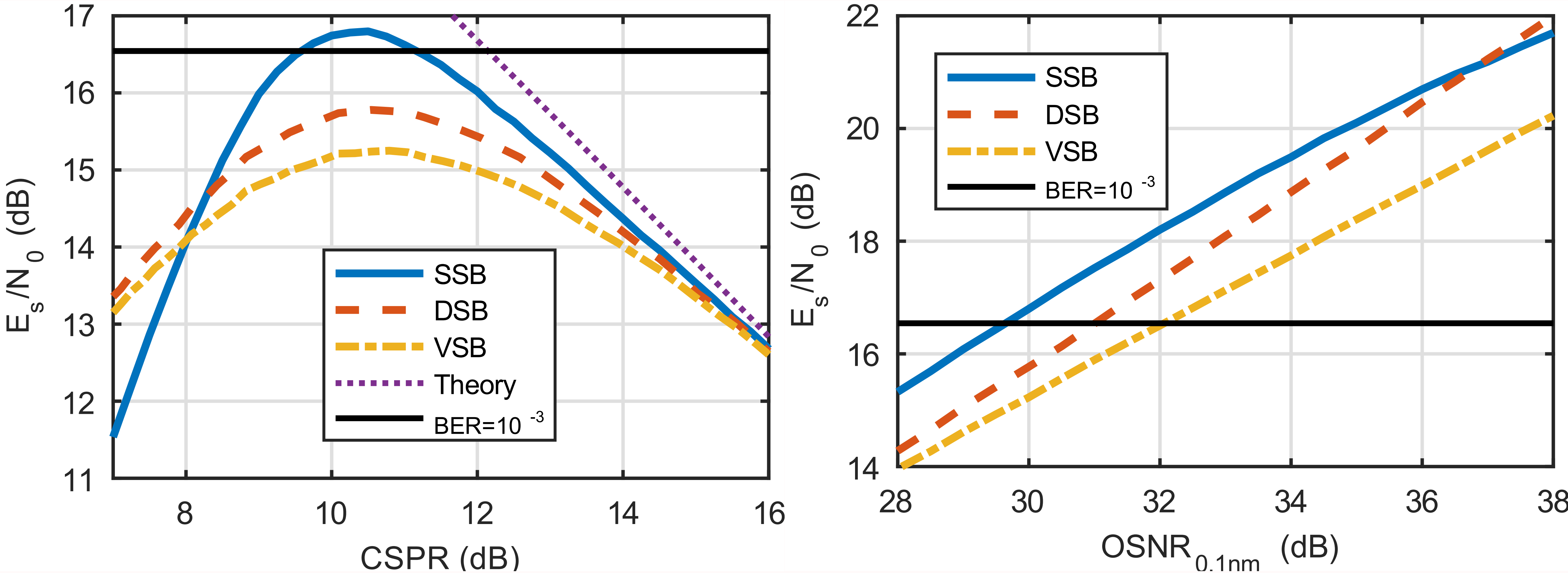
Parameter	Value
FFT size	1024
Bitrate	120 Gbit/s
DAC sampling rate	64 GS/s
BER threshold	10^{-3}
DAC 3-dB bandwidth	13 GHz
DAC resolution	6 bit



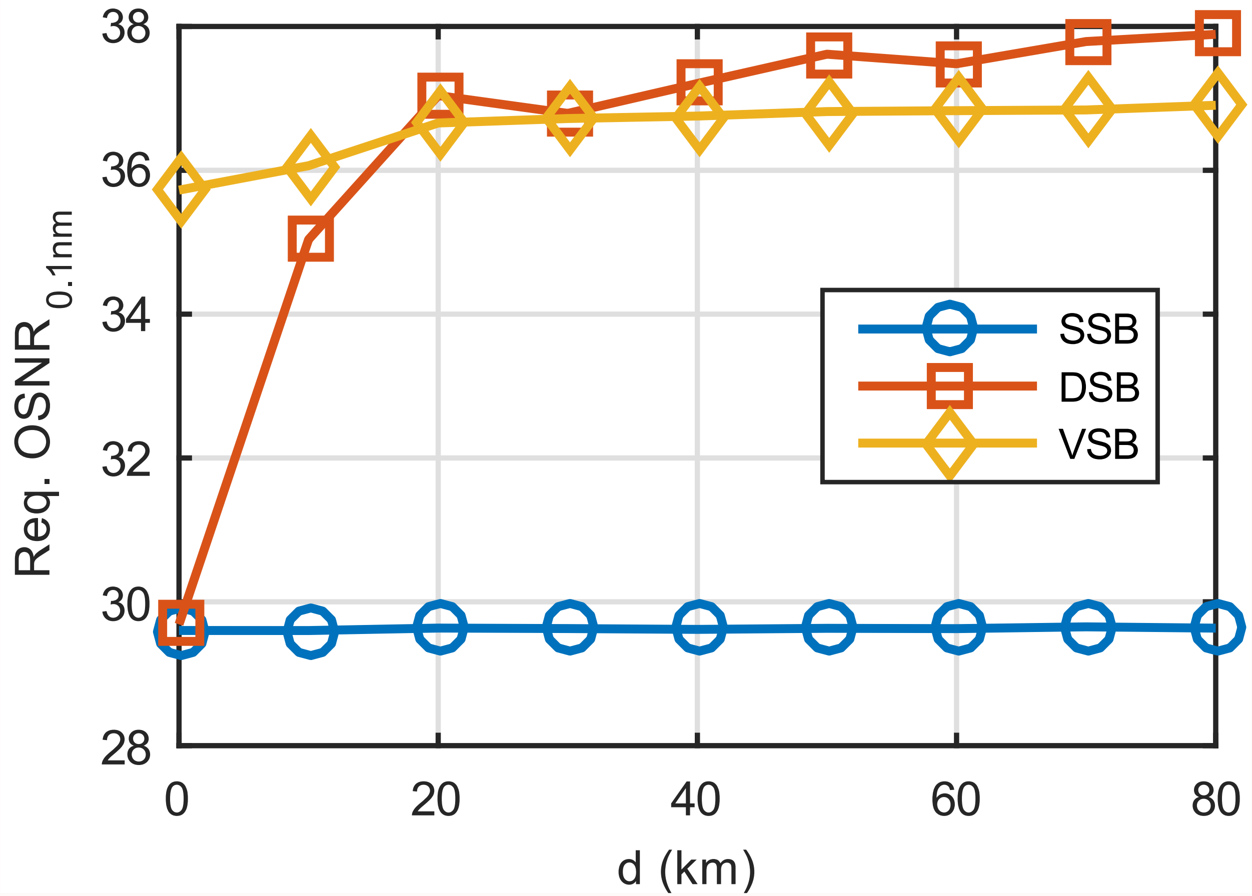
Margin-Adaptive (MA)
Levin-Campello bit-loading

D. Pilori et al., "*Comparing DMT Variants in Medium-Reach 100G Optically Amplified Systems*", J. Lightwave Technol. 34.14, 3389-3399 (2016)

BACK-TO-BACK COMPARISON



D. Pilori et al., "*Comparing DMT Variants in Medium-Reach 100G Optically Amplified Systems*", J. Lightwave Technol. 34.14, 3389-3399 (2016)



- SSB is practically unaffected by CD
- DSB/VSB: strong OSNR penalty
- VSB filter: SuperGaussian

D. Pilori et al., "*Comparing DMT Variants in Medium-Reach 100G Optically Amplified Systems*", J. Lightwave Technol. 34.14, 3389-3399 (2016)

CONCLUSIONS ON INTRA-DC

- SSB self-coherent is a viable "hybrid" between direct detection and coherent
  - Advanced techniques like Kramers-Kronig are able to fully compensate for SSBI

- Excellent performance on ~80km dispersion-uncompensated links
  - IM/DD systems **must** use optical dispersion compensation, even with DMT and bit loading
  - Nevertheless, there are still several practical implementation issues that need to be solved

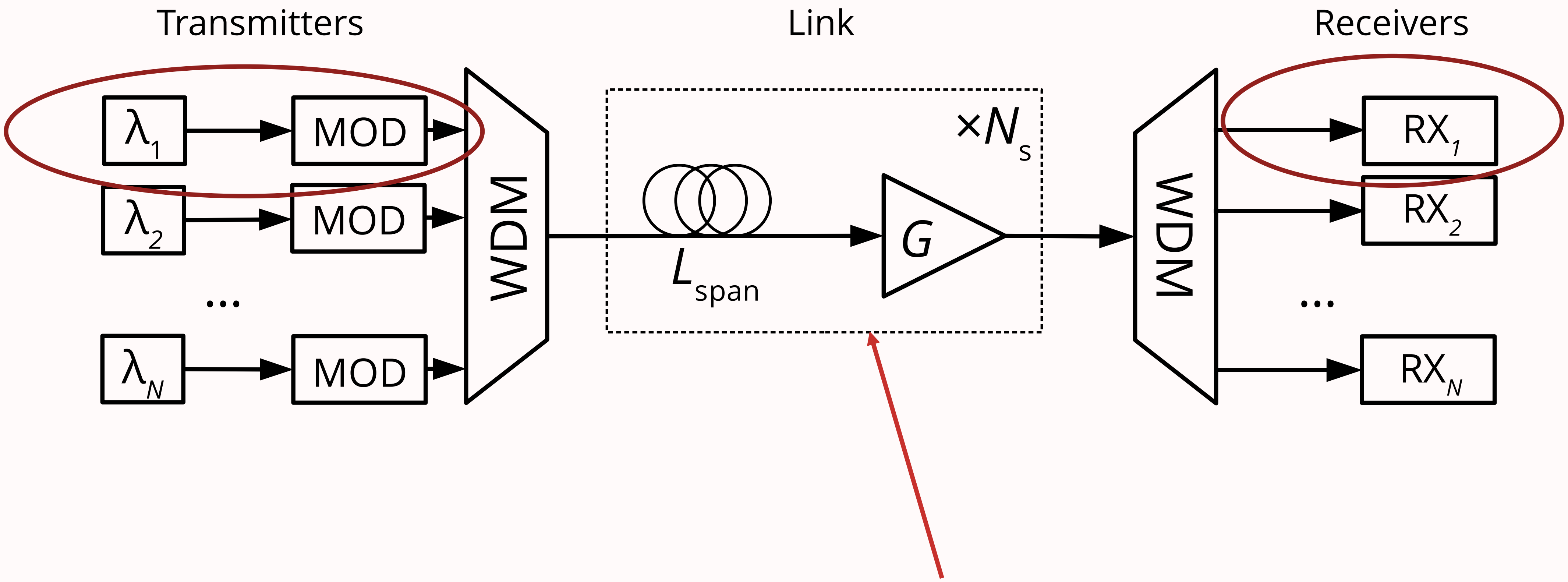
D. Pilori et al., "*Comparing DMT Variants in Medium-Reach 100G Optically Amplified Systems*", J. Lightwave Technol. 34.14, 3389-3399 (2016)

POLITECNICO DI TORINO

COHERENT SYSTEMS

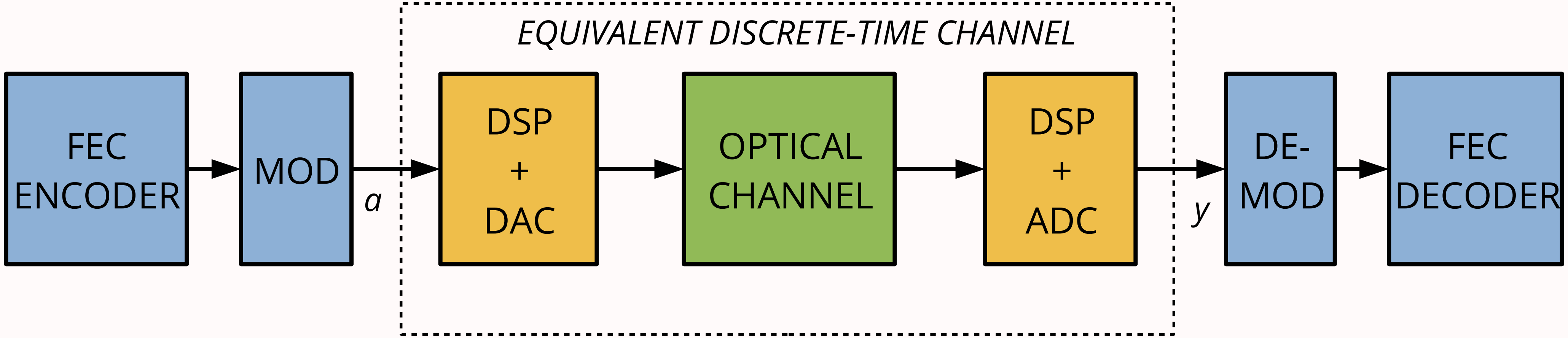
AN INTRODUCTION

GENERIC COHERENT LONG-HAUL SYSTEM



- ASE noise
- Fiber Kerr effect

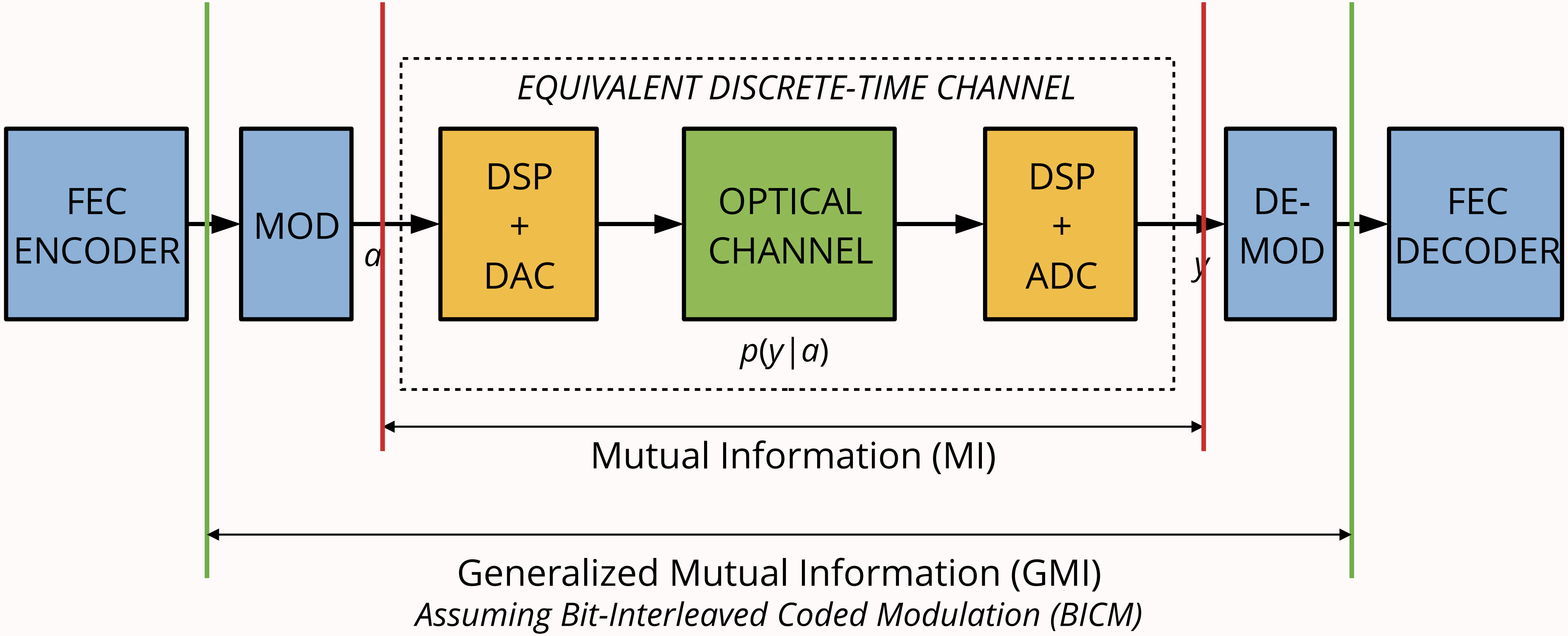
EQUIVALENT CHANNEL



- DSP point of view: equivalent channel
  - Using theoretical models, simulations or experiments DSP can be tested, and performance metrics obtained

E. Agrell and M. Secondini, "*Information-Theoretic Tools for Optical Communications Engineers*," 2018 IEEE Photonics Conference (IPC), Reston, VA, 2018

SOFT PERFORMANCE METRICS



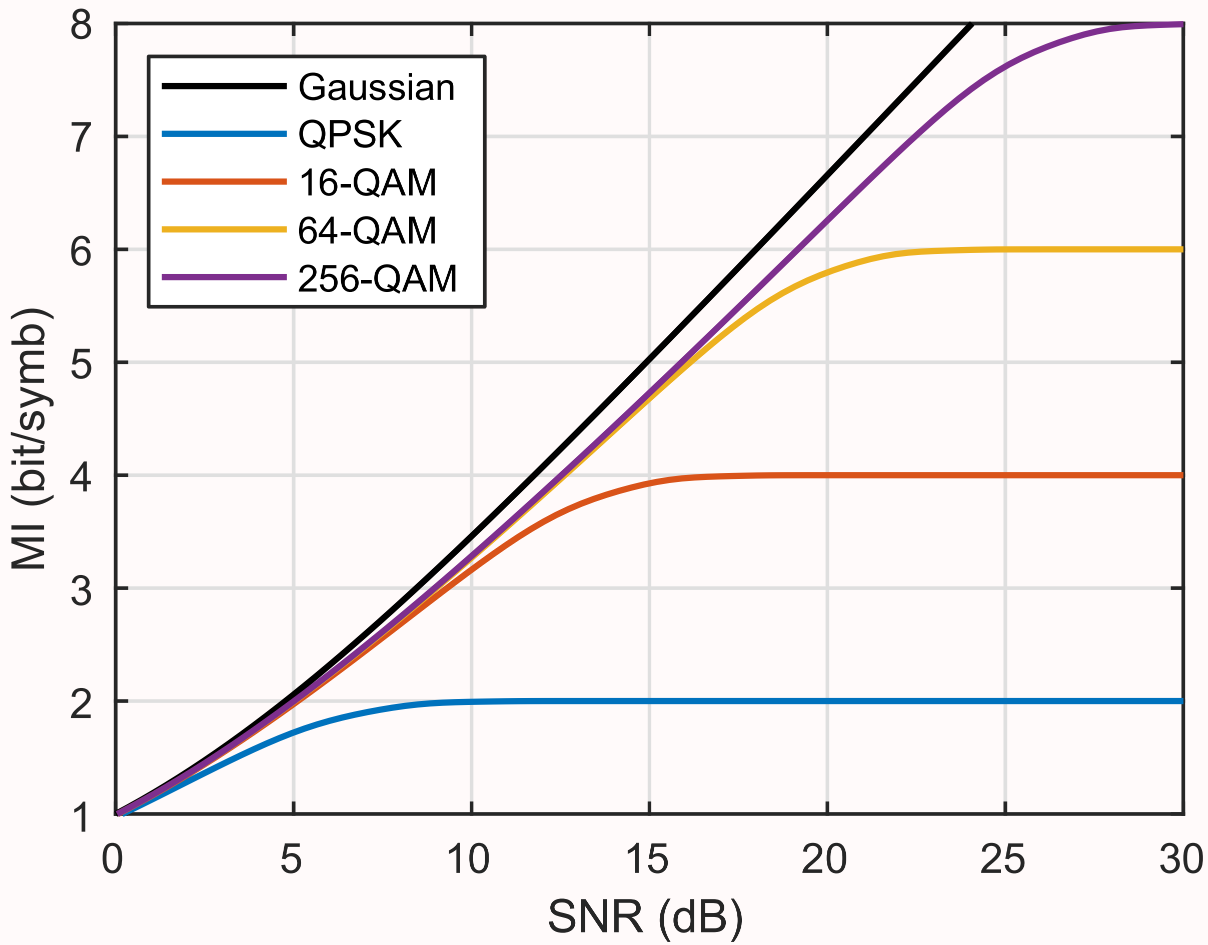
- Linked to the performance of soft-decision FEC codes

Alex Alvarado, Erik Agrell, Domaniç Lavery, Robert Maher, and Polina Bayvel, "*Replacing the Soft-Decision FEC Limit Paradigm in the Design of Optical Communication Systems*," J. Lightwave Technol. 33, 4338-4352 (2015)

PROBABILISTIC CONSTELLATION SHAPING

BASICS OVER AN AWGN CHANNEL

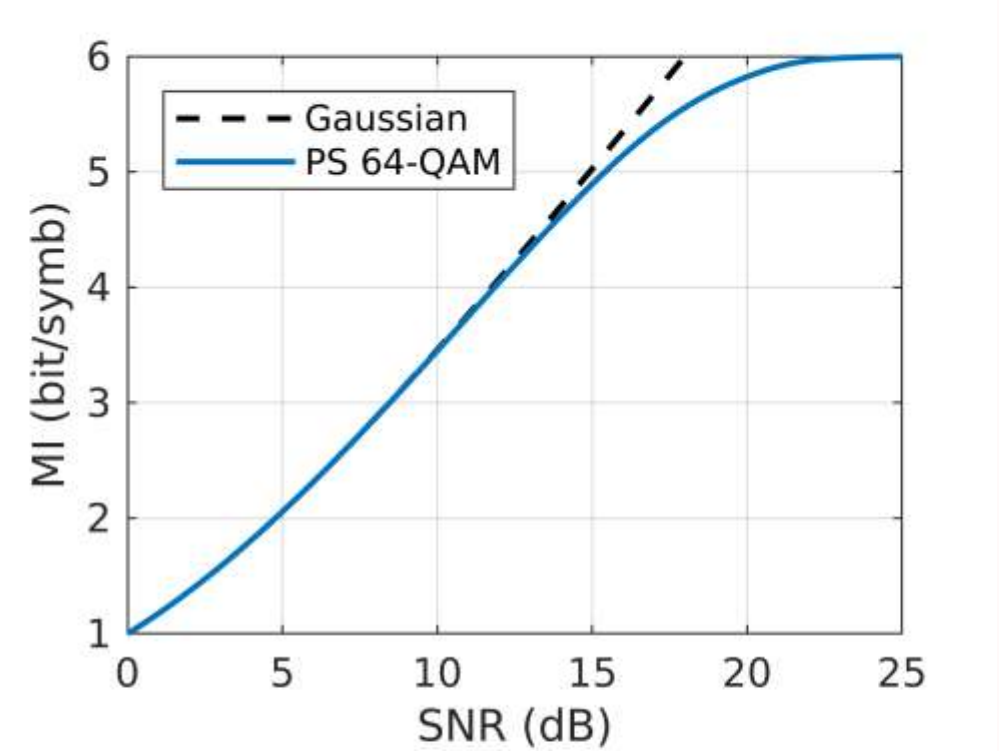
STANDARD QAM CONSTELLATIONS

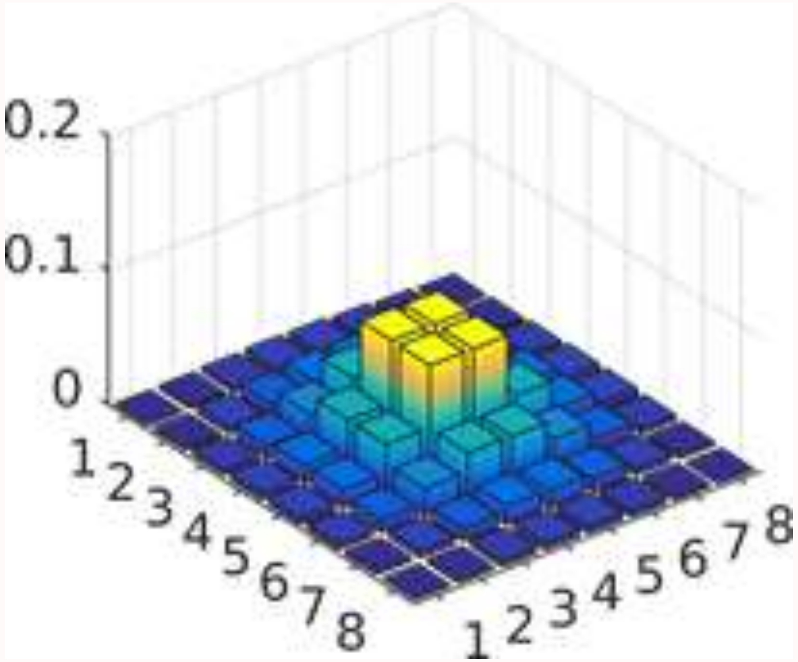


- ~1.53 dB asymptotic gap to capacity
- **Fixed** data rates!
  - Unless different FEC rates are used

PROBABILISTIC CONSTELLATION SHAPING

- The two goals can be achieved by transmitting QAM symbols with *different probability*





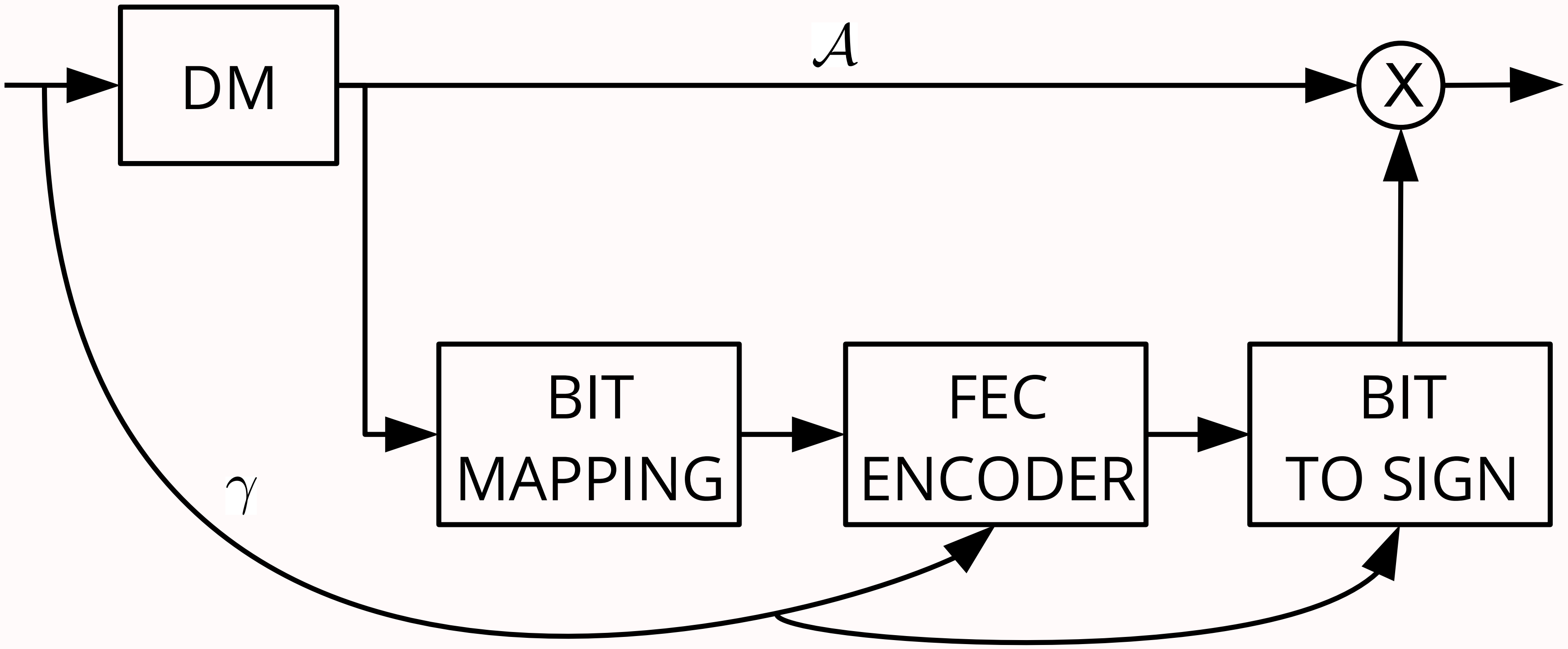
Fred Buchali, Fabian Steiner, Georg Böcherer, Laurent Schmalen, Patrick Schulte, and Wilfried Idler, "*Rate Adaptation and Reach Increase by Probabilistically Shaped 64-QAM: An Experimental Demonstration*," J. Lightwave Technol. 34, 1599-1609 (2016)

PROBABILISTIC SHAPING: PRACTICAL ISSUES

1. How to implement constellation shaping?
   - Implementable in hardware with low complexity
   - Must be combined with Forward Error Correction

2. Which probability distribution?
   - Potentially *any* distribution can be applied
   - AWGN channel: optimal distribution is Gaussian (infinite number of points…)

PROBABILITY AMPLITUDE SHAPING ARCHITECTURE



- Practical, capacity achieving combination of shaping and coding
- Distribution matcher (DM): random stream of bits to sequence of amplitudes *A* with desired distribution

G. Böcherer, F. Steiner and P. Schulte, "*Bandwidth Efficient and Rate-Matched Low-Density Parity-Check Coded Modulation*," in IEEE Transactions on Communications, vol. 63, no. 12, pp. 4651-4665, Dec. 2015.

NET (POST-FEC) DATA RATE

- Standard QAM constellations:

$$\mathrm{AIR_U} = r_\mathrm{U} m_\mathrm{U}$$

FEC code rate (r_U)

Constellation bit/symb. (m_U)

- Probabilistic shaping with PAS scheme and ideal DM:

$$\mathrm{AIR_{PS}} = \mathcal{H}(P) - (1-r)m$$

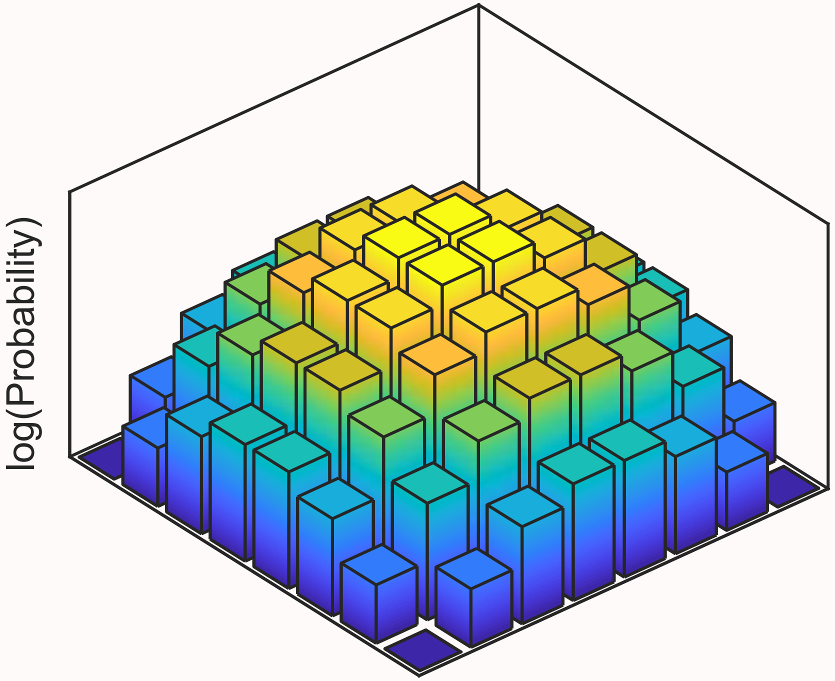
Entropy of PS constellation ($\mathcal{H}(P)$)

FEC code rate (r)

Constellation bit/symb. (m)

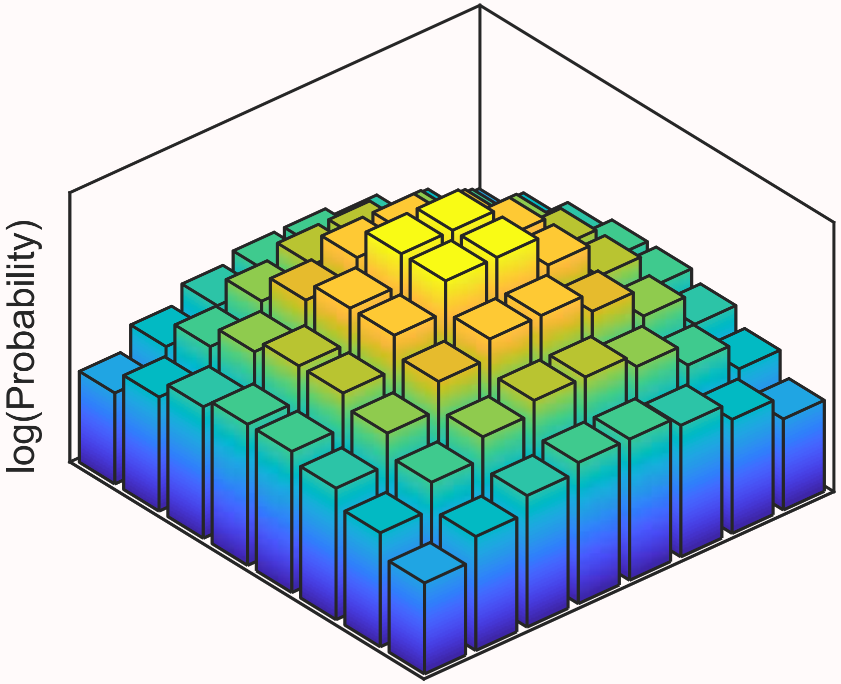
J. Cho et al., "On line rates, information rates, and spectral efficiencies in probabilistically shaped QAM systems," Opt. Express 26, 9784-9791 (2018)

MAXWELL-BOLTZMANN VS EXPONENTIAL



Maxwell-Bolzmann

$$P(a_i) \propto e^{-\lambda|a_i|^2}$$



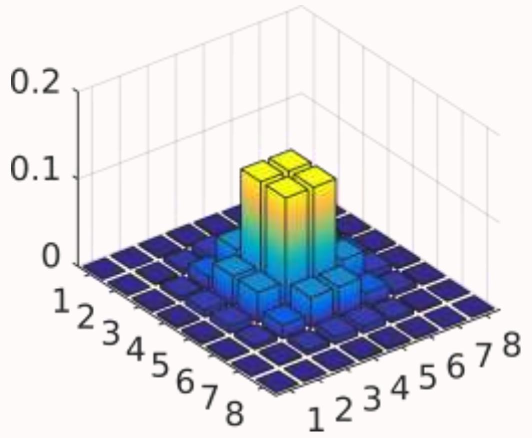
Exponential

$$P(a_i) \propto e^{-\lambda|a_i|}$$

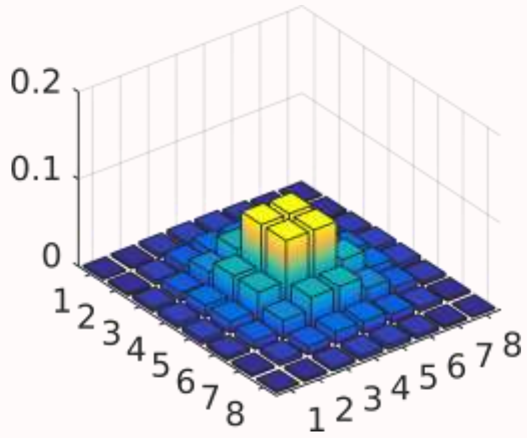
D. Pilori et al., "*Comparison of Probabilistically Shaped 64QAM With Lower Cardinality Uniform Constellations in Long-Haul Optical Systems*," J. Lightwave Technol. 36, 501-509 (2018)

AN EXPERIMENTAL COMPARISON

Constellation	Entropy (bit/symb)	FEC overhead	Distribution	Net data rate at 16 GBd
16-QAM	4	20%	-	106.6 Gbit/s
PS-64-QAM	4.33		Exponential	
32-QAM	5		-	133.3 Gbit/s
PS-64-QAM	5.17		Exponential	



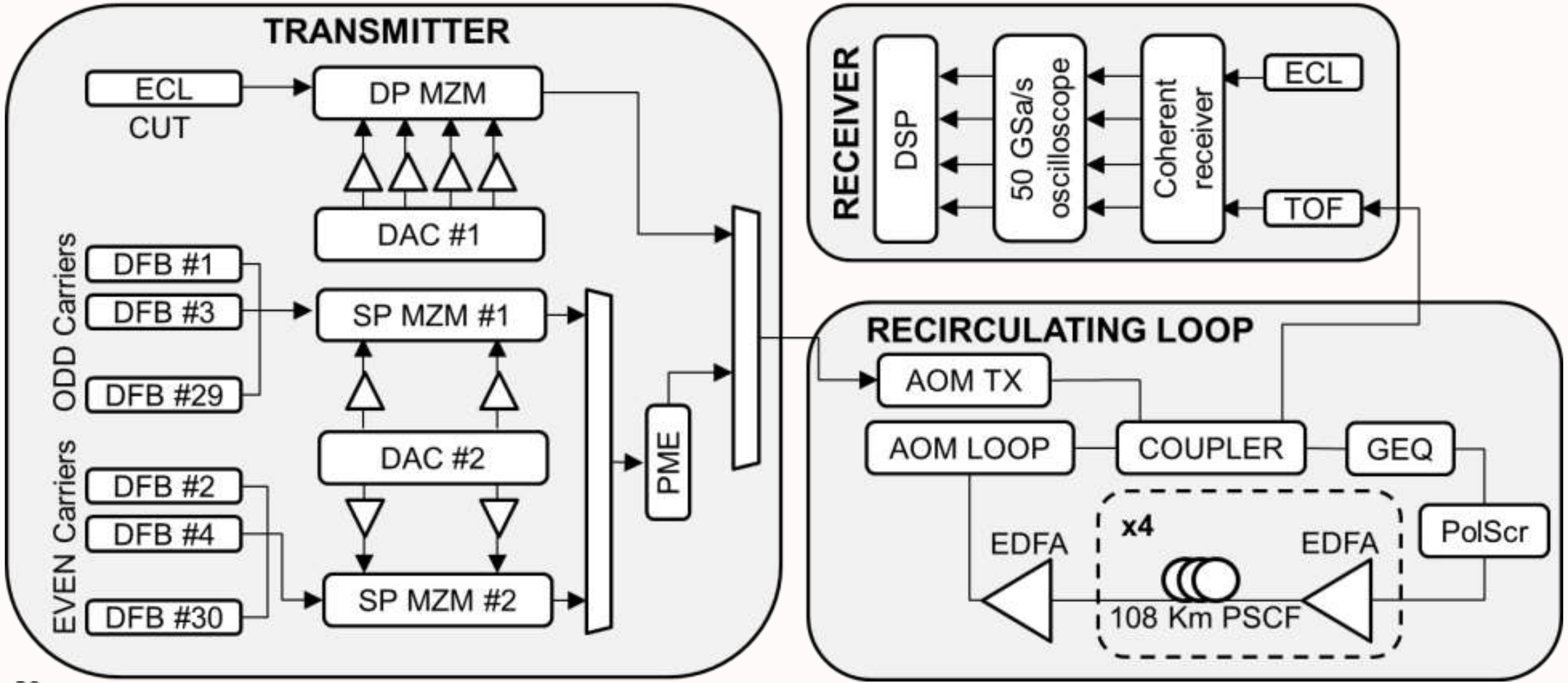
4.33 bit/symb

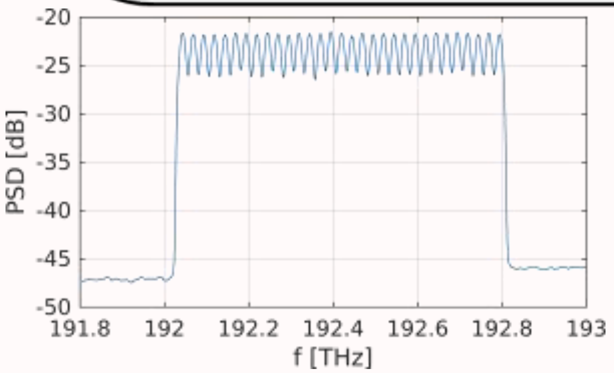


5.17 bit/symb

D. Pilori et al., "*Comparison of Probabilistically Shaped 64QAM With Lower Cardinality Uniform Constellations in Long-Haul Optical Systems*," J. Lightwave Technol. 36, 501-509 (2018)

EXPERIMENTAL SETUP





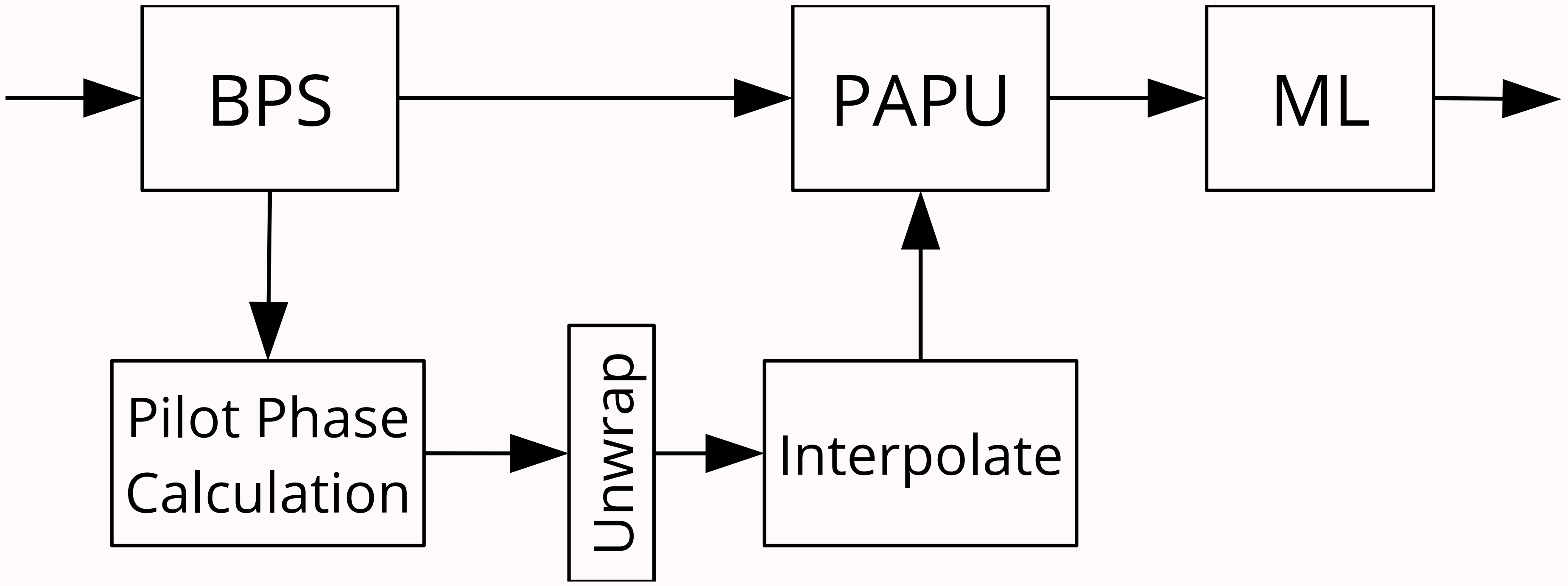
R_s=16 GBd, Δf=25 GHz

Parameter	Value
EDFA noise figure	5.2 dB
Chromatic dispersion	20.17 ps/(nm km)
Non-linearity coeff.	0.75 1/(W km)
Attenuation	0.16 dB/km

D. Pilori et al., "*Comparison of Probabilistically Shaped 64QAM With Lower Cardinality Uniform Constellations in Long-Haul Optical Systems*," J. Lightwave Technol. 36, 501-509 (2018)

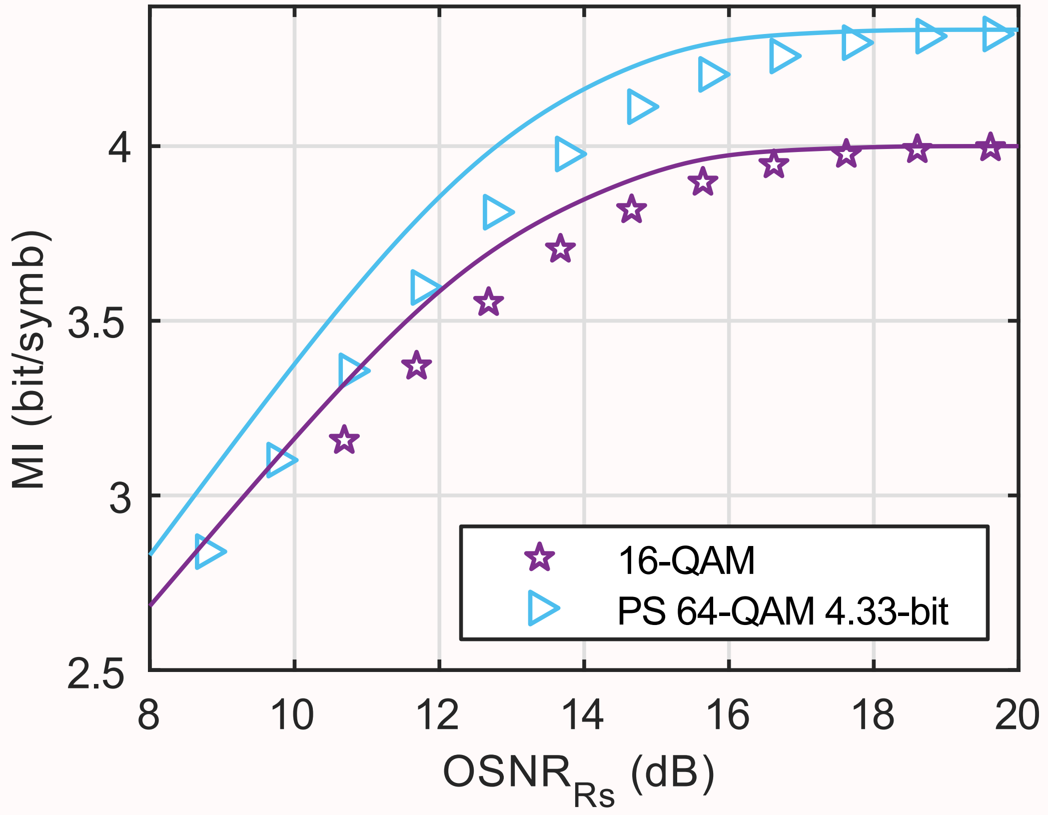
PHASE RECOVERY STRATEGIES

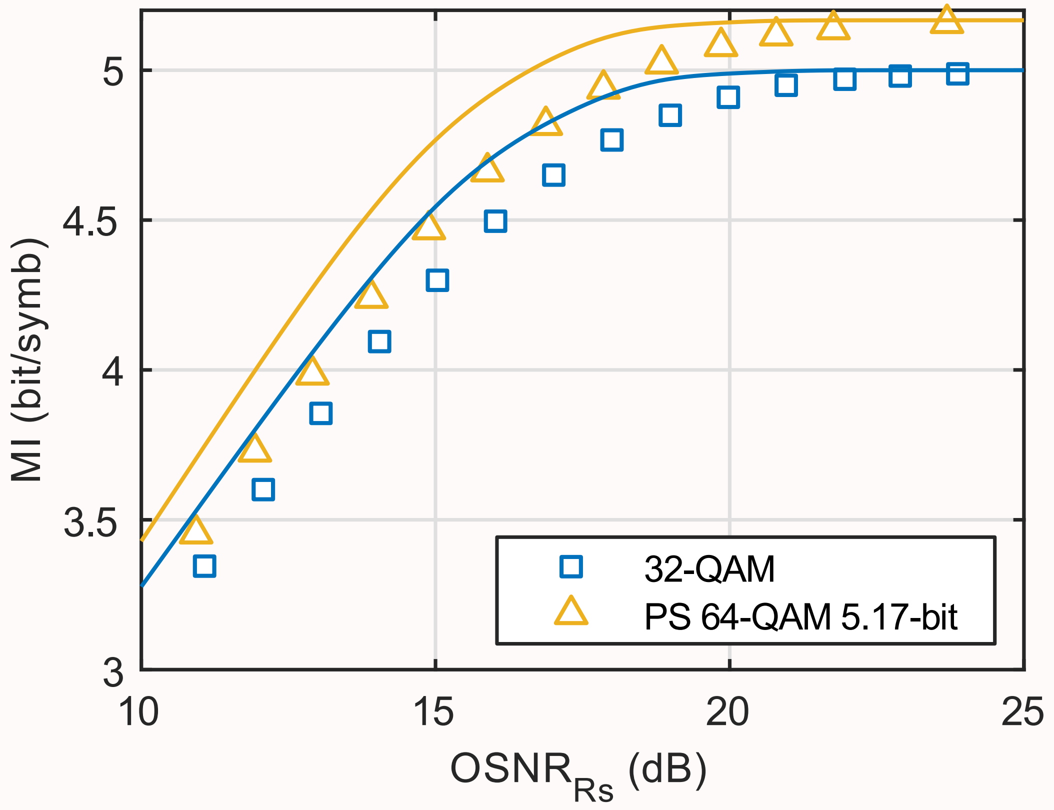
1. Ideal (i.e. genie-aided) phase noise removal (IPNR)
2. Blind Phase Search (BPS) + Maximum Likelihood (ML) with pilot tones for phase unwrapping



- M. Magarini et al., IEEE PTL, vol. 24, no. 9, pp. 739–741, May 2012.
- X. Zhou, IEEE PTL, vol. 22, no. 14, pp. 1051–1053, July 2010.

OPTICAL BACK-TO-BACK RESULTS

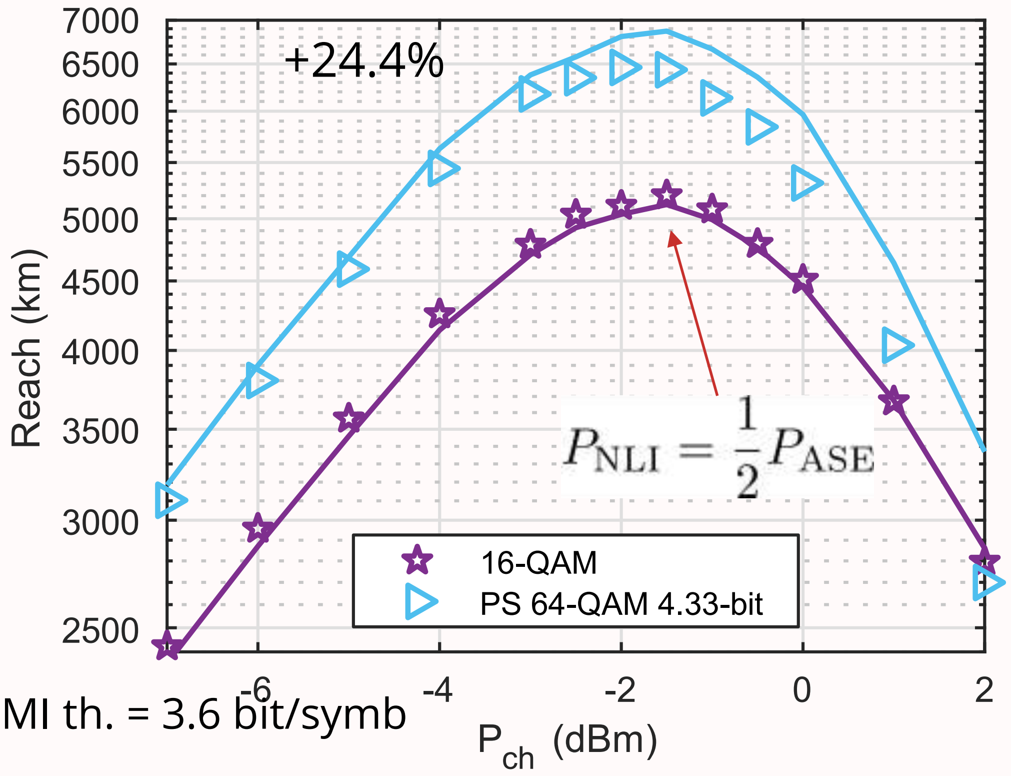


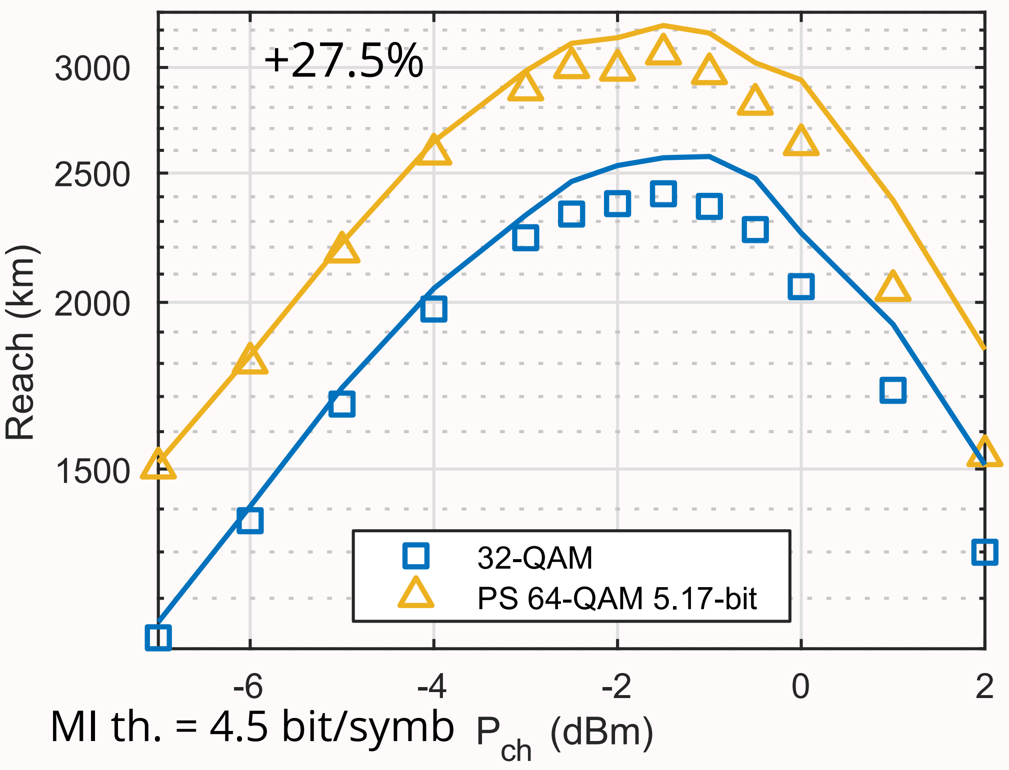


- *Solid lines*: AWGN (theory)
- *Markers*: Experimental measurements

D. Pilori et al., "*Comparison of Probabilistically Shaped 64QAM With Lower Cardinality Uniform Constellations in Long-Haul Optical Systems*," J. Lightwave Technol. 36, 501-509 (2018)

PSCF PROPAGATION RESULTS





- *Markers*: BPS+ML
- *Solid lines*: IPNR

D. Pilori et al., "*Comparison of Probabilistically Shaped 64QAM With Lower Cardinality Uniform Constellations in Long-Haul Optical Systems*," J. Lightwave Technol. 36, 501-509 (2018)

SUMMARY: PS CONSTELLATION OVER AN AWGN CHANNEL

- After propagation over PSCF, PS-64-QAM keeps the same back-to-back sensitivity gain over 16-QAM and 32-QAM
  - Directly translated to a reach increase

- In this scenario, Probabilistic Shaping does not change the impact of fiber Kerr non-linearities

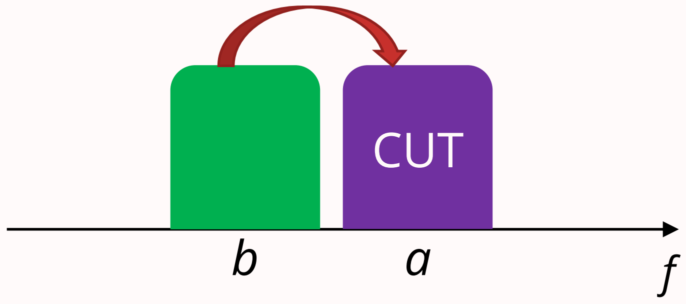
OPTCOM

D. Pilori et al., "*Comparison of Probabilistically Shaped 64QAM With Lower Cardinality Uniform Constellations in Long-Haul Optical Systems*," J. Lightwave Technol. 36, 501-509 (2018)

PROBABILISTIC SHAPING AND FIBER NON-LINEARITIES

NON-LINEAR PHASE NOISE AND ITS IMPACT

CONSTELLATION-SHAPE DEPENDENT NLI



XPM (Cross Phase Modulation)

$$\Delta a_0 = 2j\gamma \sum_{h,k,m} a_h b_k^* b_m X_{h,k,m}$$

h=0 and k=m -> one of the largest contributor of the sum

$$\Delta a_{0_p} = j a_0 \left(2\gamma \sum_m |b_m|^2 X_{0,m,m} \right)$$

Phase noise component, with variance

$$\Delta\theta^2 = 4\gamma^2 \left(\langle |b_0|^4 \rangle - \langle |b_0|^2 \rangle^2 \right) \sum_m X_{0,m,m}^2$$

OPTCOM

R. Dar et al., "*Properties of nonlinear noise in long, dispersion-uncompensated fiber links*," Opt. Express 21, 25685-25699 (2013)

PROPERTIES OF NON-LINEAR PHASE NOISE

- Modulation format dependence:

$$\langle |b_0|^4 \rangle - \langle |b_0|^2 \rangle^2 = \begin{cases} 0 & \text{QPSK} \\ 0.32\sigma_b^4 & \text{16-QAM} \\ 0.381\sigma_b^4 & \text{64-QAM} \\ \sigma_b^4 & \text{Gaussian} \end{cases}$$

SHAPING

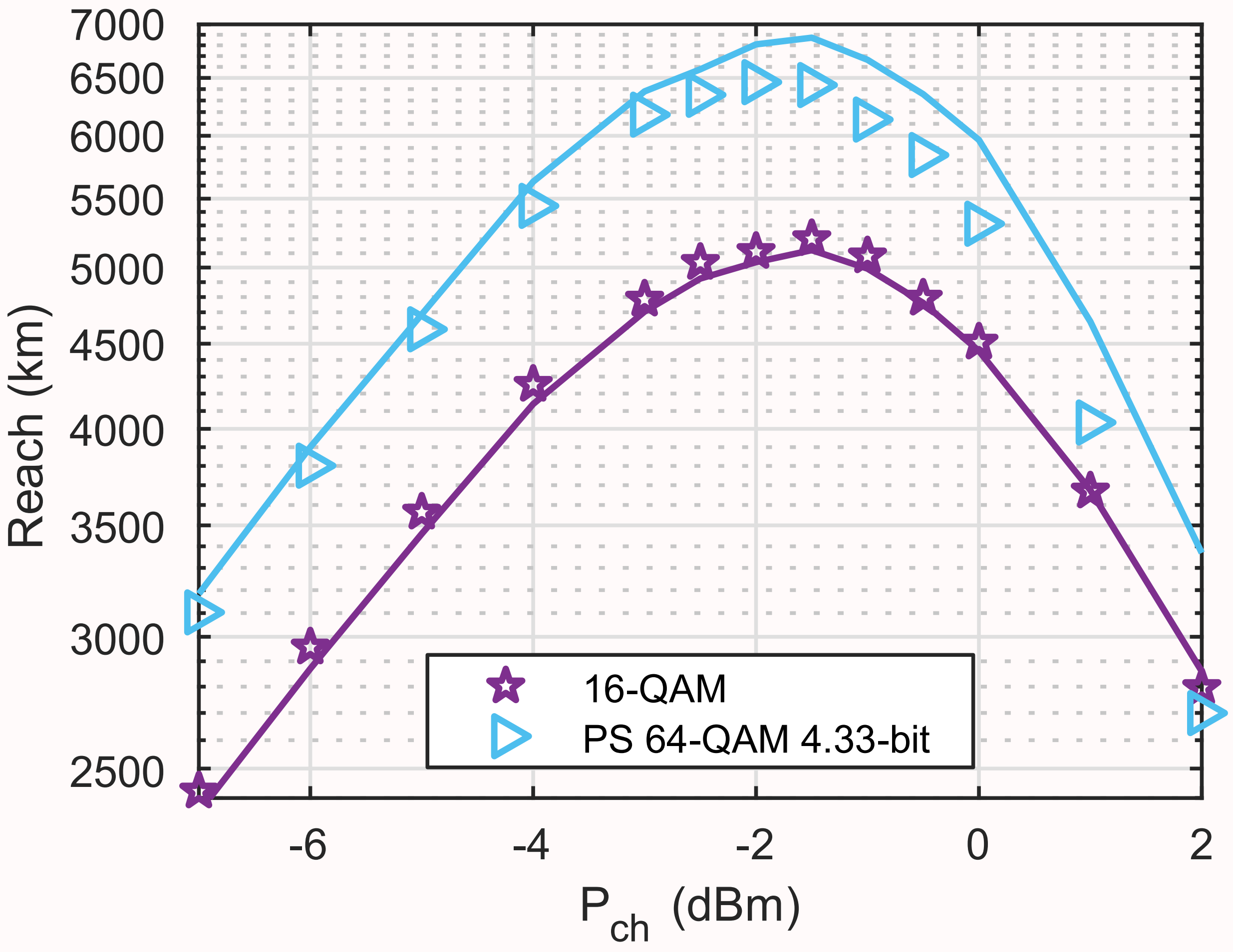
- Auto-correlation function of phase noise:
  - Simple approximation:

$$R_\theta(l) \approx \Delta\theta^2 \left[1 - \frac{|l|T}{|\beta_2 \Omega| L} \right]^+$$

Distance, dispersion and symbol rate *enlarge* the auto-correlation

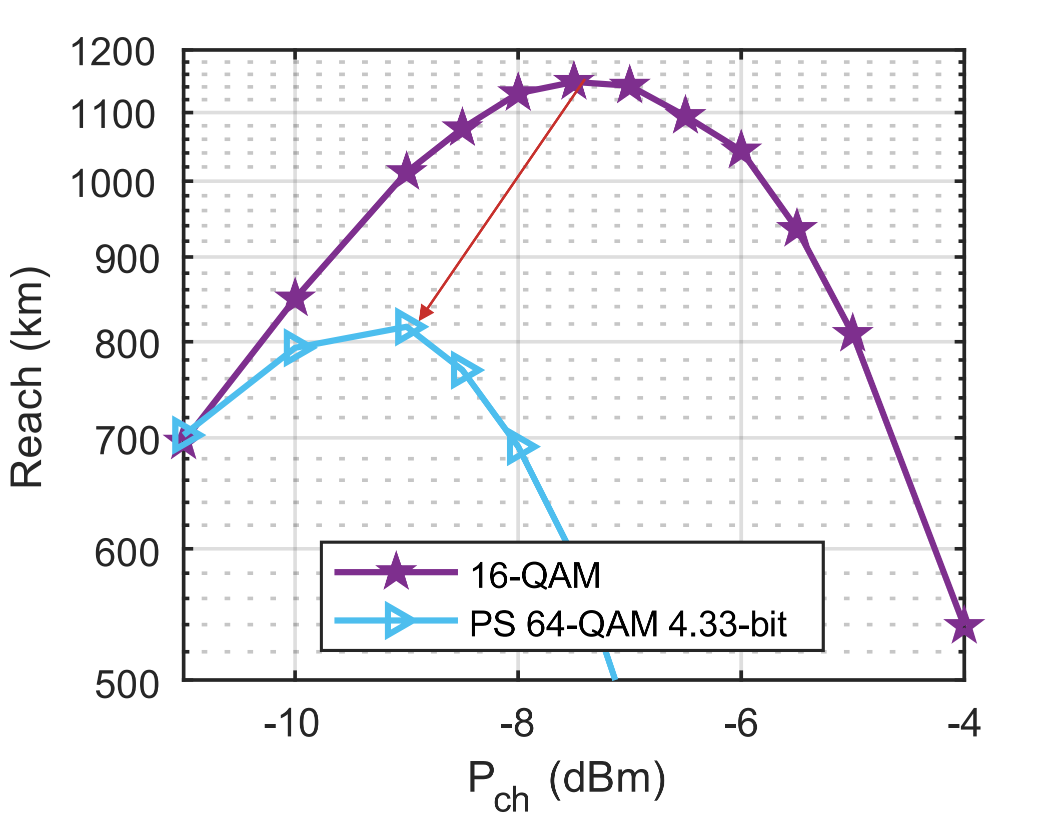
R. Dar et al., "*Properties of nonlinear noise in long, dispersion-uncompensated fiber links*," Opt. Express 21, 25685-25699 (2013)

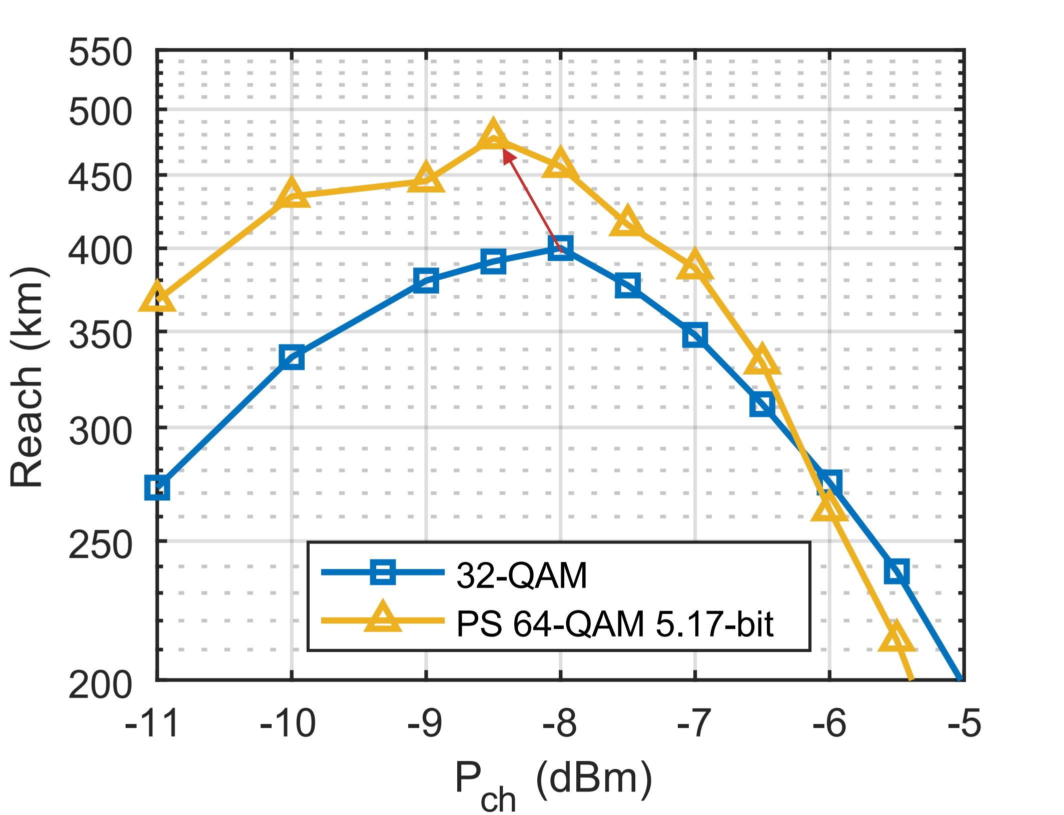
FIRST EXPERIMENT REVISITED



- Over PSCF we found no difference in NLI between the two constellations
- Non-linear phase noise (NLPN) is almost fully compensated for by the CPE

EXAMPLE I: LOW DISPERSION FIBER (NZDSF)





NGMI th. = 0.9

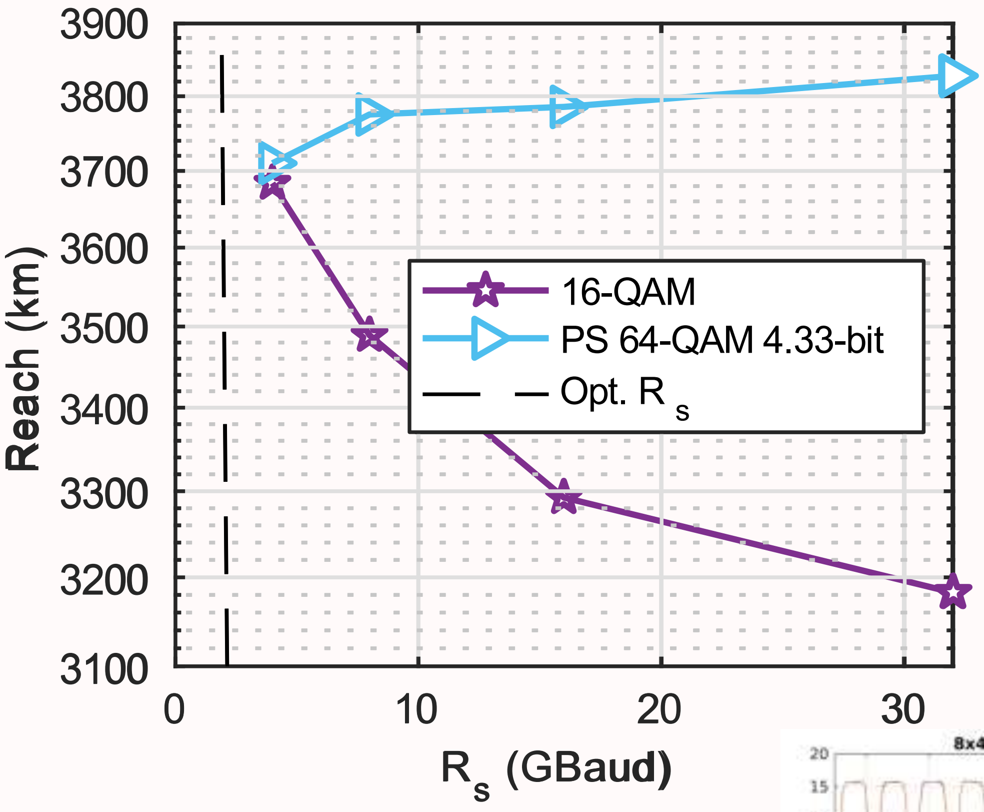
Parameter	Value
Chromatic dispersion	2.65 ps/(nm km)
Non-linearity coeff.	2 1/(W km)
Attenuation	0.23 dB/km

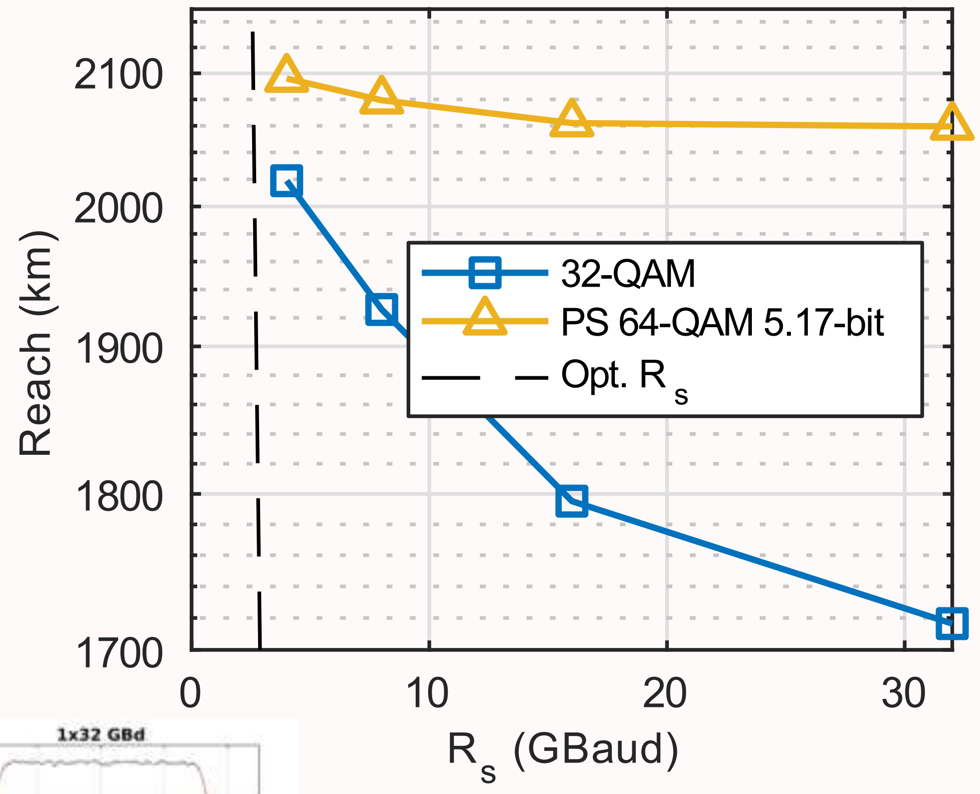
NGMI th. = 0.9

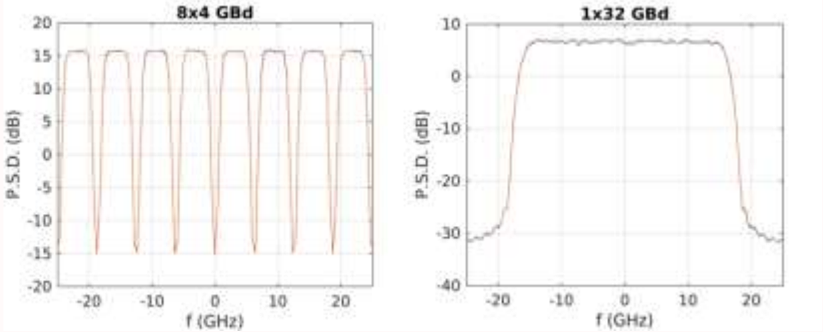
D. Pilori et al., “*Low-complexity non-linear phase noise mitigation using a modified soft-decoding strategy*”, OFC conference 2019, San Diego CA, M1I.2

EXAMPLE II: LOW SYMBOL RATE

15 x 32 GBaud, 100-km SMF, simulations







OPTCOM

D. Pilori et al., "*Residual non-linear phase noise in probabilistically-shaped 64-QAM optical links*", OFC conference 2018, San Diego CA, M3C.6

SUMMARY

- As predicted by NLI models, PS constellations generate *more* non-linear phase noise
  - If its memory (autocorrelation) is large (e.g. PSCF propagation), the CPE at the receiver is able to compensate for it

- In some situations (e.g. low dispersion fibers, low symbol rates, …) the CPE cannot fully compensate for NLPN
  - Significant penalties can be expected

D. Pilori et al., "*Residual non-linear phase noise in probabilistically-shaped 64-QAM optical links*", OFC conference 2018, San Diego CA, M3C.6

COMPENSATION PROPOSALS

- Several works were devoted to this topic

- In this thesis are proposed two techniques:

  1. Modified soft-decoding metric at the receiver
  2. Geometrical constellation shaping

MODIFIED SOFT-DECODING STRATEGY

- Channel model:

$$y[k] = a[k]e^{j\phi[k]} + n_{\mathrm{ASE}}[k] + n_{\mathrm{NLI}}[k]$$

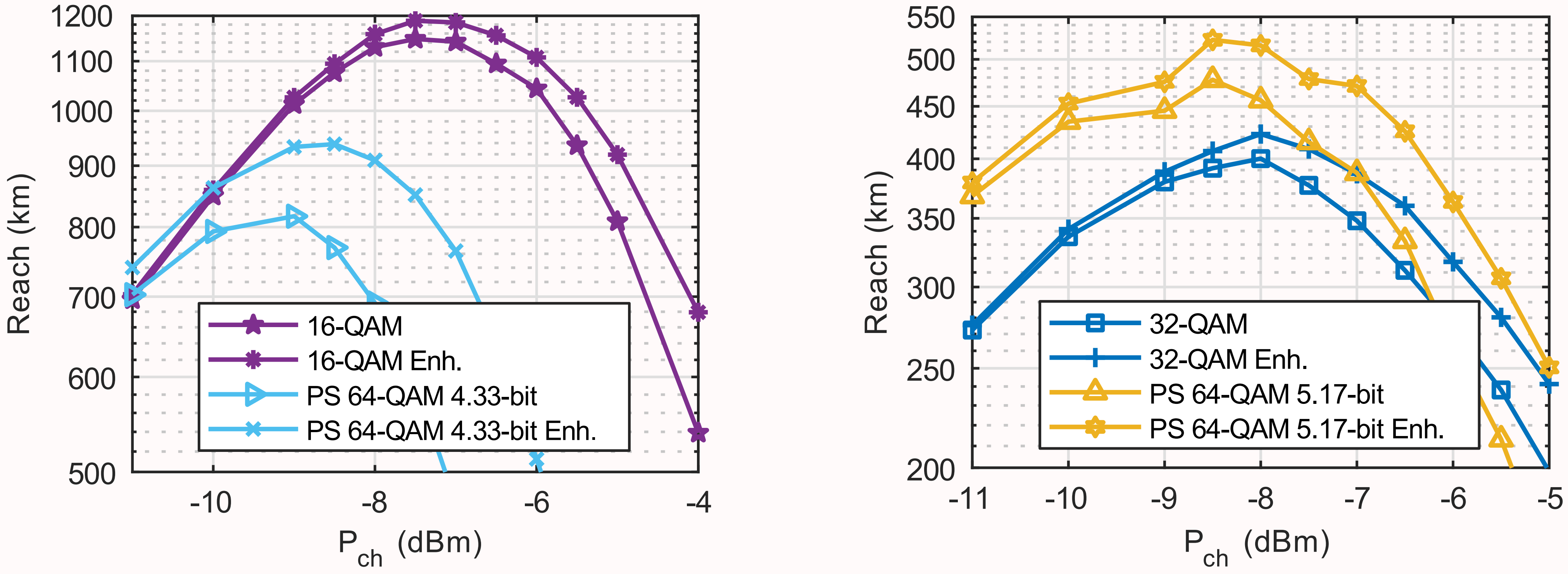
- Assuming *memoryless* phase noise, channel probability can be expressed as:

$$p(y|a) \approx \sqrt{\frac{\kappa_\phi}{8\pi^3}} \frac{e^{-\kappa_\phi}}{\sigma_n^2} \exp\left(-\frac{|y|^2+|a|^2}{2\sigma_n^2} + \left|\frac{ya^*}{\sigma_n^2} + \kappa_\phi\right|\right)$$

- Mitigation of *residual* (i.e. post-CPE) phase noise

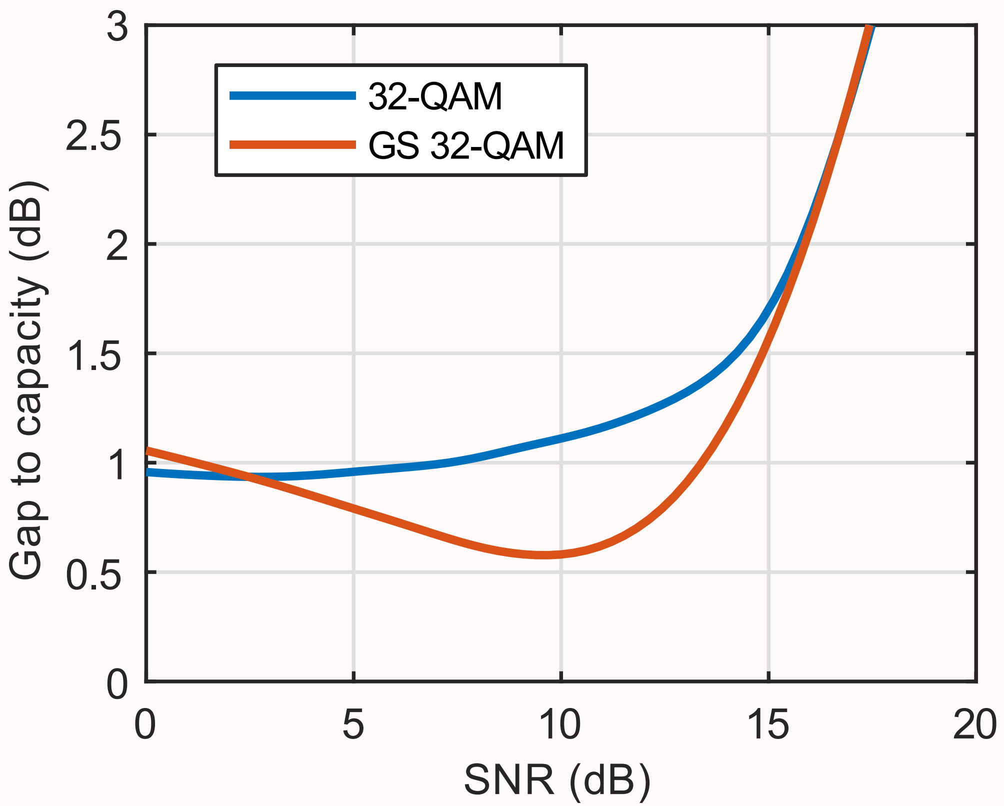
F. Kayhan and G. Montorsi, IEEE Trans. Wireless Commun. **13**(5), 2874-2883 (2014)

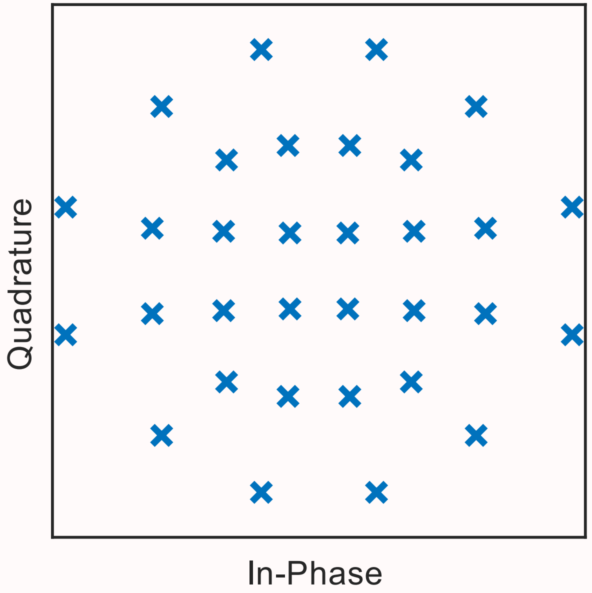
BENEFIT OF MODIFIED STRATEGY



- Experiment over low-dispersion fibers previously presented
- Significant reach gain on PS-64-QAM
- Smaller gain over standard QAM constellations

CONSTELLATION OPTIMIZATION

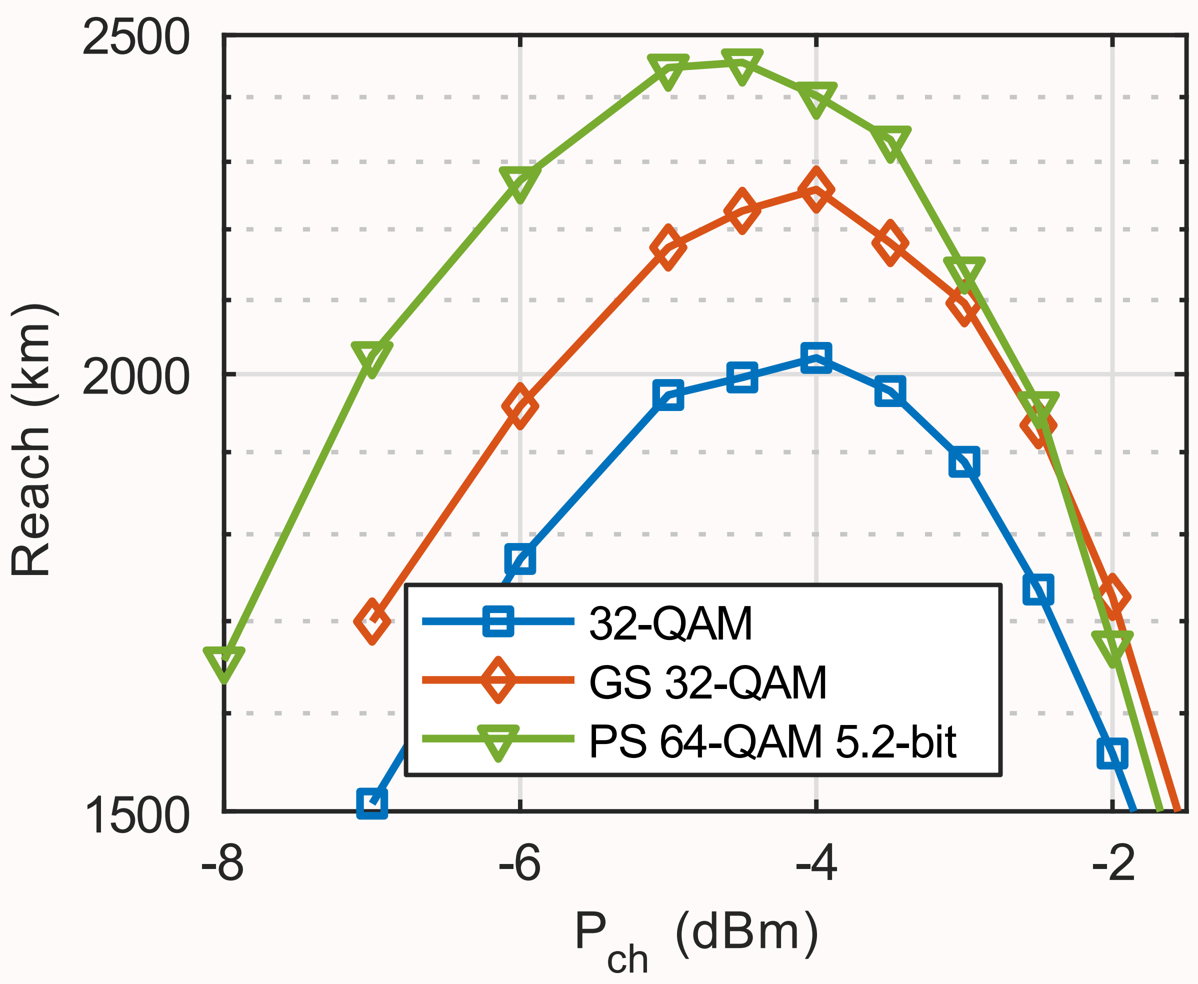




- Simulated annealing algorithm
  - Optimization metric: modified soft-decoding strategy
- A 32-point constellation (GS 32-QAM) was generated

D. Pilori et al., "*Non-linear phase noise mitigation over systems using constellation shaping*", submitted to J. Lightw. Technol.

EXPERIMENTAL RESULTS



- 31 x 16 GBaud, 80-km SMF, experiment
- All constellation have the same spectral efficiency
  - NGMI threshold = 0.86
- No NLI penalty with GS 32-QAM
  - PS 64-QAM is still better

D. Pilori et al., "*Non-linear phase noise mitigation over systems using constellation shaping*", submitted to J. Lightw. Technol.

CONCLUSIONS

- Constellation shaping is a powerful technique to allow high data-rate flexibility
- However, it inevitably triggers more non-linear effects
  - Mostly, as non-linear phase noise
- In “standard” conditions (high dispersion, high symbol rates) receiver CPE compensates for it
  - At least for PS-64-QAM and reach ~hundreds of km
- Specific focus on NLPN mitigation must be taken into account in this cases
  - Or don’t use shaping ☺

LIST OF JOURNAL PUBLICATIONS

1. **Dario Pilori**, Antonino Nespola, Fabrizio Forghieri and Gabriella Bosco. "*Non-Linear Phase Noise Mitigation over Systems using Constellation Shaping*". Submitted to: Journal of Lightwave Technology
2. **Dario Pilori**, Luca Bertignono, Antonino Nespola, Fabrizio Forghieri, Marco Mazzini, and Roberto Gaudino. "*Bidirectional 4-PAM to Double Per-Fiber Capacity in 2-km Intra-Datacenter Links*". In: IEEE Photonics Journal 10.2 (Apr. 2018), pp. 1–10.
3. **Dario Pilori**, Luca Bertignono, Antonino Nespola, Fabrizio Forghieri, and Gabriella Bosco. "*Comparison of Probabilistically Shaped 64QAM With Lower Cardinality Uniform Constellations in Long-Haul Optical Systems*" . In: Journal of Lightwave Technology 36.2 (Jan. 2018), pp. 501–509. [invited from top-scoring OFC 2017 contribution]
4. **Dario Pilori**, Chris Fludger, and Roberto Gaudino. "*Comparing DMT Variants in Medium-Reach 100G Optically Amplified Systems*". In: Journal of Lightwave Technology 34.14 (July 2016), pp. 3389–3399.
5. M. Cantono, A. Ferrari, **D. Pilori**, E. Virgillito, J. L. Augé, and V. Curri. "*Physical Layer Performance of Multi-Band Optical Line Systems Using Raman Amplification*". In: Journal of Optical Communications and Networking 11.1 (Jan. 2019), A103. [invited from top-scoring OFC 2018 contribution]
6. Mattia Cantono, **Dario Pilori**, Alessio Ferrari, Clara Catanese, Jordane Thouras, Jean-Luc Augé, and Vittorio Curri. "On the Interplay of Nonlinear Interference Generation With Stimulated Raman Scattering for QoT Estimation". In: Journal of Lightwave Technology 36.15 (Aug. 2018), pp. 3131–3141.
7. Seyed Sadra Kashef, Paeiz Azmi, Gabriella Bosco, Mehdi D. Matinfar, and **Dario Pilori**. "Non-Gaussian statistics of CO-OFDM signals after non-linear optical fibre transmission". In: IET Optoelectronics 12.3 (June 2018), pp. 150–155.

LIST OF PRESENTATIONS

1. Dario Pilori, Antonino Nespola, Pierluigi Poggiolini, Fabrizio Forghieri, and Gabriella Bosco. "*Low-Complexity Non-Linear Phase Noise Mitigation using a Modified Soft-Decoding Strategy*". Optical Fiber Communication Conference (OFC), San Diego CA (USA), paper M1I.2, March 2019.
2. Dario Pilori. "*Fiber Nonlinearities: A Communications Engineer Perspective*". DEIB, Politecnico di Milano, seminar. October 2018.
3. Dario Pilori and Roberto Gaudino. "*Direct-Detection Single-Sideband Systems: Performance Comparison and Practical Implementation Penalties*". International Conference on Transparent Optical Networks (ICTON), Bucharest (Romania), July 2018.
4. Dario Pilori. "*Impact of Fiber Non-Linearities on Probabilistic Shaping in Long-Haul Optical Systems*". Symposium on Challenges to Achieving Capacity in Nonlinear Optical Networks, Grasmere (UK). June 2018.
5. Dario Pilori, F. Forghieri, and Gabriella Bosco. "*Residual Non-Linear Phase Noise in Probabilistically Shaped 64-QAM Optical Links*". Optical Fiber Communication Conference (OFC), San Diego CA (USA), March 2018.
6. Dario Pilori. "*The Advantage of Probabilistic Constellation Shaping on Long-Haul Optical Systems*". In Institute of Photonics and Quantum Electronics (IPQ) – Karlsruhe Institute of Technology (KIT) weekly seminar, Karlsruhe (Germany), October 2017.
7. Dario Pilori, Mattia Cantono, Andrea Carena, and Vittorio Curri. "*FFSS: The fast fiber simulator software*". International Conference on Transparent Optical Networks (ICTON), Girona (Spain), July 2017.
8. Dario Pilori, Fabrizio Forghieri, and Gabriella Bosco. "*Maximization of the Achievable Mutual Information using Probabilistically Shaped Squared-QAM Constellations".* Optical Fiber Communication Conference (OFC), Los Angeles CA (USA), March 2017. [poster]
9. L. Bertignono, D. Pilori, A. Nespola, F. Forghieri, and G. Bosco. "*Experimental Comparison of PM-16QAM and PM-32QAM with Probabilistically Shaped PM-64QAM*". Optical Fiber Communication Conference (OFC), Los Angeles CA (USA), March 2017. [top-scoring paper]

THANK YOU

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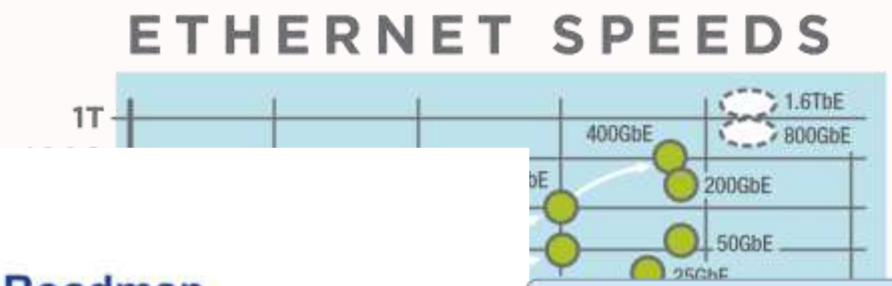
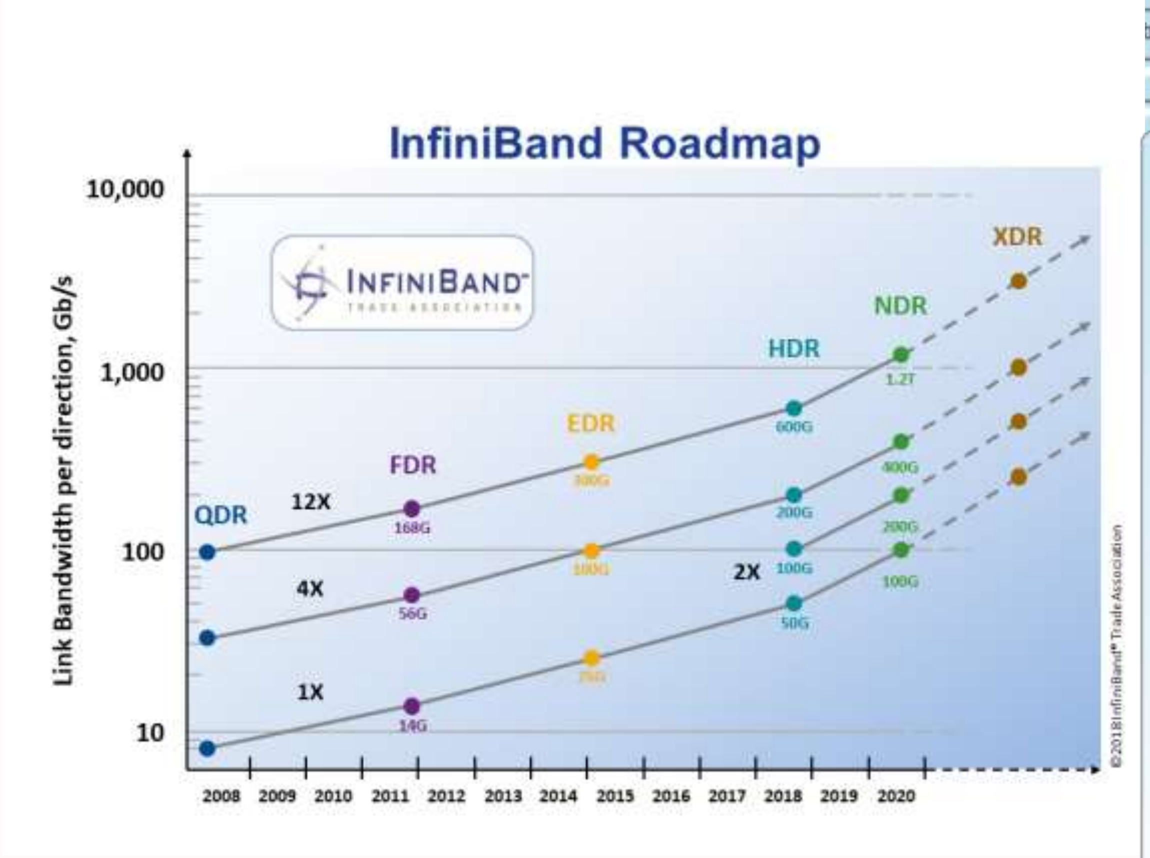
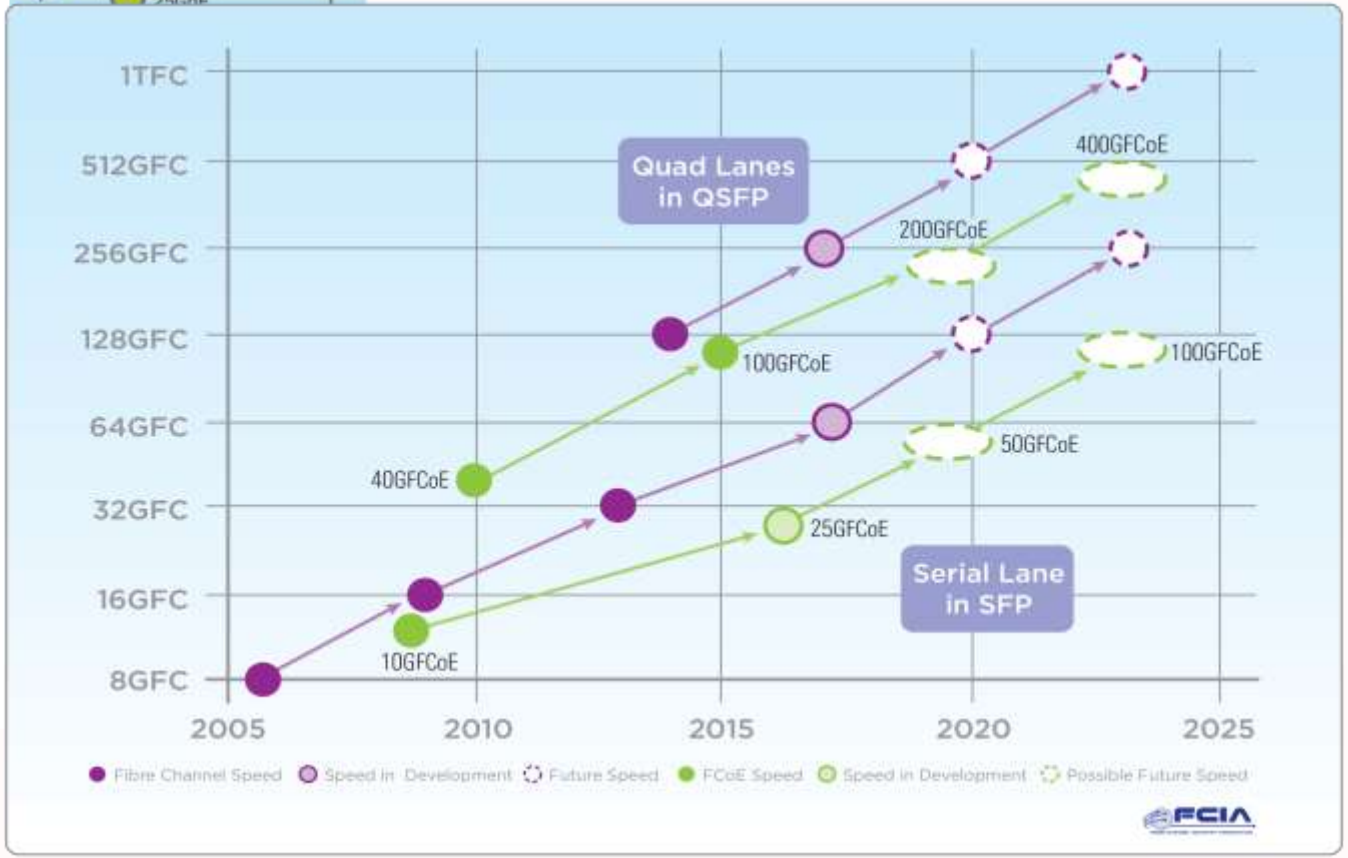
BACKUP SLIDES

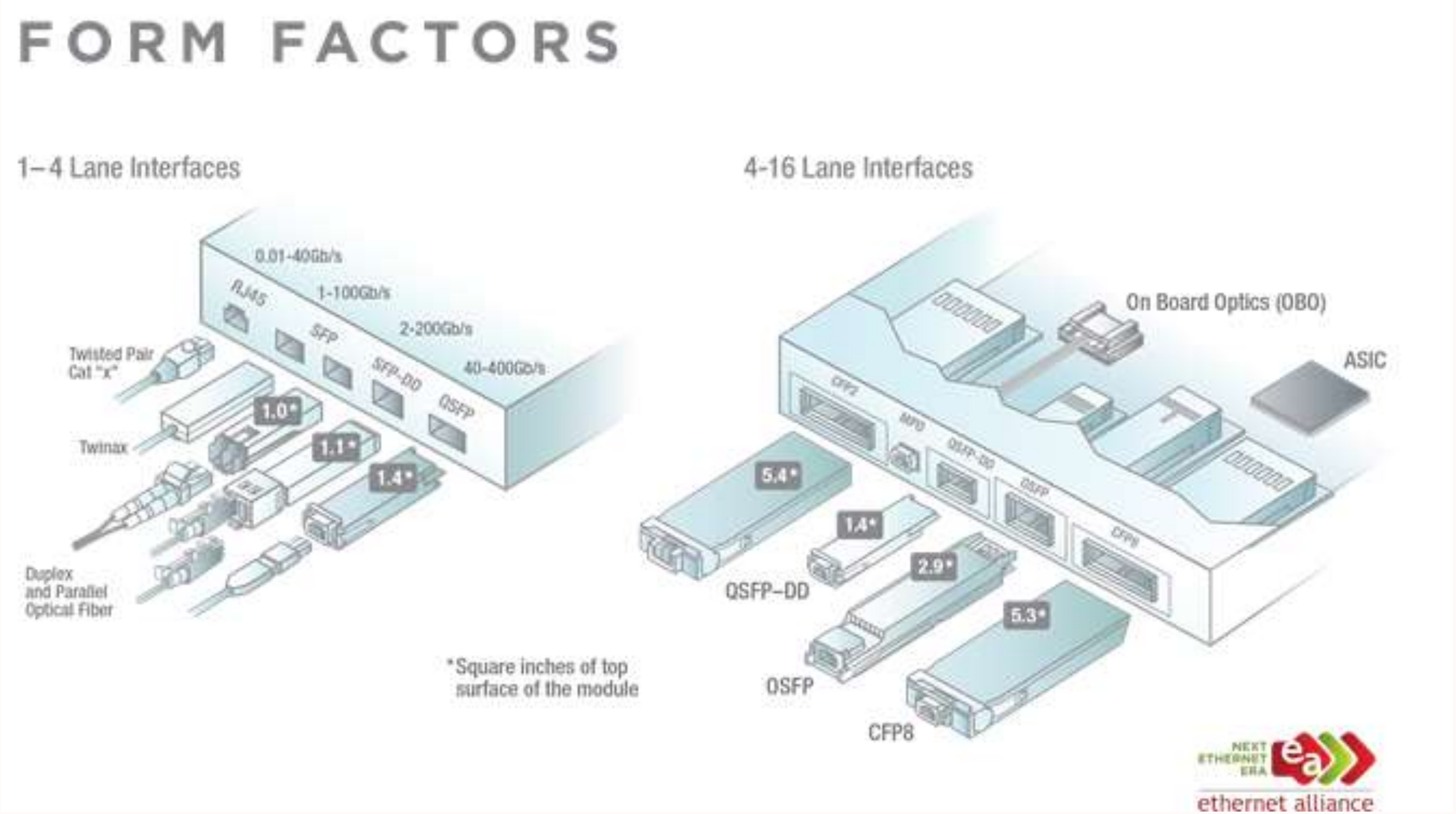
SPEED OF INTRA-DC INTERFACES



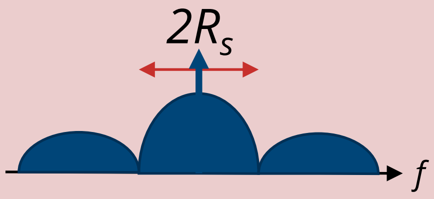
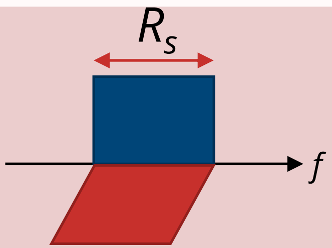
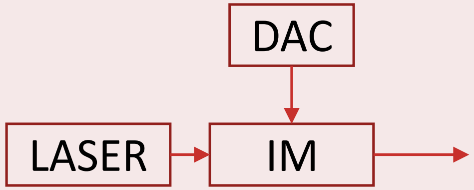
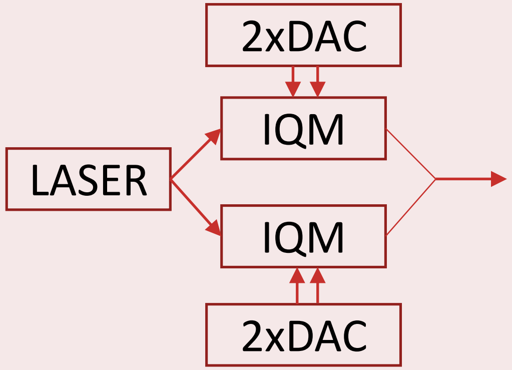
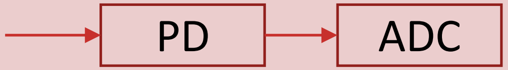
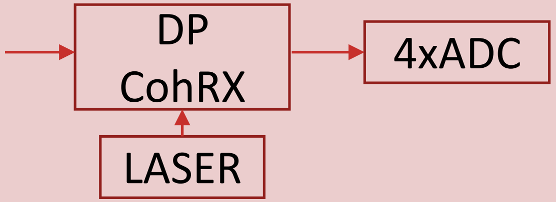




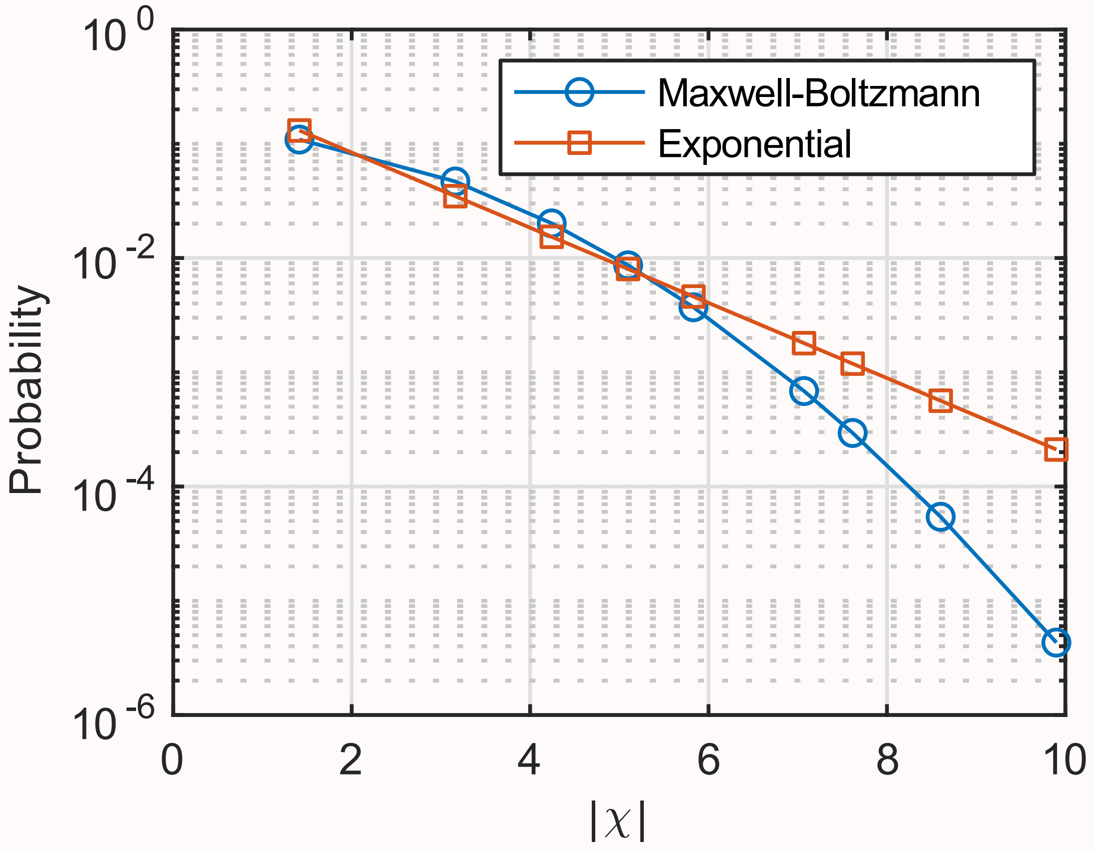
FORM FACTORS

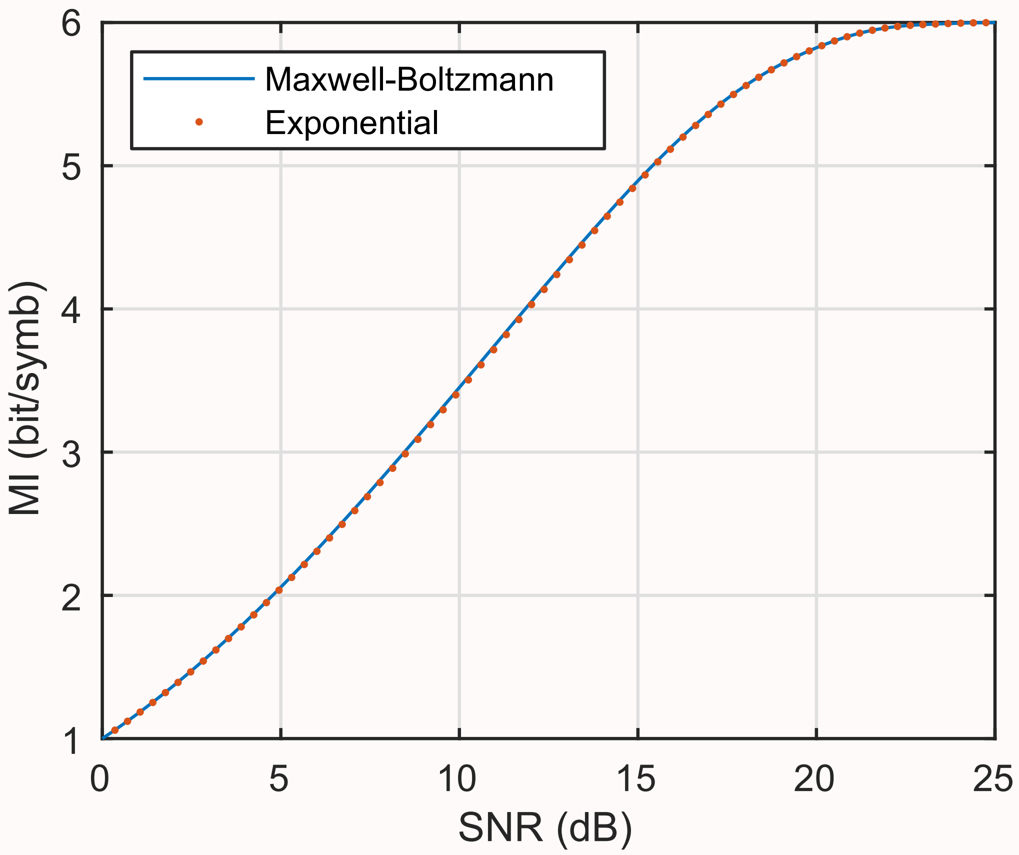


COHERENT OR DIRECT DETECTION?

	PAM-4 (direct detection)	**16-QAM (coherent detection)**
Spectral efficiency		
TX architecture		
RX architecture		
Dispersion compensation	Optical	Electrical

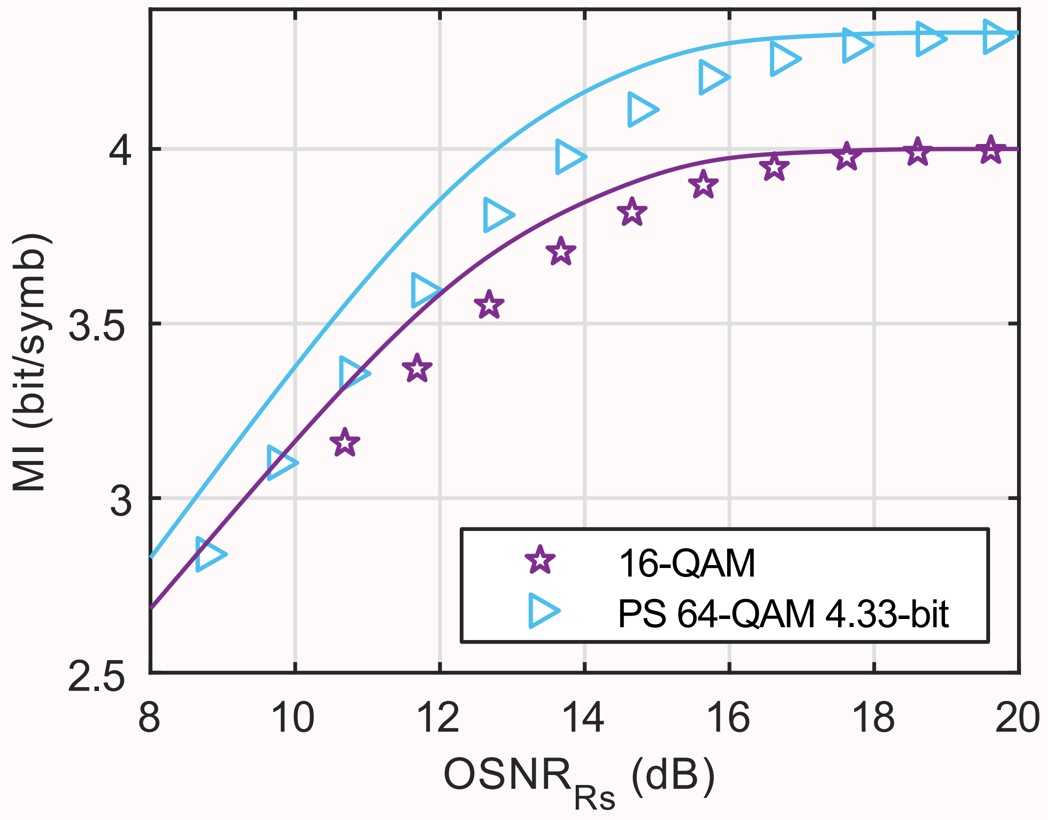
PERFORMANCE COMPARISON: EXP VS MB

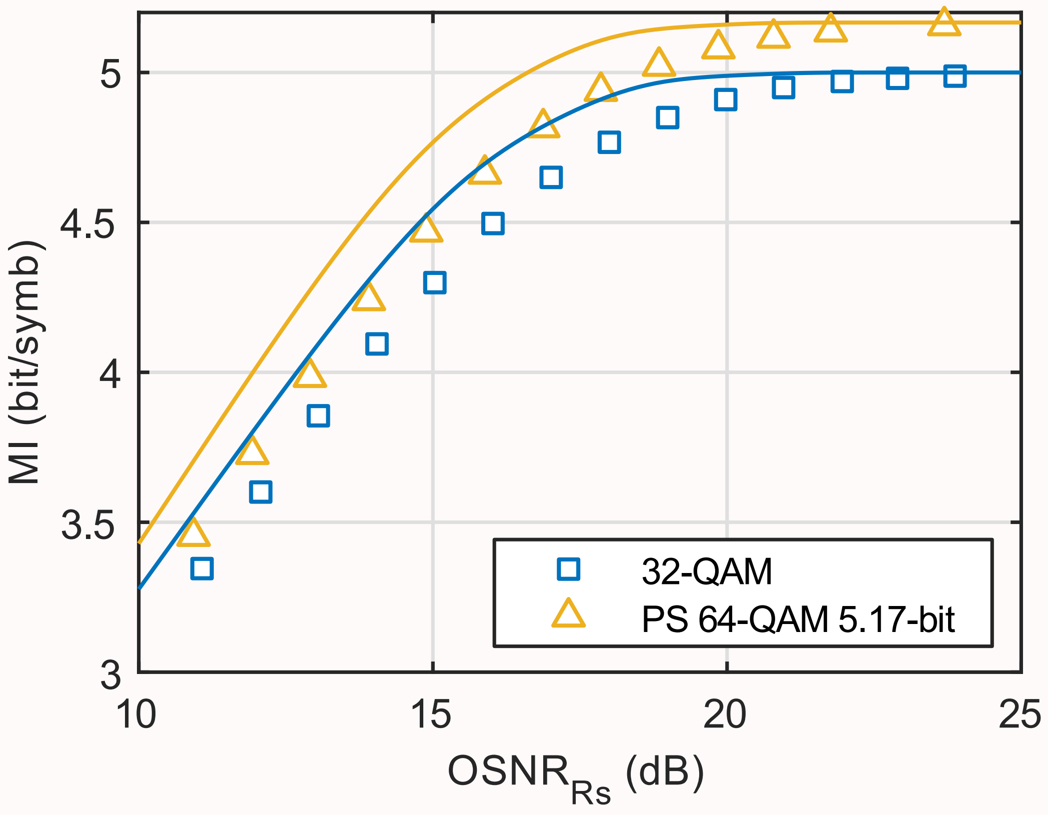




OPTCOM

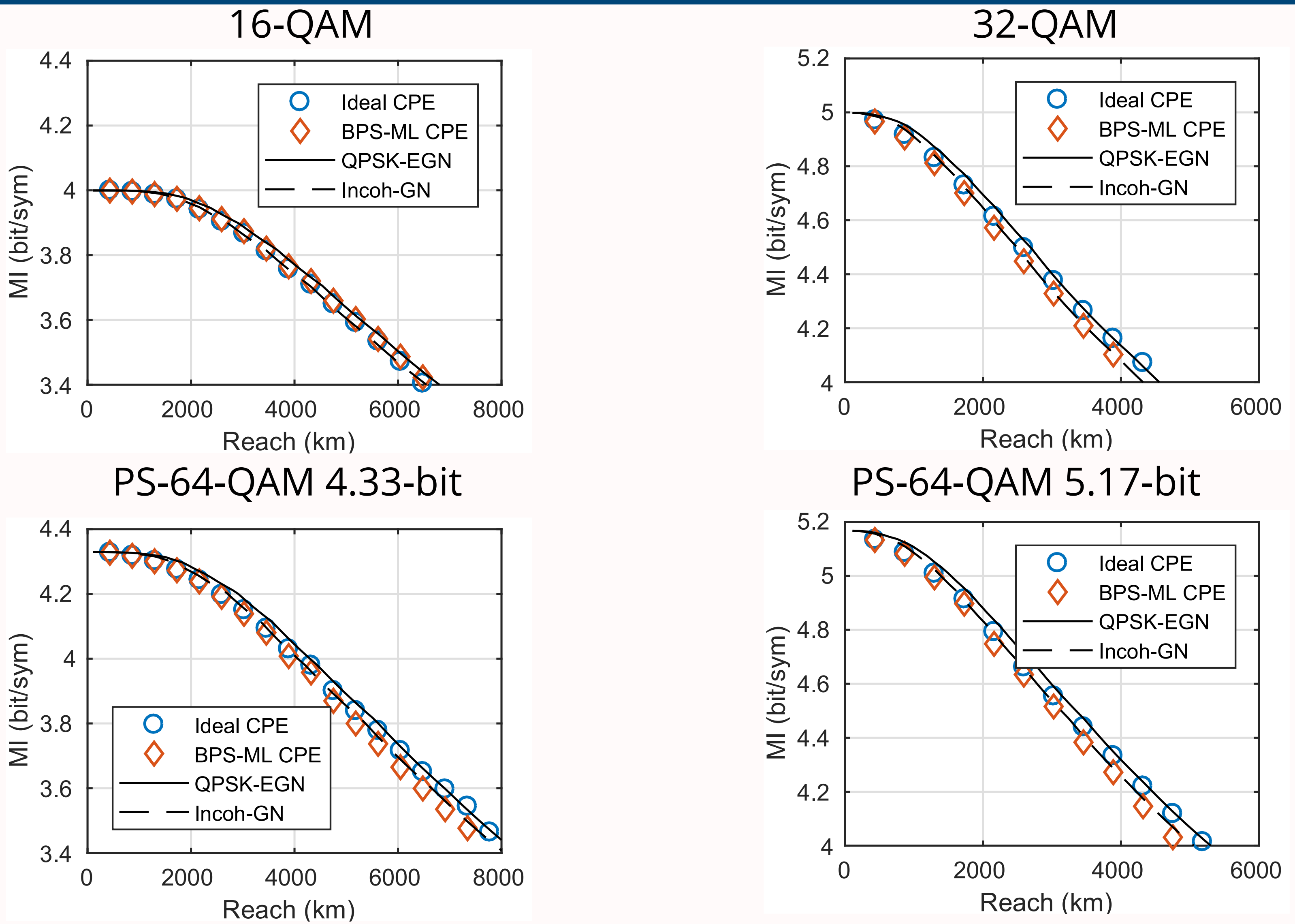
BACK-TO-BACK RESULTS



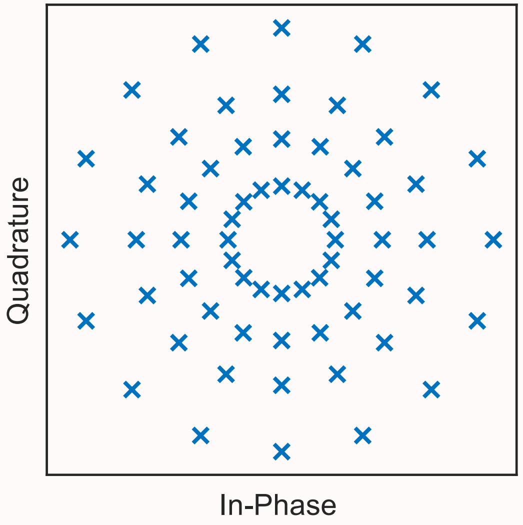


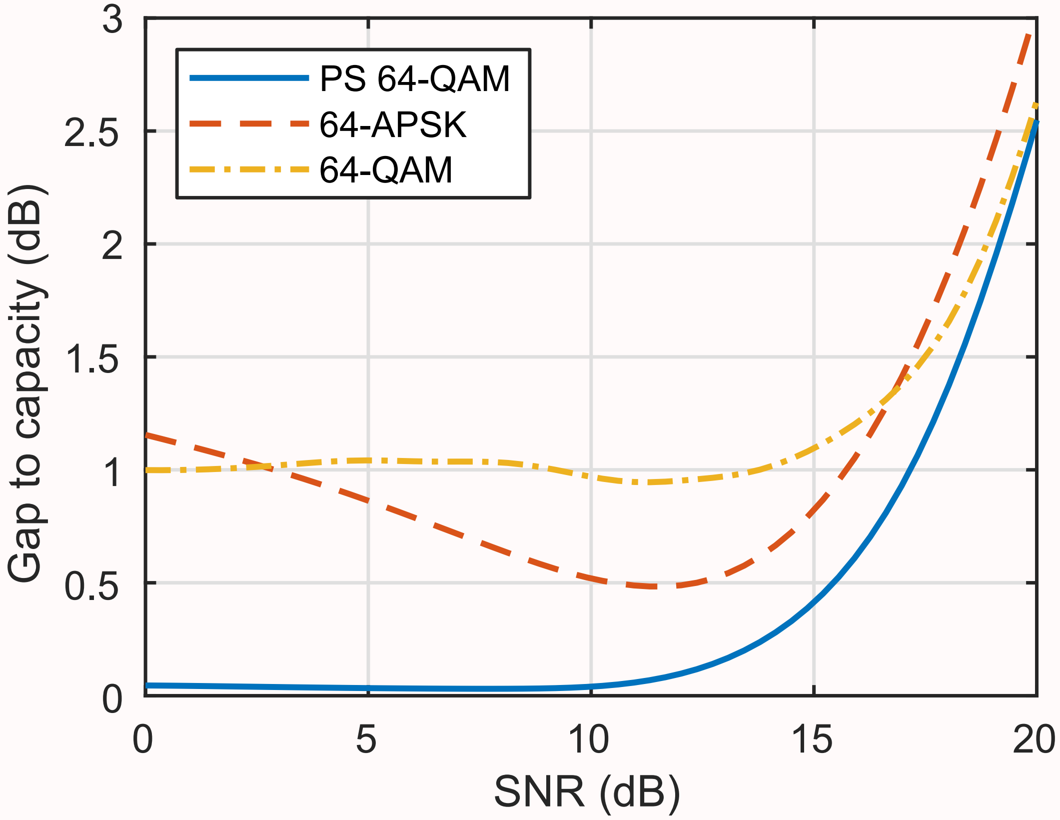
- Penalty is ~0.9 dB for standard QAM and ~1.05 dB for PS 64QAM

COMPARISON WITH NLI MODELS



64-APSK CONSTELLATION





CHOICE OF SYMBOL RATE

- To carry out a fair comparison we kept *fixed*:
  - Total optical bandwidth
  - Relative channel spacing
  - Total bit rate is also constant
- Same laser phase noise: **2.5 kHz / GBaud**

- The reference single-channel case is:
  - R_s=32GBaud, Δf=50GHz, N_{ch}=15 channels, ρ=15%
- We reduced symbol rate to 16, 8 and 4 GBaud