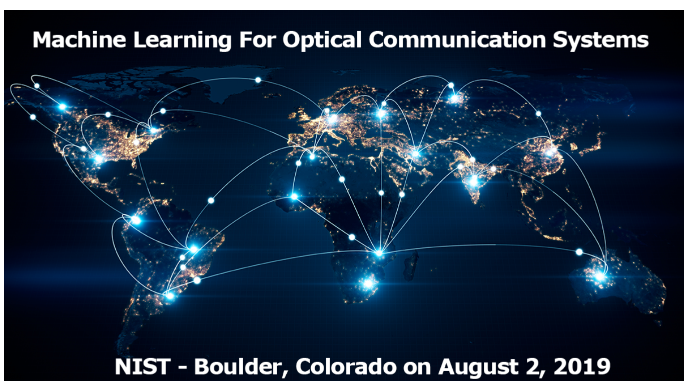
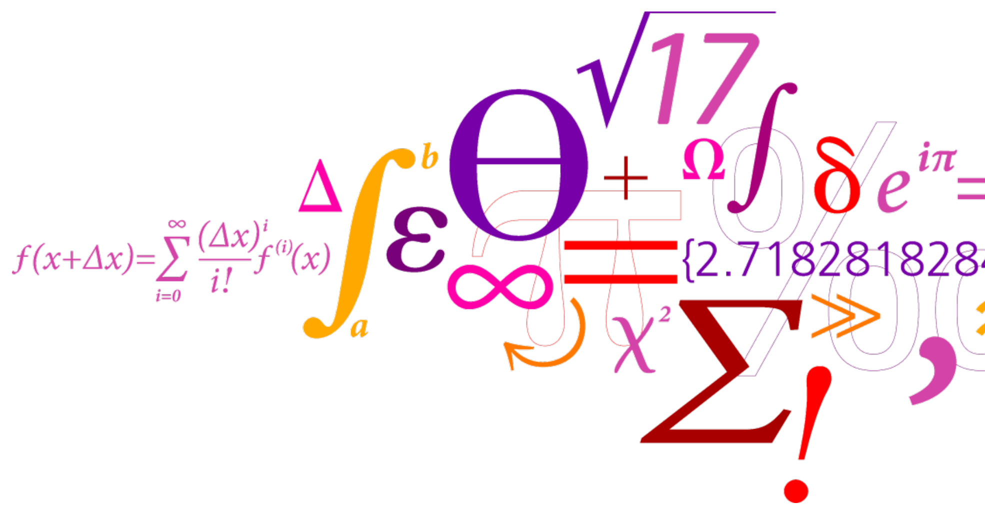
What data matters for optical communications

Uiara de Moura, Darko Zibar, Francesco Da Ros
uiamo@fotonik.dtu.dk
Machine Learning in Photonic Systems (M-LiPS) group
DTU Fotonik, Technical University of Denmark, DK-2800, Kgs. Lyngby





DTU Fotonik
Department of Photonics Engineering

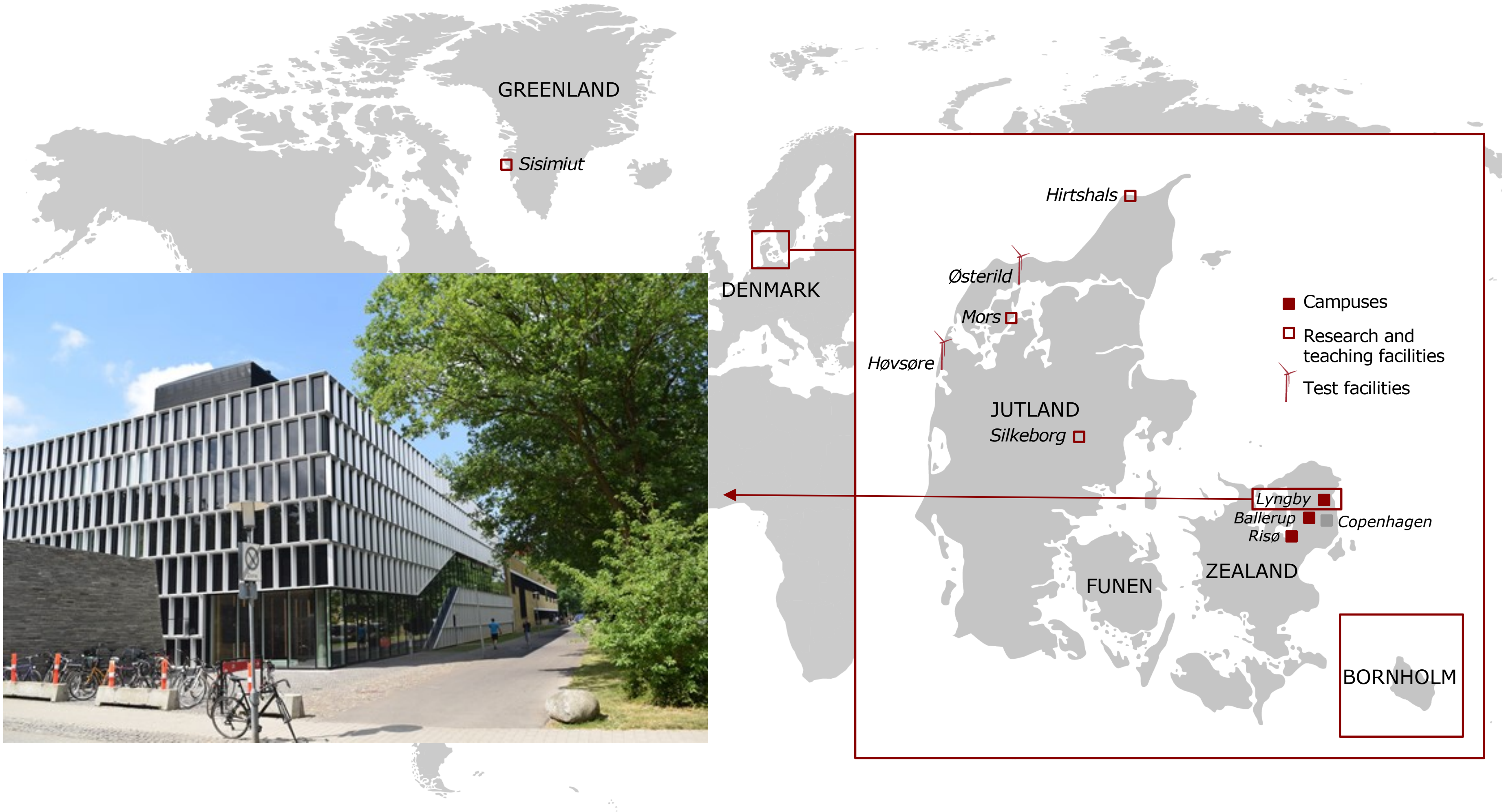
These slides are not NIST's slides. NIST is not responsible for the content of these slides.

Outline

- Introduction to DTU and M-LiPS group
- Machine learning in optical communications
  - Relevant problems for machine learning
  - State-of-the-art
- **What data matters for optical communications**
- Summary

These slides are not NIST's slides. NIST is not responsible for the content of these slides.

Technical University of Denmark (DTU)



These slides are not NIST's slides. NIST is not responsible for the content of these slides.

Machine Learning in Photonic Systems (M-LiPS)

Group leader:

Darko Zibar

Senior Staff:

Francesco Da Ros
Simone Gaiarin
Hou-Man Chin
Uiara Celine Moura

PhD students:

Martin Djurhuus
Nicola De Renzis
Stenio Magalhaes Ranzini
Ognjen Jovanovic
Thyago Monteiro

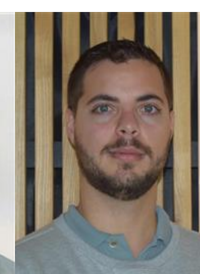
Research assistant:

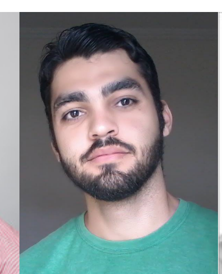
Giovanni Brajato

- In 2019, 11 group members
- 5 Ph.D. candidates
- 5 nationalities








These slides are not NIST's slides. NIST is not responsible for the content of these slides.

Research activities

Machine learning
(and signal processing)
for Photonics Systems

Nonlinear Fourier transform

Wide-band systems

Phase noise characterization

Niels Bohr Institutet

Prof. T W. Hansch group

Jesper Mørk

End-to-End Learning

Quantum phase tracking

DTU Fysik
Institut for Fysik

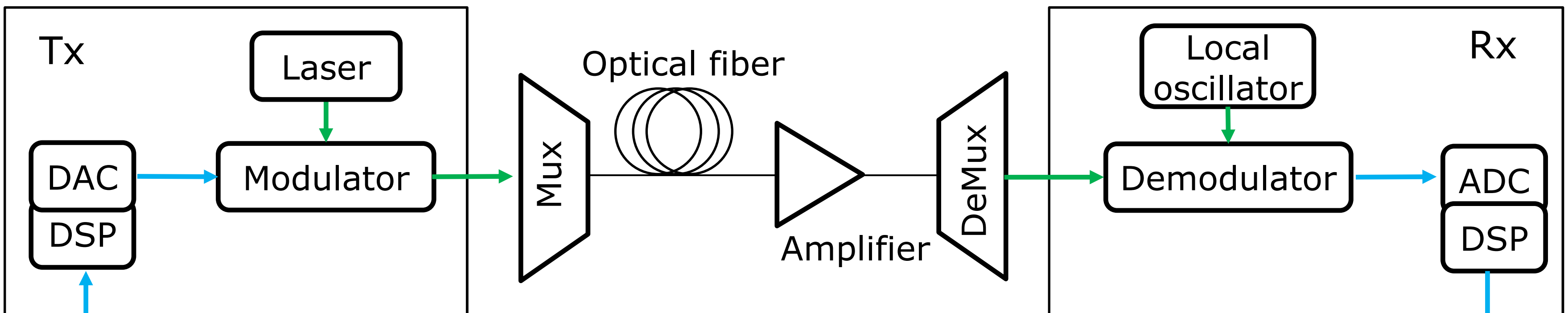
Fiber impairment compensation

Fiber sensing

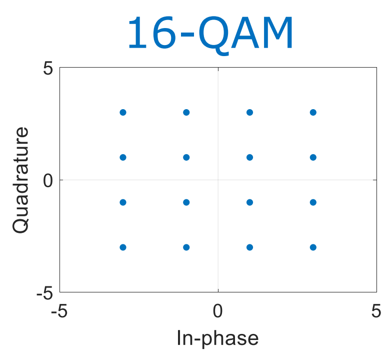
These slides are not NIST's slides. NIST is not responsible for the content of these slides.

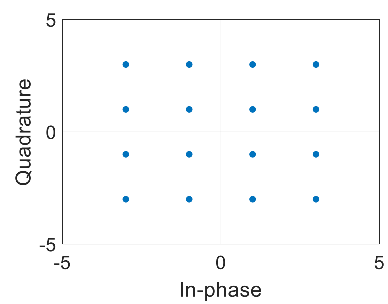
Optical communication systems

Optical coherent transmission illustration

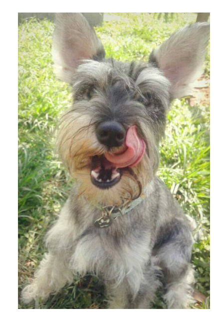


...01010011...





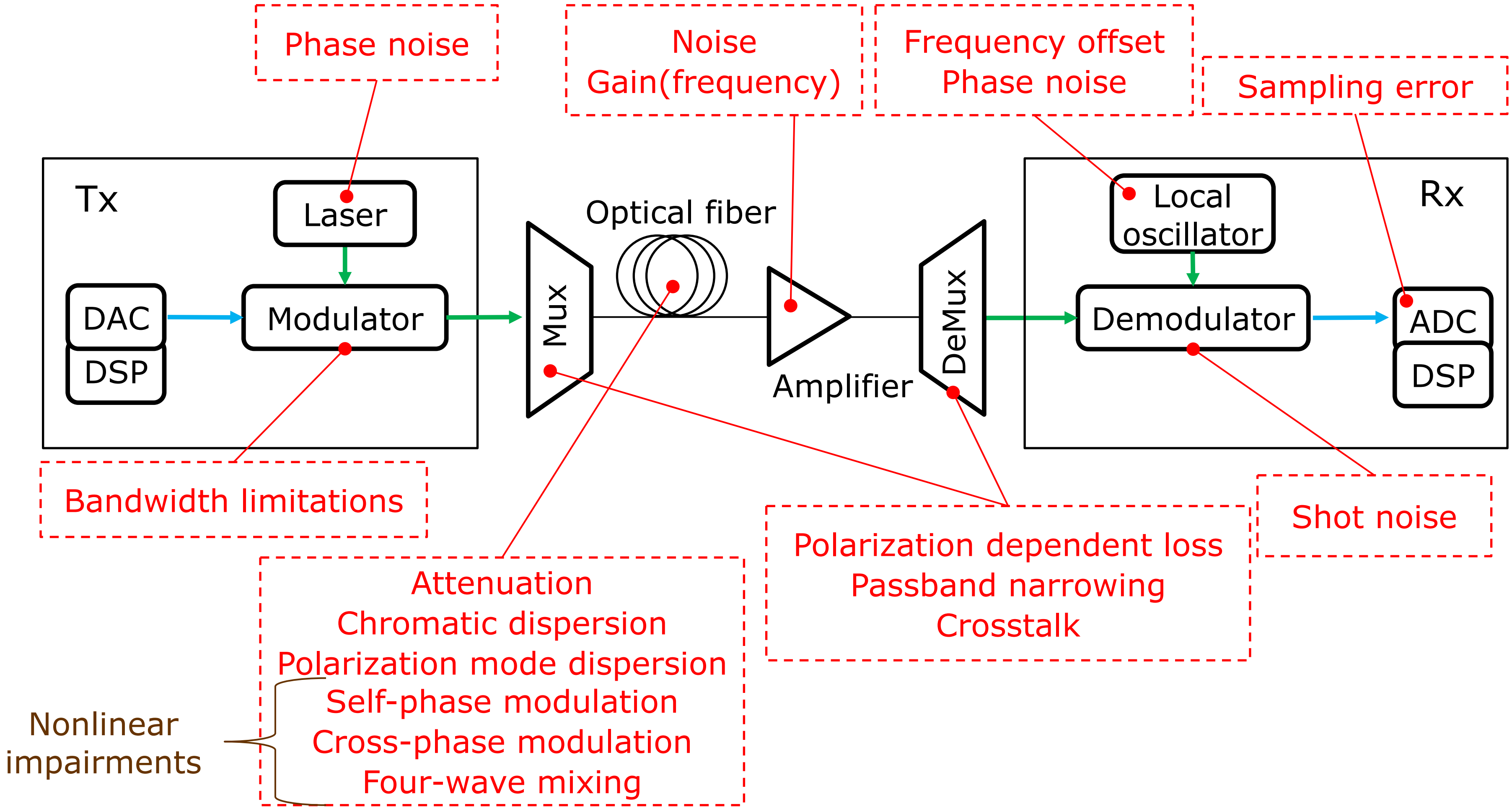
...01010011...



DSP: digital signal processing
DAC: digital-to-analog converter
ADC: analog-to-digital converter

These slides are not NIST's slides. NIST is not responsible for the content of these slides.

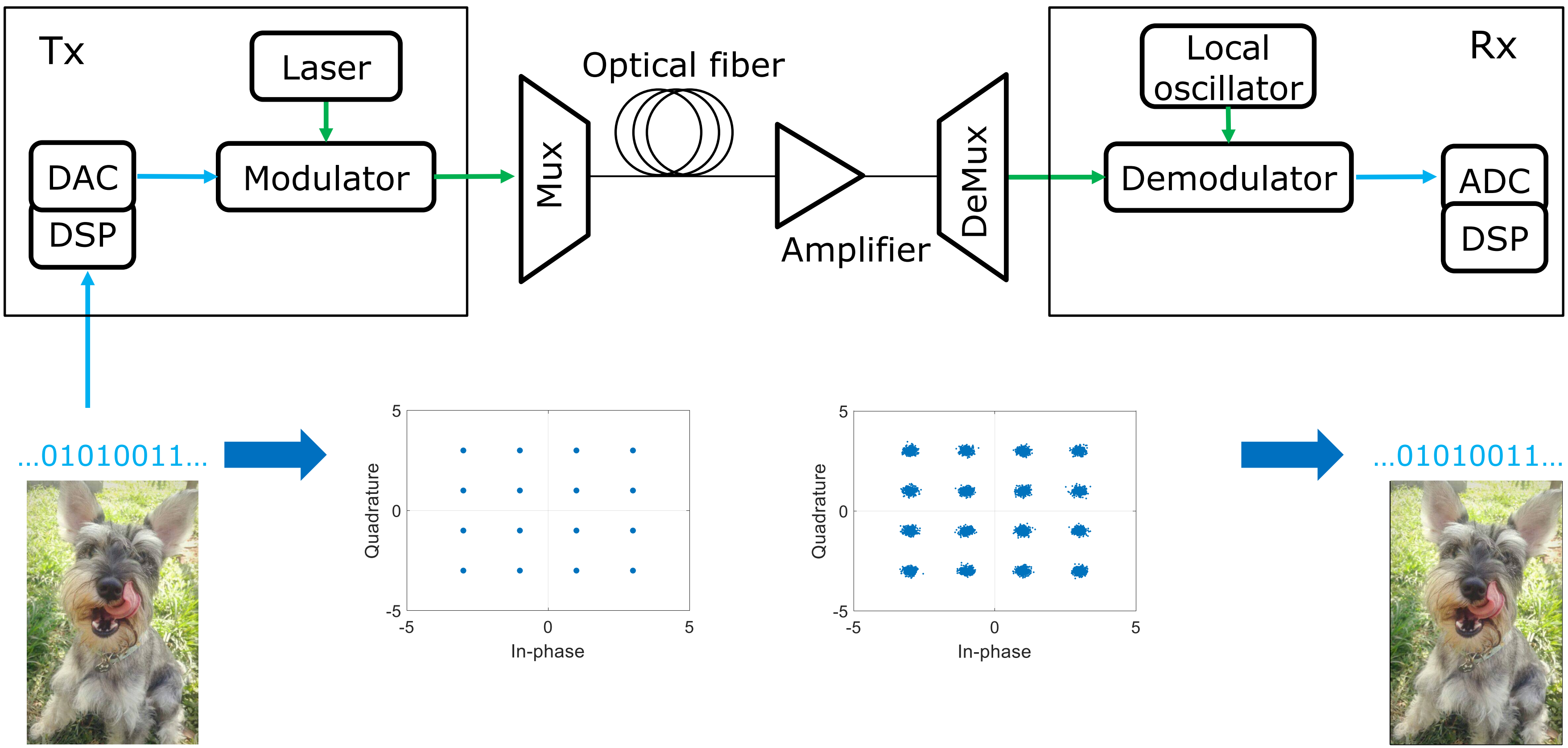
Optical communication systems



These slides are not NIST's slides. NIST is not responsible for the content of these slides.

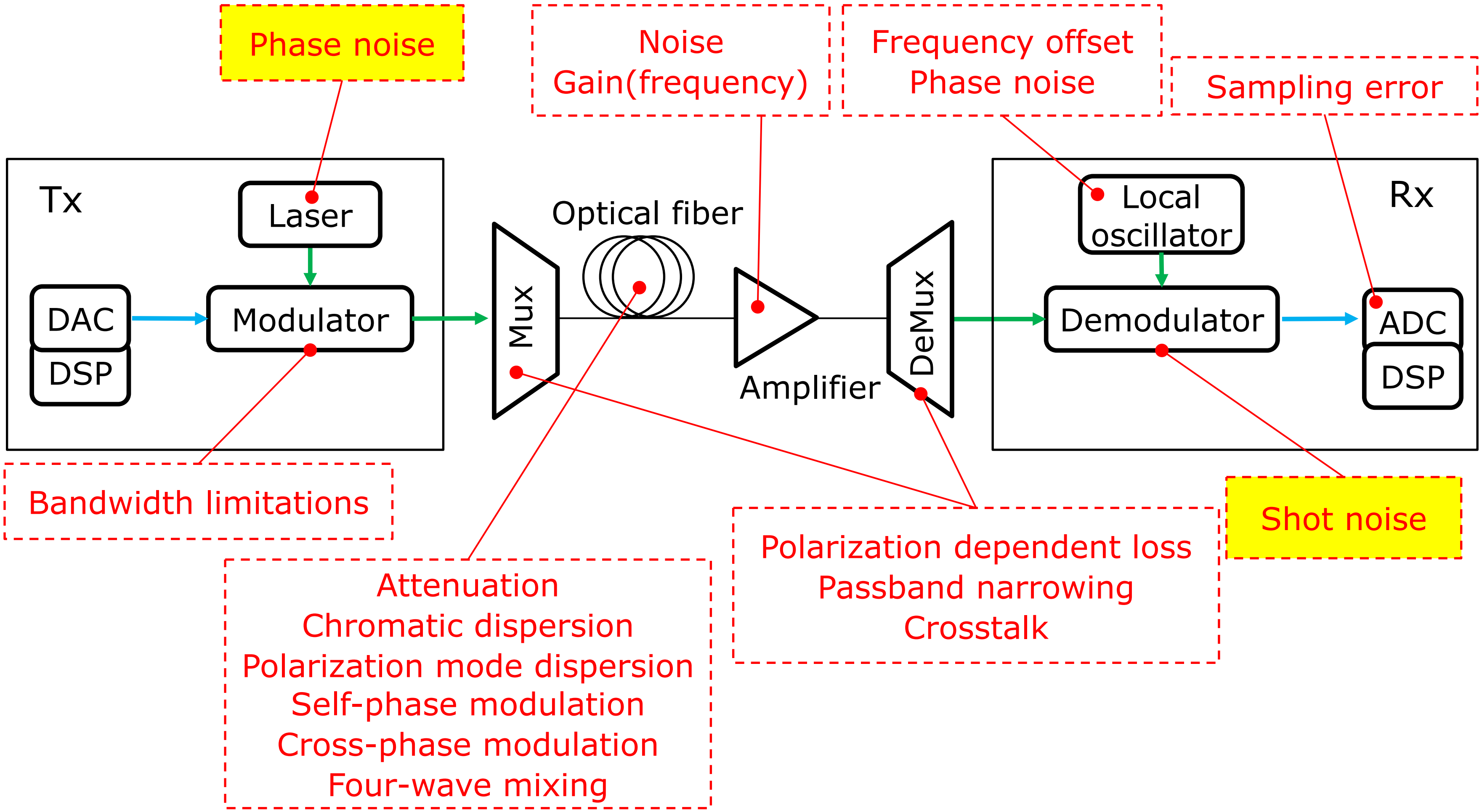
Optical communication systems

Optical coherent transmission illustration



These slides are not NIST's slides. NIST is not responsible for the content of these slides.

M-LiPS works

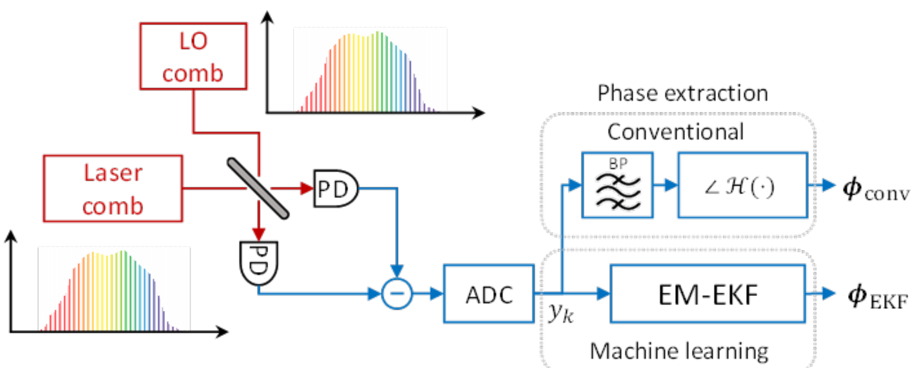


These slides are not NIST's slides. NIST is not responsible for the content of these slides.

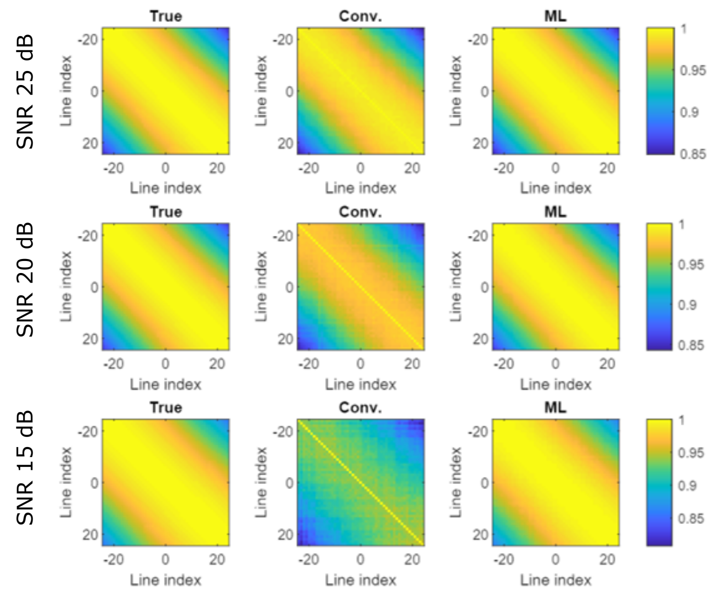
Frequency combs noise characterization

- *potential for becoming a reference tool*

Joint phase noise tracking



Extracted correlation matrix for different SNR scenarios



EM-EKF = expectation maximization algorithm with extended Kalman filter

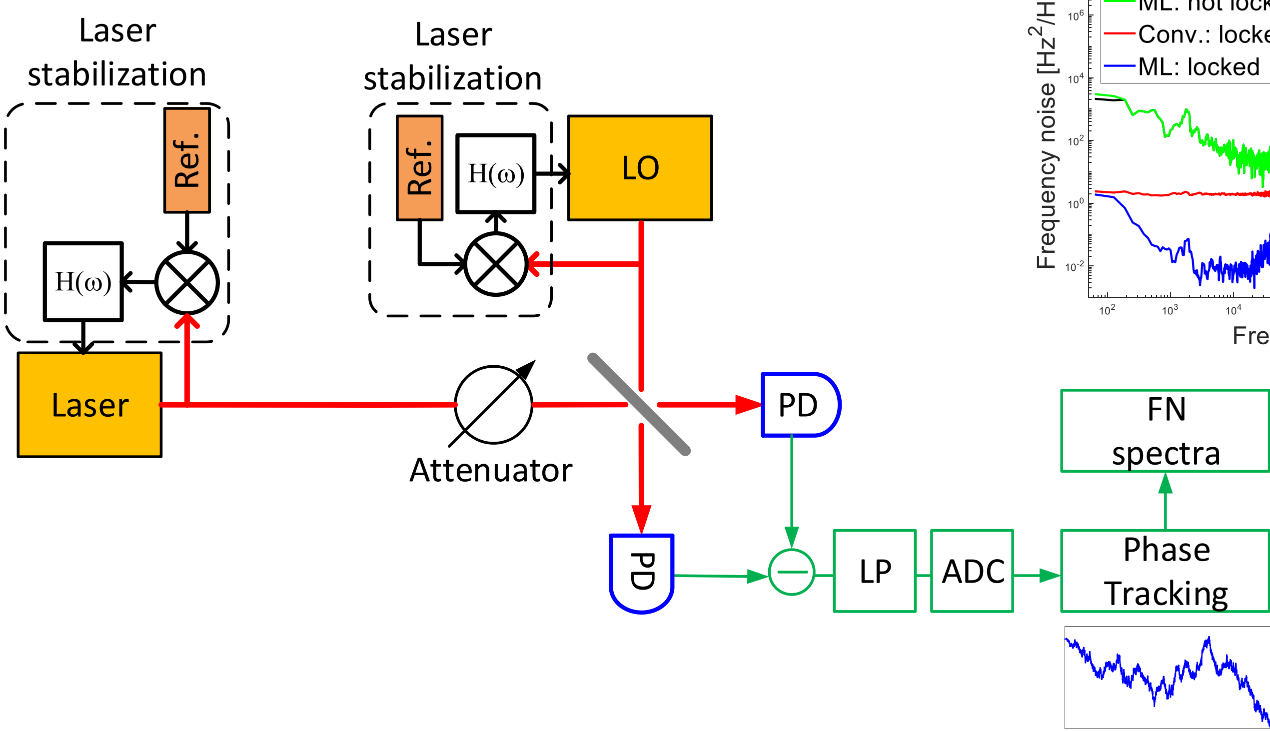
[1] B. Giovanni et al., Optical Frequency Comb Noise Characterization Using Machine Learning, accepted ECOC 2019.

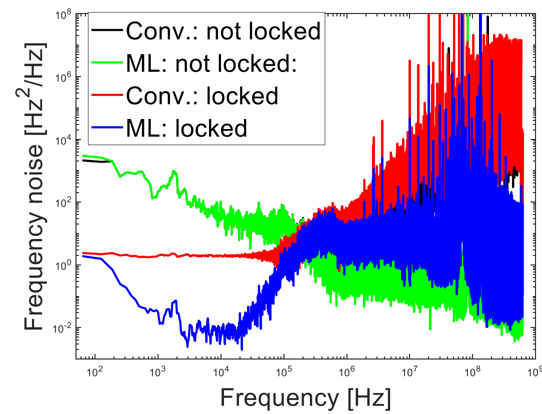
These slides are not NIST's slides. NIST is not responsible for the content of these slides.

Laser noise characterization

- *potential for becoming a reference tool*

Use Bayesian inference to remove measurement noise (shot noise)

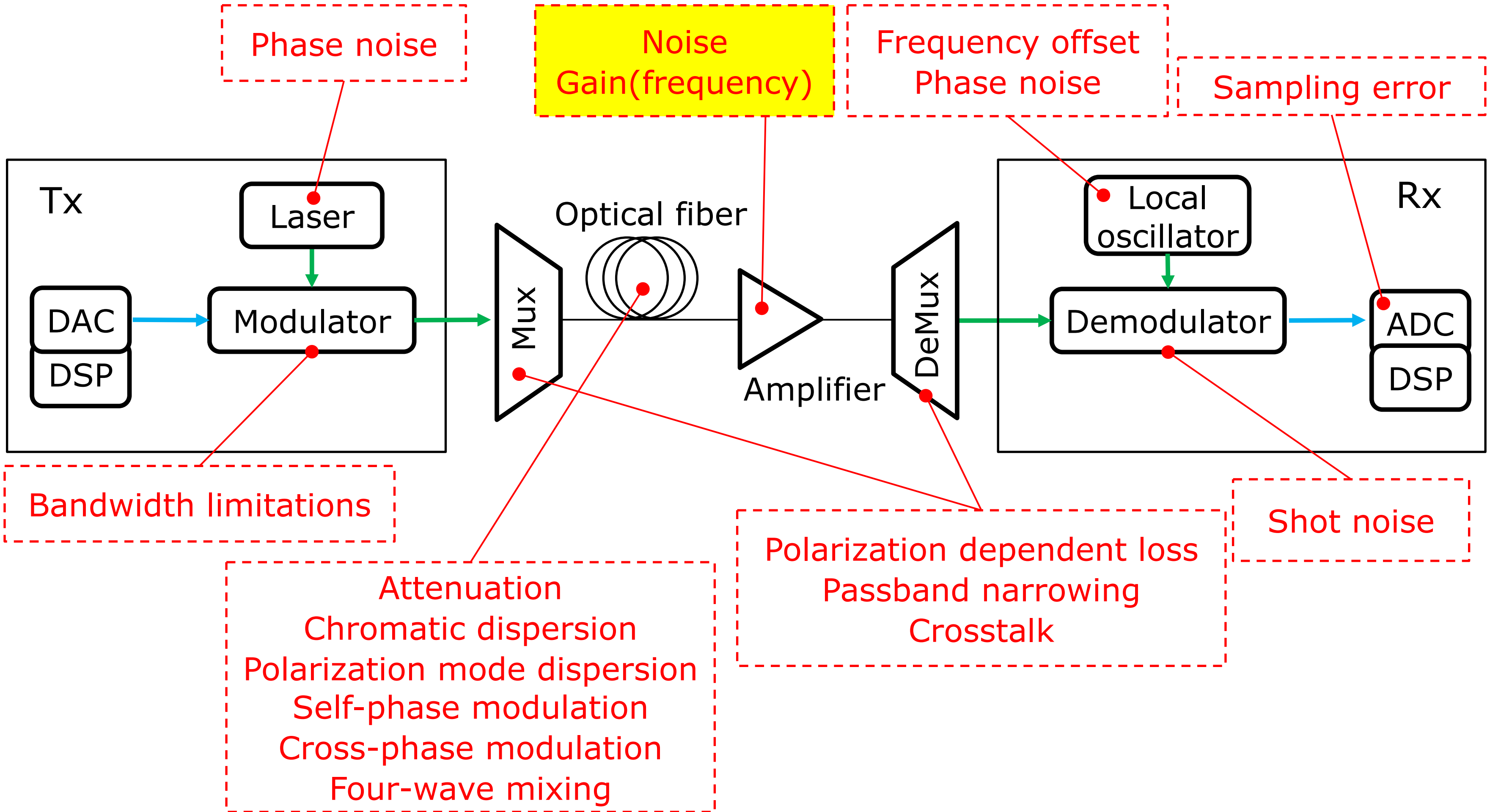




[1] H. Chin, D. Zibar, N. Jain, T. Gehring, and U. L. Andersen, Phase Compensation for Continuous Variable Quantum Key Distribution, in *CLEO* 2019.

These slides are not NIST's slides. NIST is not responsible for the content of these slides.

M-LiPS works

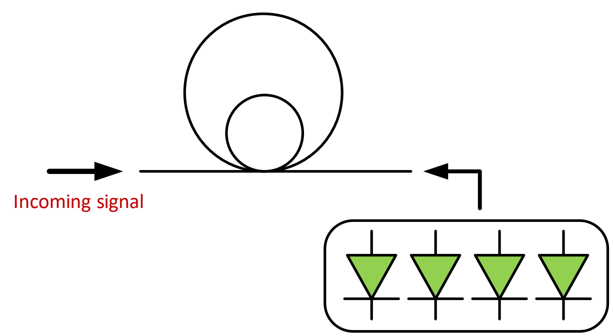


These slides are not NIST's slides. NIST is not responsible for the content of these slides.

Raman amplifier for optical communication

Name	O-Band	E-Band	S-Band	C-band	L-Band
Wavelength range (nm)	1260-1360	1360-1460	1460-1530	1530-1565	1565-1625
C-band system				35 nm	
C+L-band system				95 nm	
WON	365 nm				

Fig. 1: Optical wavelength bands in the low-loss window of single-mode fibres. Wideband optical networks (WON) offer more than 10× increased optical bandwidth compared to C-band systems.

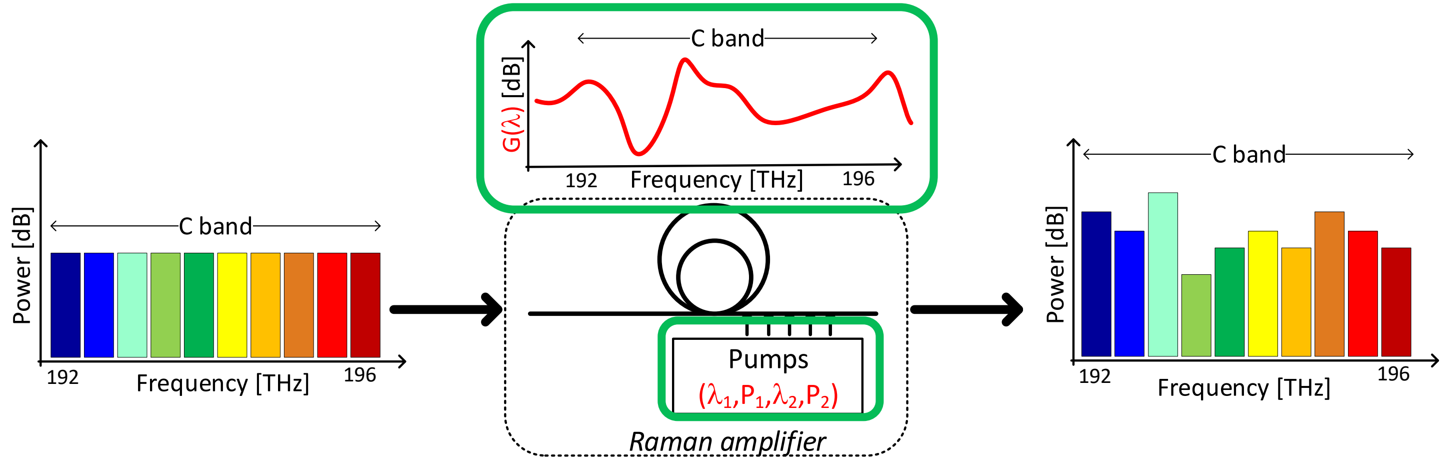


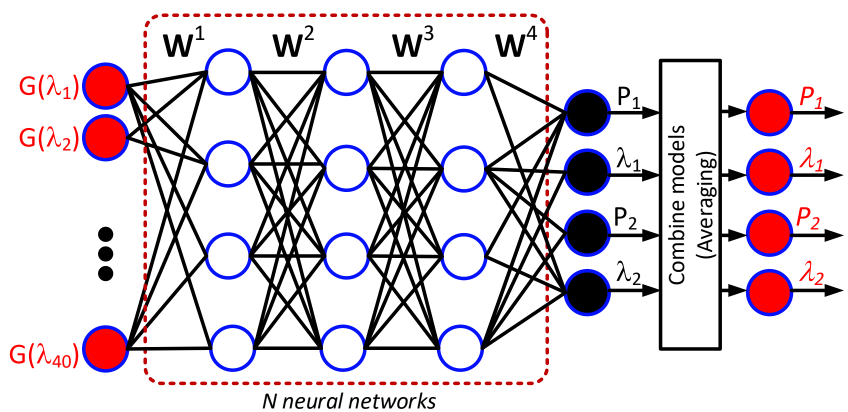
Employing O, E, S and L band requires rethinking optical amplification design

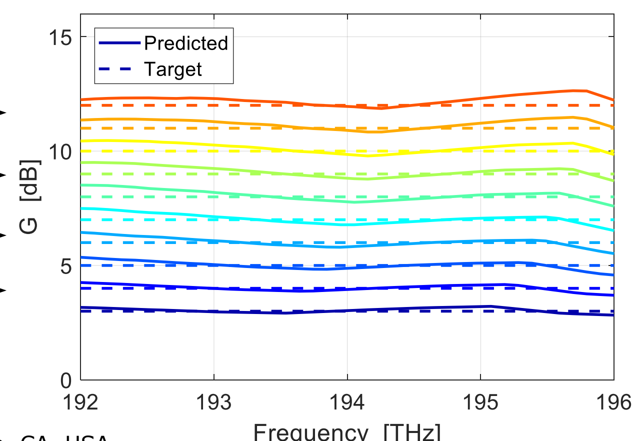
These slides are not NIST's slides. NIST is not responsible for the content of these slides.

Raman amplifier inverse design

Objective: given a Raman gain profile determine pump powers and wavelengths





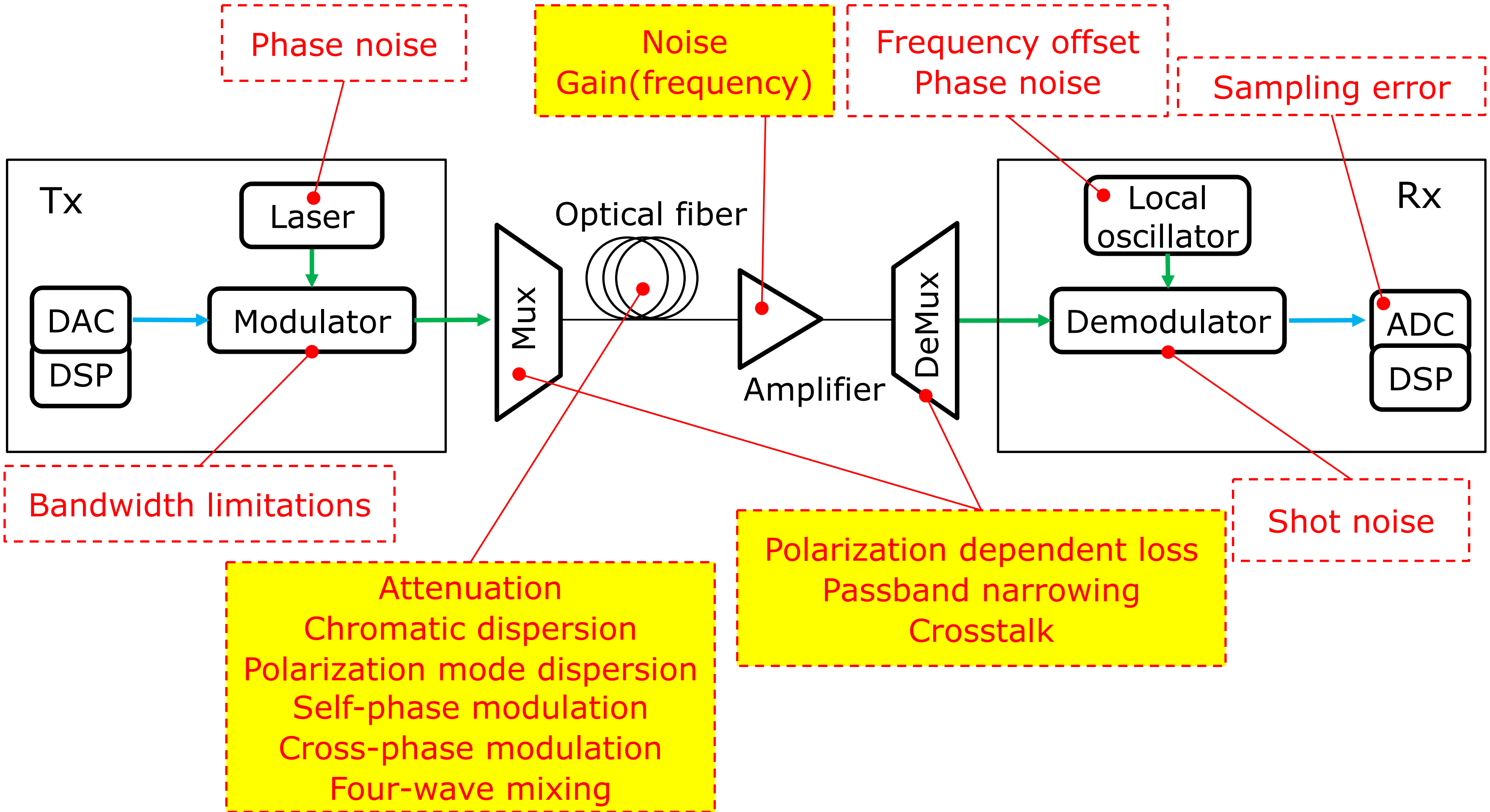


[1] D. Zibar et. al., Machine Learning-Based Raman Amplifier Design, OFC *2019*, San Diego, CA, USA.

[2] D. Zibar et. al., Inverse System Design using Machine Learning: the Raman Amplifier Case, submitted JLT.

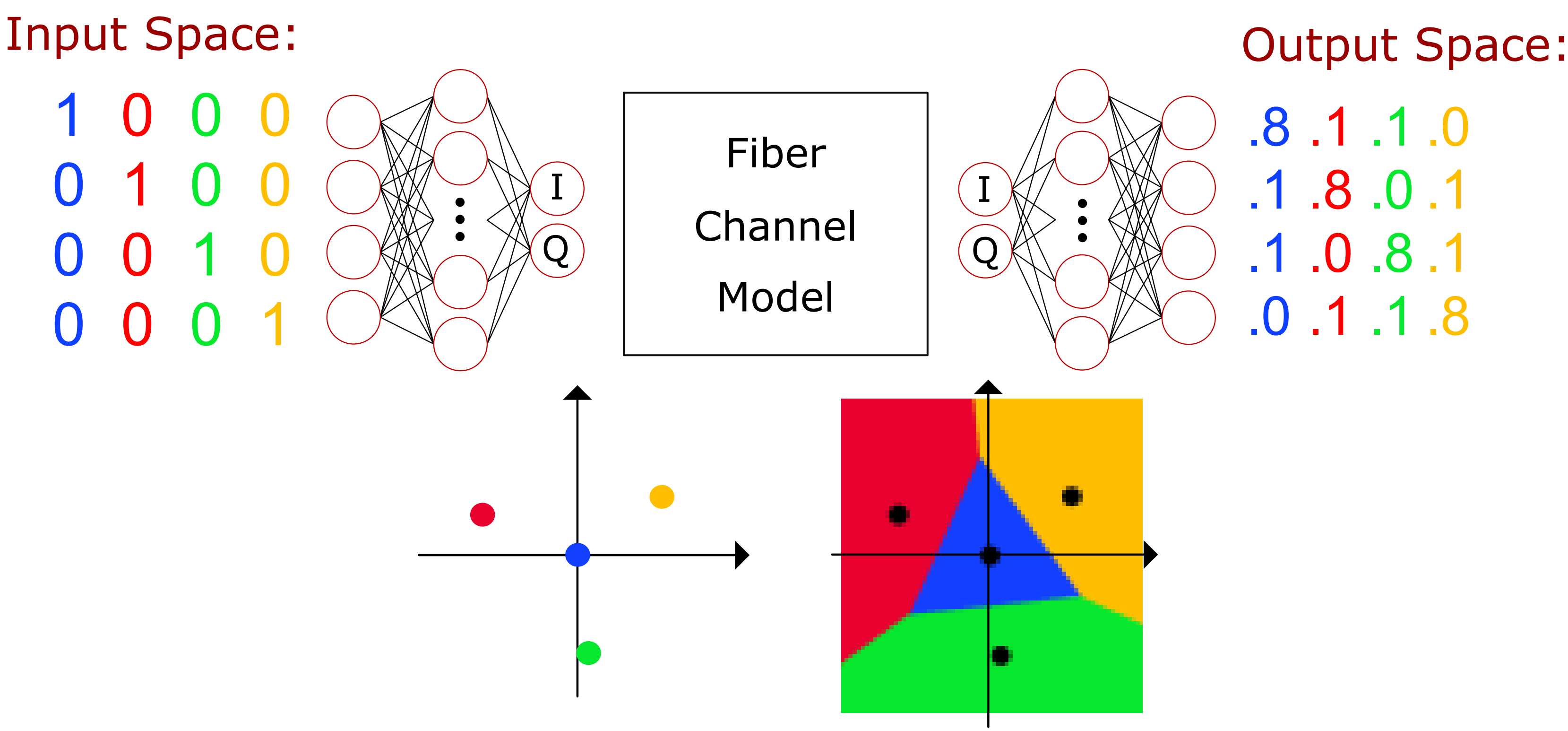
These slides are not NIST's slides. NIST is not responsible for the content of these slides.

M-LiPS works



These slides are not NIST's slides. NIST is not responsible for the content of these slides.

Learning to communicate using auto-encoders



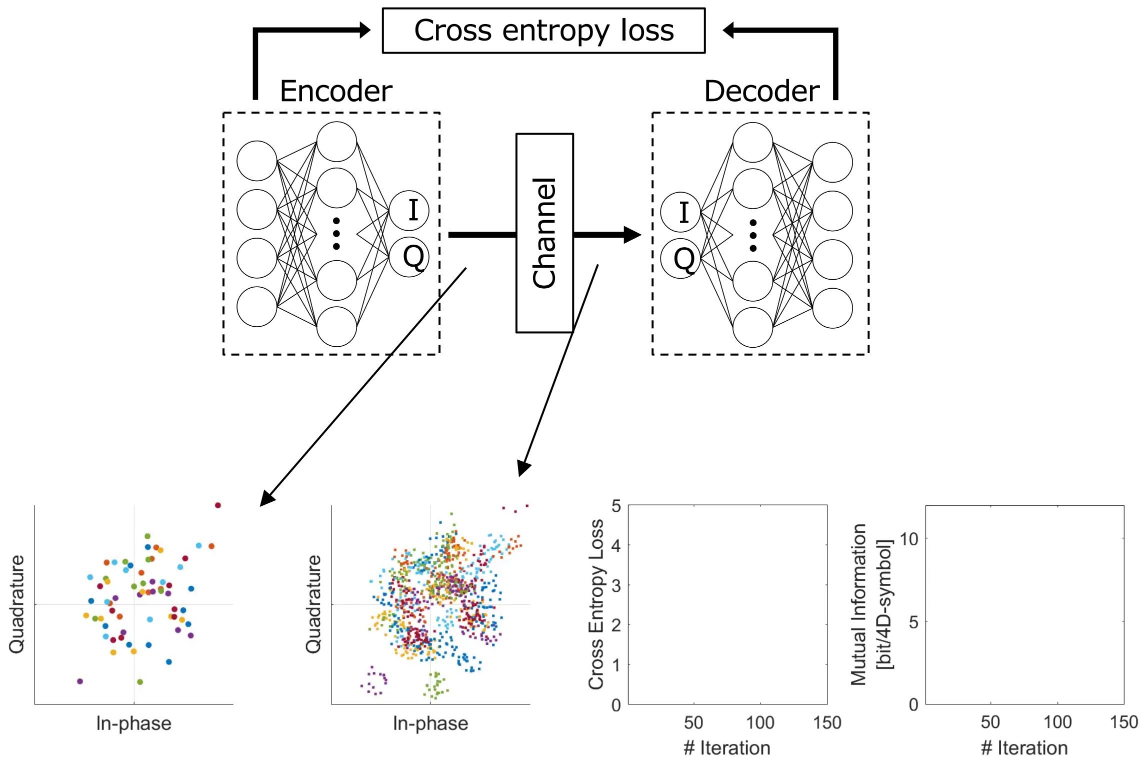
Objective: increase the transmitted information over a nonlinear channel

[1] R. Jones et al., Deep Learning of Geometric Constellation Shaping including Fiber Nonlinearities, in Proceedings of ECOC 2018.
[2] R. Jones et al., Geometric Constellation Shaping for Fiber Optic Communication Systems via End-to-end Learning, submitted to JLT
[3] R. Jones et al., End-to-end Learning for GMI Optimized Geometric Constellation Shape, accepted ECOC 2019.

These slides are not NIST's slides. NIST is not responsible for the content of these slides.

Learning to communicate using auto-encoders

Auto-encoder learning constellation
robust to channel impairments



[1] R. Jones et al., Deep Learning of Geometric Constellation Shaping including Fiber Nonlinearities, in Proceedings of ECOC 2018.
[2] R. Jones et al., Geometric Constellation Shaping for Fiber Optic Communication Systems via End-to-end Learning, submitted to JLT

These slides are not NIST's slides. NIST is not responsible for the content of these slides.

Group mission statement: research with impact

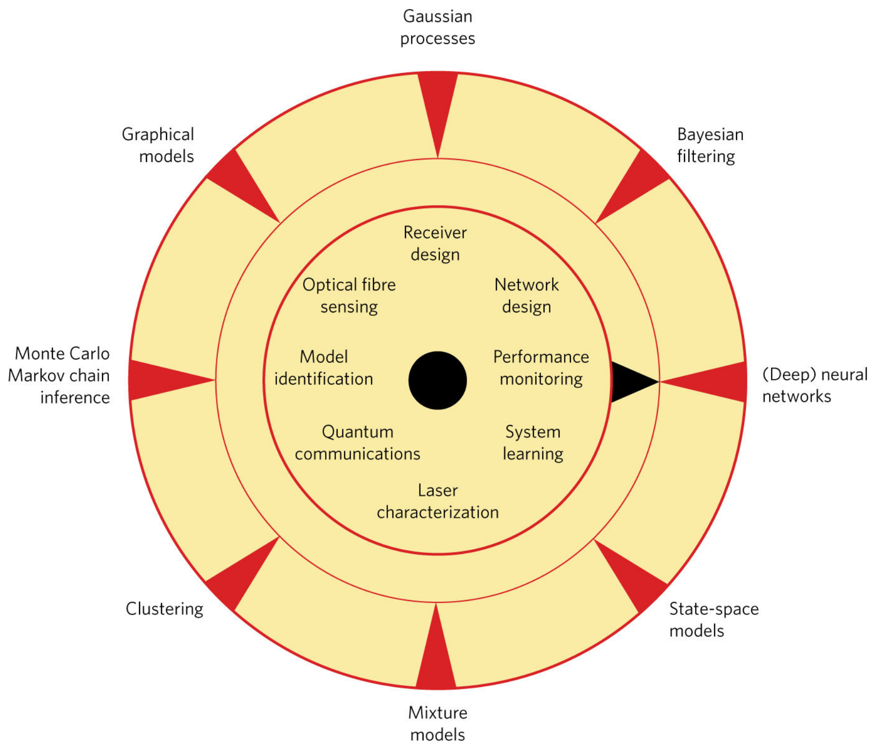
- Unifying framework for noise characterization of lasers, frequency combs and mode-locked lasers - move all functionalities into digital domain

- Nonlinear distortion-free communication over the nonlinear optical fibre channel

- Orders of magnitude improvements in accuracy of optical fibre sensor and quantum measurements using machine learning

These slides are not NIST's slides. NIST is not responsible for the content of these slides.

Machine learning in optical communication



[1] D. Zibar et al., Machine learning under the spotlight, Nature Photonics, (11) 749-751, 2017

New topics 2019:

- **Photonic neural network**
- **Optical Amplifier design**
- **End-to-end learning**
- **Back-propagation learning**

[2] F. Musumeci, C. Rottondi, A. Nag, I. Macaluso, D. Zibar, M. Ruffini, M. Tornatore, "An Overview on Application of Machine Learning Techniques in Optical Networks," in IEEE Communications Surveys & Tutorials, vol. 21, no. 2, pp. 1383-1408, 2019.

These slides are not NIST's slides. NIST is not responsible for the content of these slides.

Problems that will benefit from ML

- Noise characterization of lasers and frequency combs:
  - Optical phase tracking at the quantum limit
  - Noise correlation matrix of frequency combs lines
- Design of optical components (inverse system design):
  - Given laser linewidth and noise find the physical parameters
  - Given modulator bandwidth find the physical parameters
  - Instead of running time-consuming simulation build fast ML based models
- Optical amplifiers for multiband-wavelength and SDM systems:
  - Complex relation between pumps and gain
  - Pump power and wavelength allocation for specific gain profile challenging
  - Minimization of mode dependent loss
- Communication over the nonlinear fiber-optic channel:
  - Channel highly complex
  - Capacity **unknown**?
  - Optimum receiver architecture **unknown**
  - Optimum modulation and pulse-shapes **unknown**

SDM: spatial division multiplexing

These slides are not NIST's slides. NIST is not responsible for the content of these slides.

Problems that will not benefit from ML

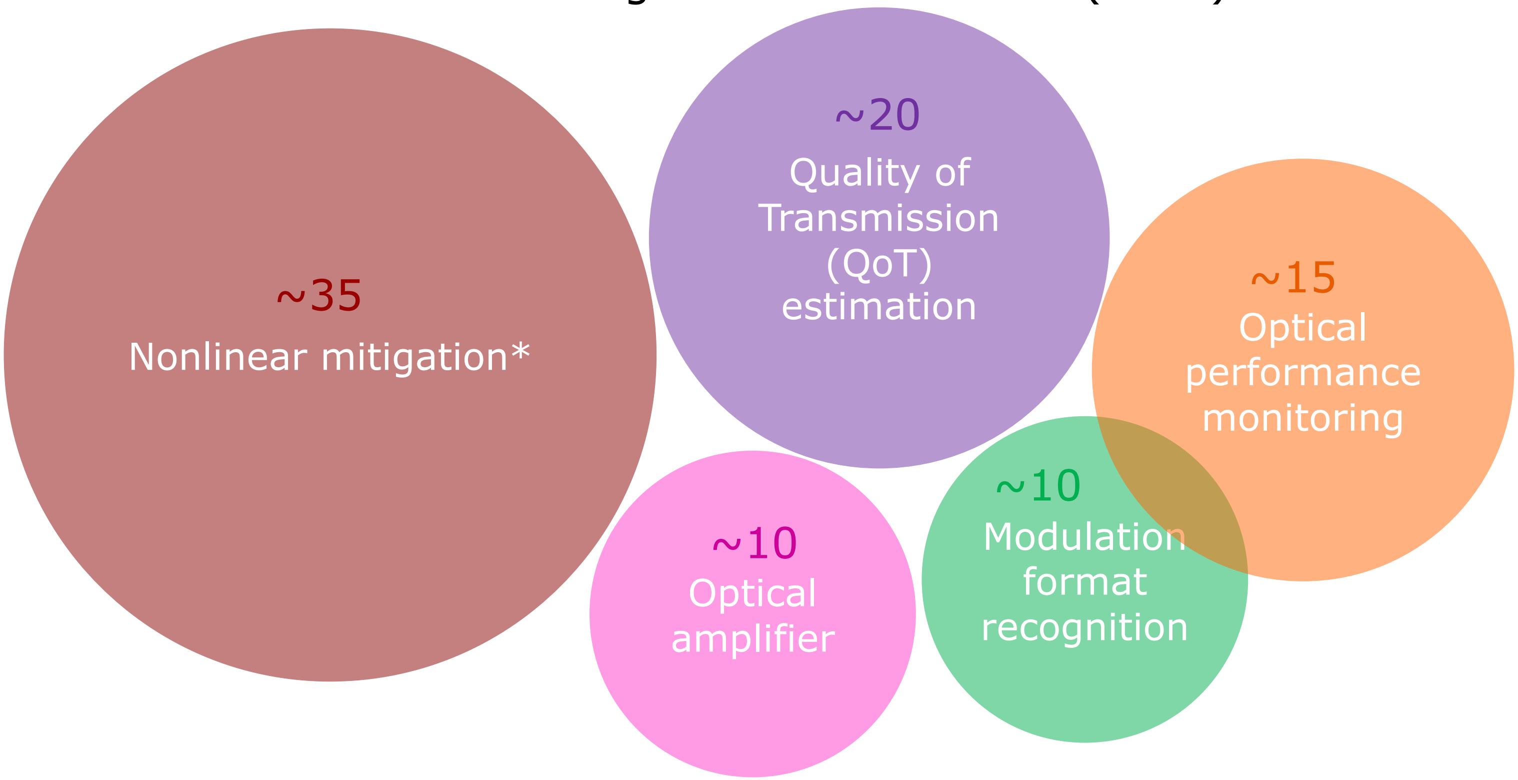
- Problems that we have a good knowledge, (low cost) models and analytical solutions such as:
  - Linear impairment compensation (chromatic dispersion) in coherent systems
  - EDFA design*

* Possible in an SDM scenario

These slides are not NIST's slides. NIST is not responsible for the content of these slides.

State-of-the-art (physical layer)

- Number of solutions according to the use case[1-3] (2019)



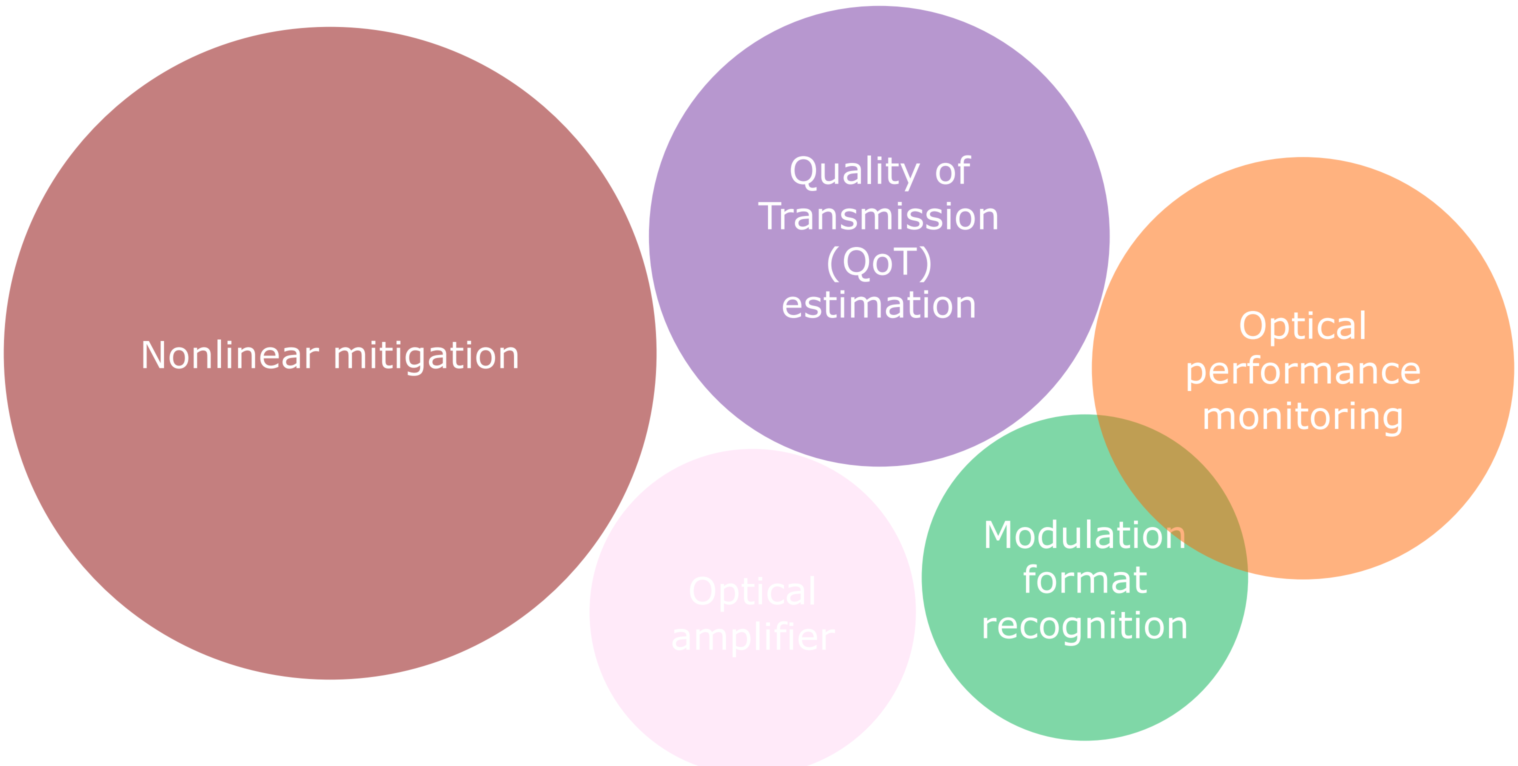
* Including receiver/transmitter design and end-to-end learning

[1] J. Mata, I. de Miguel, R. J. Durán, N. Merayo, S. K. Singh, A. Jukan, M. Chamania, Artificial intelligence (AI) methods in optical networks: A comprehensive survey, Optical Switching and Networking, 2018.
[2] F. Musumeci, C. Rottondi, A. Nag, I. Macaluso, D. Zibar, M. Ruffini, M. Tornatore, "An Overview on Application of Machine Learning Techniques in Optical Networks," in IEEE Communications Surveys & Tutorials, vol. 21, no. 2, pp. 1383-1408, 2019.
[3] F. N. Khan, Q. Fan, C. Lu and A. P. T. Lau, "An Optical Communication's Perspective on Machine Learning and Its Applications," in JLT, vol. 37, no. 2, pp. 493-516, 2019.

These slides are not NIST's slides. NIST is not responsible for the content of these slides.

What data matters (M-LiPS view)

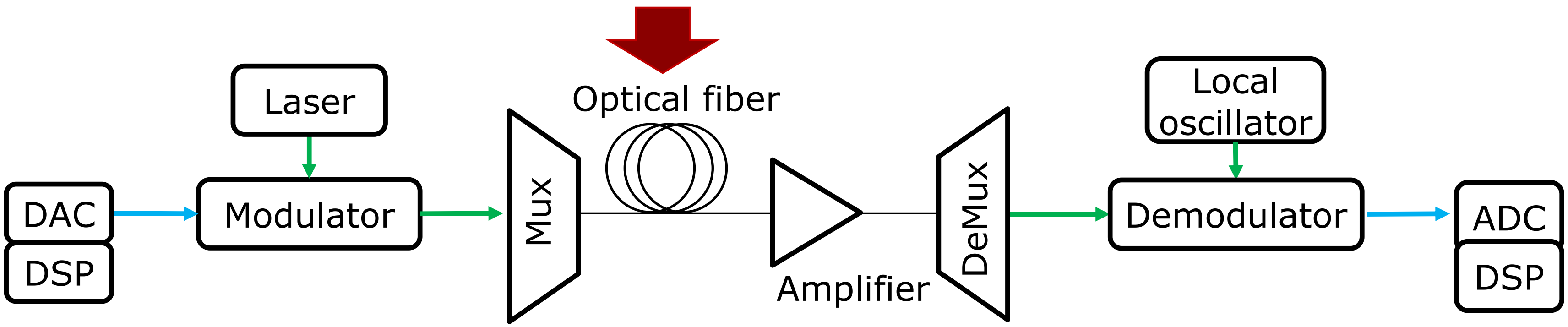
Does it depend on the use case?



These slides are not NIST's slides. NIST is not responsible for the content of these slides.

What data maters for **nonlinear mitigation**

Self-phase modulation (SPM)
Cross-phase modulation (XPM)
Four-wave mixing (FWM)



Aid/replace: DSP

- Received constellation
- Received symbols

Machine learning model

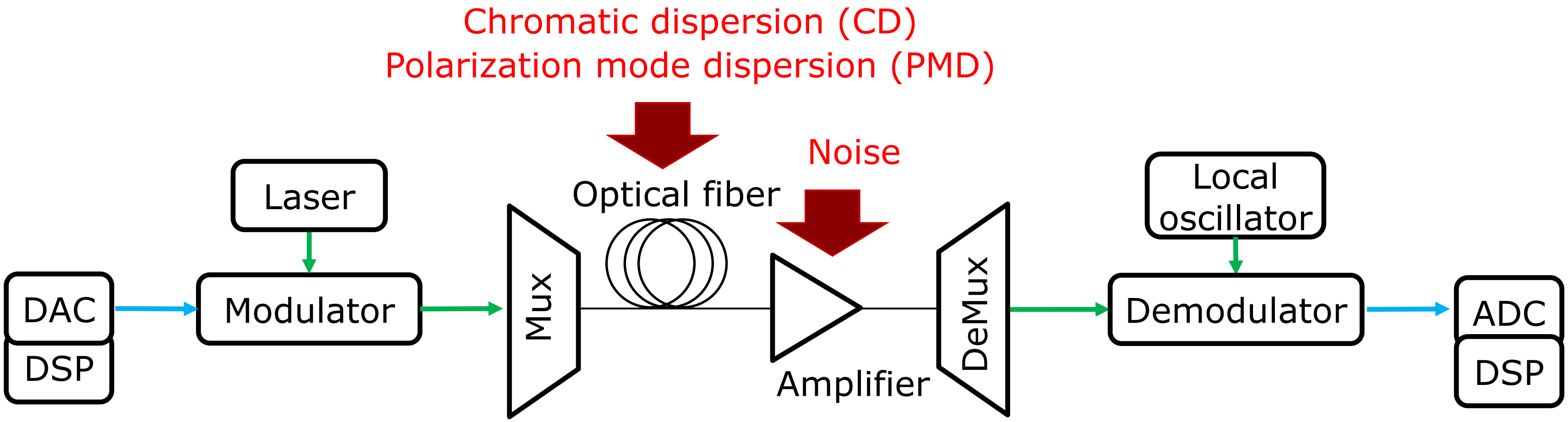
- Decoded symbols with impairment estimated or mitigated
- Nonlinearity mitigated constellation points
- Symbol decision boundaries

Data generation: random sequence of bits

These slides are not NIST's slides. NIST is not responsible for the content of these slides.

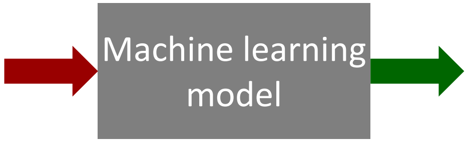
[1] F. Musumeci, et. al, in IEEE Communications Surveys & Tutorials, vol. 21, no. 2, pp. 1383-1408, 2019.

What data maters for optical performance monitoring



It will trigger actions depending on the current performance

- Amplitude histogram
- Constellation
- Eye diagram



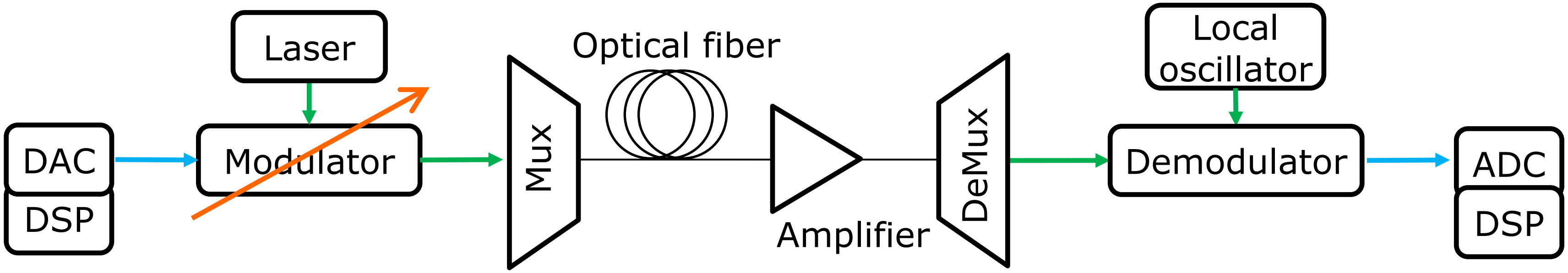
- OSNR
- PMD
- CD
- Q-factor

Data generation: vary the interested parameter (CD, PMD, noise) or a combination + random sequence of bits

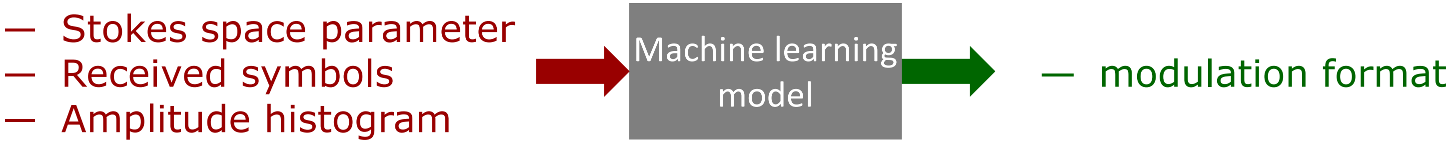
These slides are not NIST's slides. NIST is not responsible for the content of these slides.

[1] F. Musumeci, et. al, in IEEE Communications Surveys & Tutorials, vol. 21, no. 2, pp. 1383-1408, 2019.

What data maters for modulation format recognition



Flexible transmitters/receivers



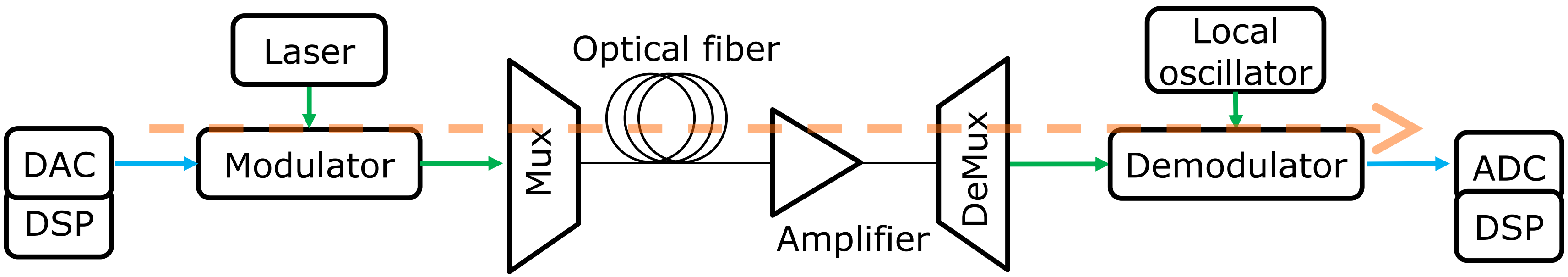
Data generation: vary the modulation format + random sequence of bits

These slides are not NIST's slides. NIST is not responsible for the content of these slides.

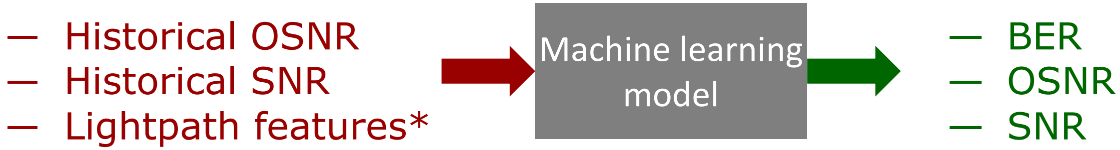
[1] F. Musumeci, et. al, in IEEE Communications Surveys & Tutorials, vol. 21, no. 2, pp. 1383-1408, 2019.

These slides are not NIST's slides. NIST is not responsible for the content of these slides.

What data maters for quality of transmition estimation



Estimation before connection deployment



Data generation: historical data collected from monitors or generate different connections with different lightpath features with the real QoT measured.

*Lightpath features: number of links, links' lengths, number of amplifiers along the link, modulation format, baud rate, channel launch power, …

[1] F. Musumeci, et. al, in IEEE Communications Surveys & Tutorials, vol. 21, no. 2, pp. 1383-1408, 2019.

What data matters (M-LiPS view)

Does it depend on the use case?

Yes

But for most of the cases on the literature, the **input data** can be represented by the received waveforms (after ADC)

And the **output data** will depend on the application

These slides are not NIST's slides. NIST is not responsible for the content of these slides.

Summarizing

Parameters

Tx

Modulation format
Baud rate
Pulse shaping
Constellation shaping
…

Optical channel

Fiber type
Fiber length
Fiber attenuation
Fiber CD/PMD
Number of channels
Fiber nonlinear param.
Channel input power
Amplifier noise figure
Amplifier gain
Channel allocation
….

Signal representation

Tx/Rx

Digital samples
Symbols
Constellation (I/Q)
Stokes space
Amplitude histogram
Eye diagram
…
= Waveforms

Signal parameters

Rx

Modulation format
Baud rate
…

Penalties

Rx

CD
PMD
PDL
SPM
XPM
FWM
…

Figure of merit

Rx

BER
Q-factor
SNR
AIR
OSNR
…

These slides are not NIST's slides. NIST is not responsible for the content of these slides.

Thank you for your attention.

Acknowledgements

CoG FRECOM (grant agreement no. 771878)

European Union's Horizon 2020 research and innovation programme under the Marie Sklodowska-Curie grant agreement No 754462.

These slides are not NIST's slides. NIST is not responsible for the content of these slides.