Machine Learning Enabled Nonlinear Phase Noise Mitigation for Coherent Optical Systems

Master's Thesis

Sergio Steven Gutiérrez[1]

Supervised by Cord Arnold[1] & Sergei Popov[2]

[1] *Department of Physics*
Lund University

[2] *Kungliga Tekniska Högskolan* KTH &
Research Institutes of Sweden RISE

May 2020

Outline

1. Introduction & Motivation
   - Optical Communication
   - Improvements to a OOK System
   - Impairments of a Coherent Optical Link
2. Digital Signal Processing
   - Analytical NLPN Compensation
   - Machine Leaning Enabled DSP
3. VPI mQAM Link with ML Assisted Detection
   - NLPN in a Long-Haul Communication Link
   - NLIN in a WDM Communication Link
4. Conclusion
   - Final Remarks

Outline

1. Introduction & Motivation
   - Optical Communication
   - Improvements to a OOK System
   - Impairments of a Coherent Optical Link
2. Digital Signal Processing
   - Analytical NLPN Compensation
   - Machine Leaning Enabled DSP
3. VPI mQAM Link with ML Assisted Detection
   - NLPN in a Long-Haul Communication Link
   - NLIN in a WDM Communication Link
4. Conclusion
   - Final Remarks

Optical Communication Link

Motivation & Context

Why is fiber optics a fundamental technology ? Why extend the transmission length or prolong the lifetime of a fiber?

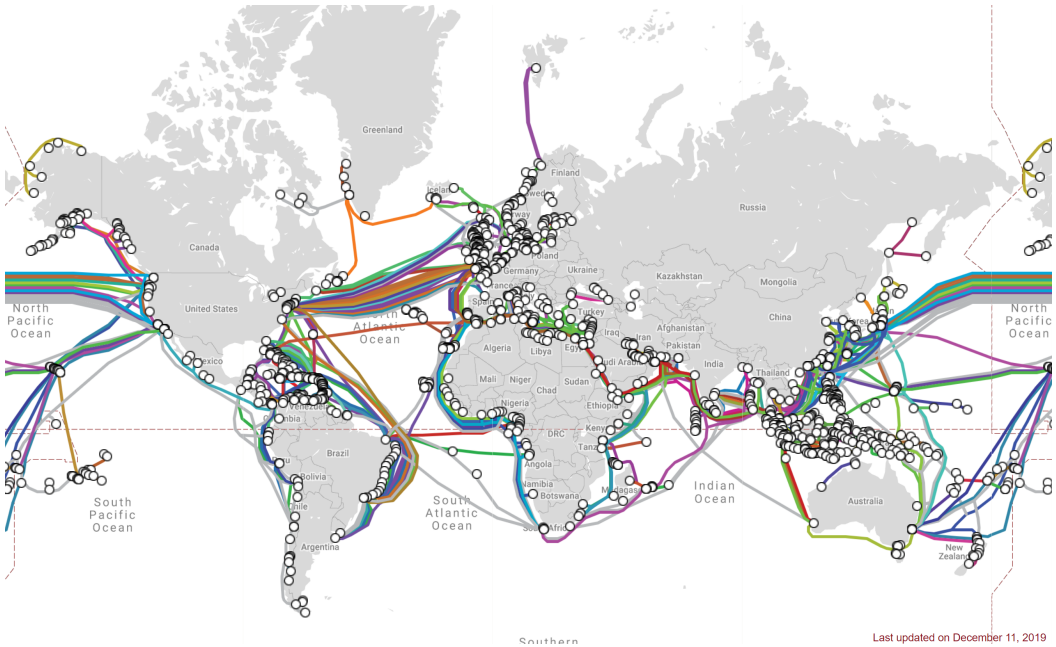


Figure: Global submarine fiber cable map currently operational.

[1] Submarine Cable Map. (2020). Retrieved 24 May 2020, from https://www.submarinecablemap.com/

Optical Communication Link

Motivation & Context

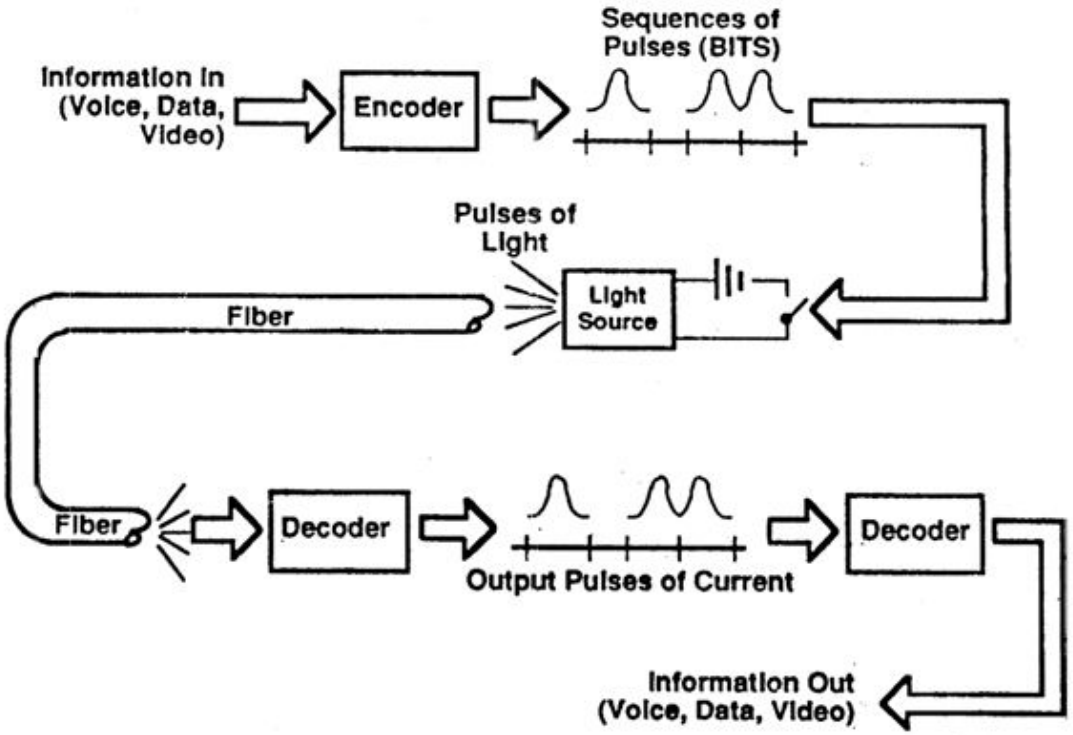


Figure: Basic components of a fiber link using on-off keying.

[2] Optical Fiber Cable. (2020). Retrieved 24 May 2020, from here4share.blogspot.com

Outline

1. Introduction & Motivation
   - Optical Communication
   - Improvements to a OOK System
   - Impairments of a Coherent Optical Link
2. Digital Signal Processing
   - Analytical NLPN Compensation
   - Machine Leaning Enabled DSP
3. VPI mQAM Link with ML Assisted Detection
   - NLPN in a Long-Haul Communication Link
   - NLIN in a WDM Communication Link
4. Conclusion
   - Final Remarks

Optical Communication Link

Capacity Improvements

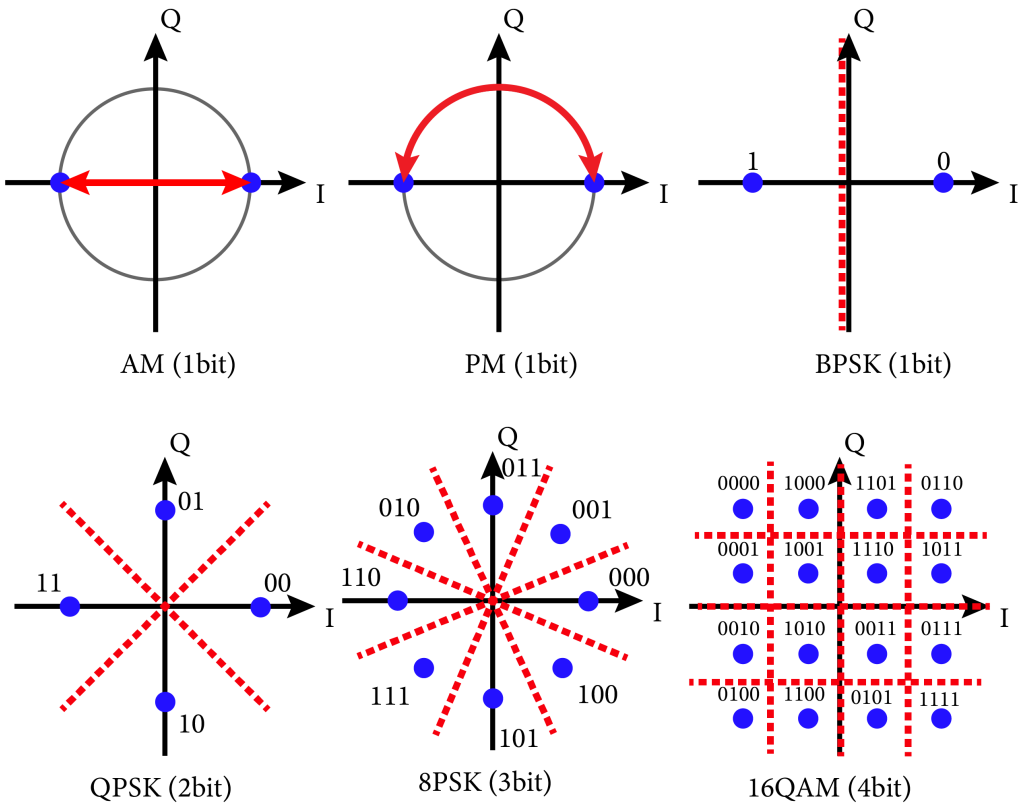
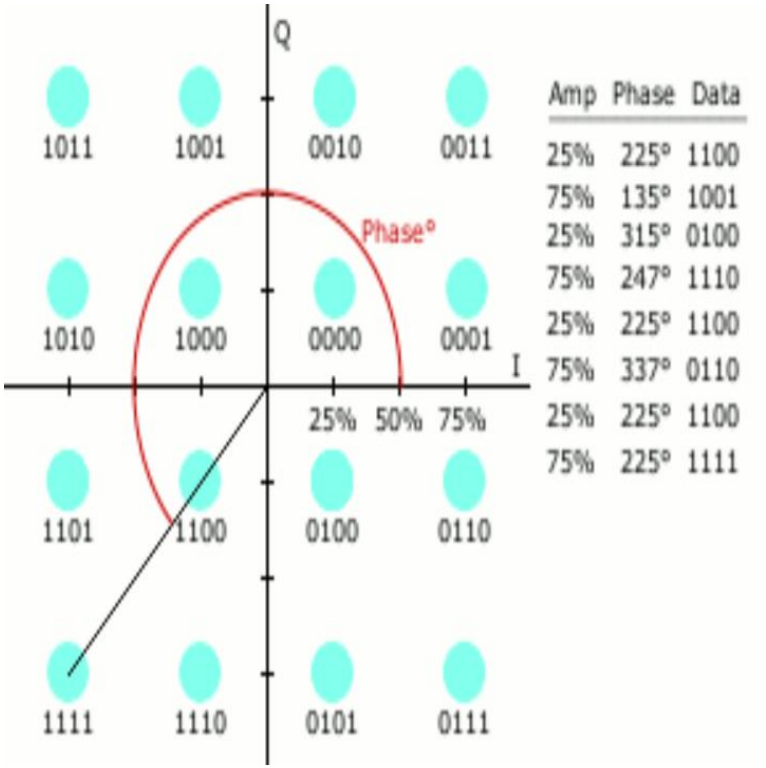


Figure: Higher order modulation of a carrier signals phase and amplitude to increasing the capacity of the channel.

Coherent Optical Communication Link

Motivation & Context



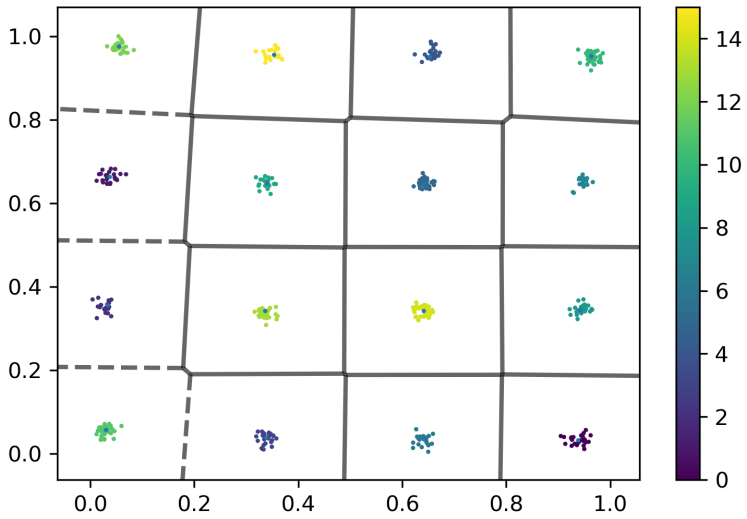


Figure: 16QAM constellation classification implemented through decision regions.

Optical Communication Link

Capacity Improvement

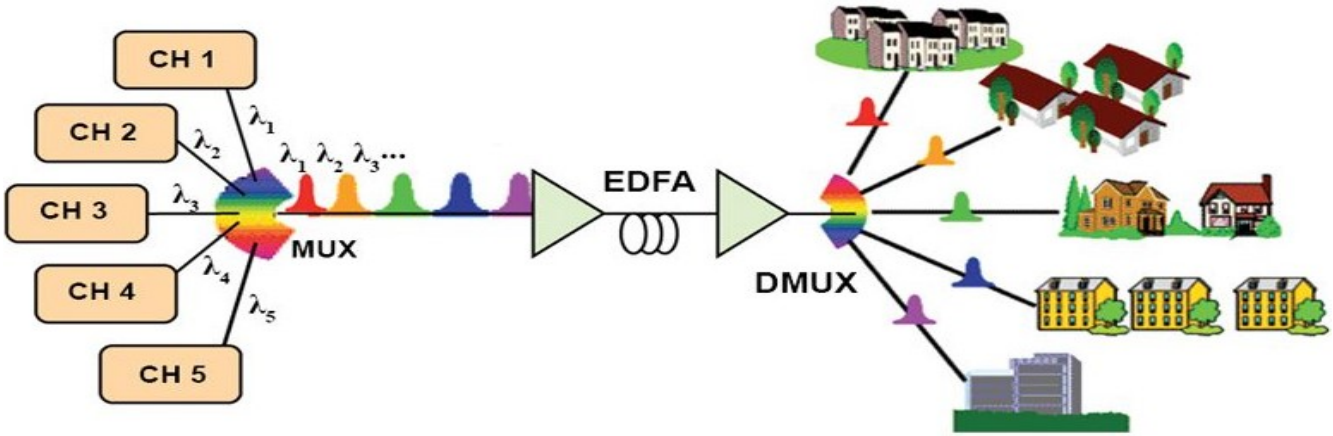


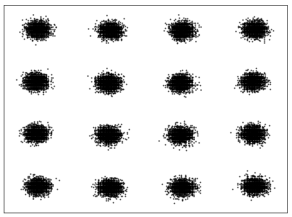
Figure: Wave length division multiplexing to increase the transmission capacity of a fiber link by adding more channels over the same fiber.

[3] High-Speed DWDM Technology | Page 3 of 7 | Electronics For You. (2020). Retrieved 24 May 2020, from https://www.electronicsforu.com/technology-trends/high-speed-dwdm-technology/3

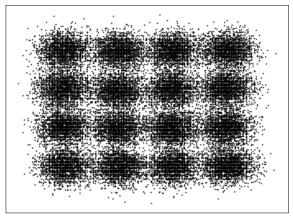
Outline

1. Introduction & Motivation
   - Optical Communication
   - Improvements to a OOK System
   - Impairments of a Coherent Optical Link
2. Digital Signal Processing
   - Analytical NLPN Compensation
   - Machine Leaning Enabled DSP
3. VPI mQAM Link with ML Assisted Detection
   - NLPN in a Long-Haul Communication Link
   - NLIN in a WDM Communication Link
4. Conclusion
   - Final Remarks

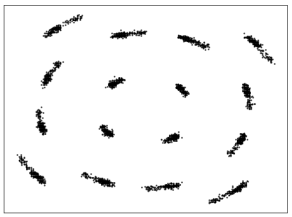
Linear & Non-linear Noise



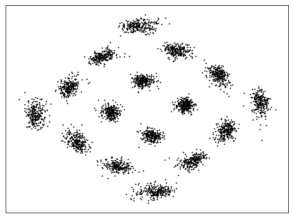
(a) SNR 25dB



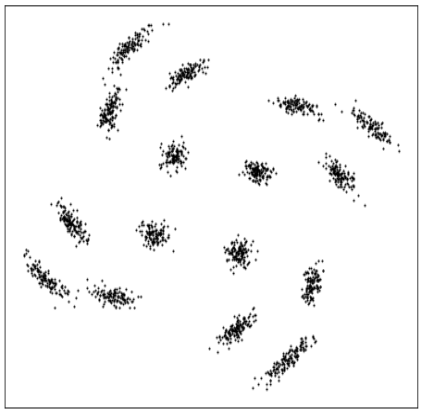
(b) SNR 15 dB



(c) LPN



(d) XPM+SPM



(e) NLPN

Figure: Linear noise sources like AWGN or linear phase noise (LPN) can be compensated for with DSP. Nonlinear noise is the current bottleneck of an optical link, manifested as cross phase modulation (XPM), self phase modulation (SPM) and nonlinear phase noise (NLPN).

Outline

1. Introduction & Motivation
   - Optical Communication
   - Improvements to a OOK System
   - Impairments of a Coherent Optical Link
2. Digital Signal Processing
   - Analytical NLPN Compensation
   - Machine Leaning Enabled DSP
3. VPI mQAM Link with ML Assisted Detection
   - NLPN in a Long-Haul Communication Link
   - NLIN in a WDM Communication Link
4. Conclusion
   - Final Remarks

Parameter Based Approach

$$E_C = E_R e^{-j\alpha P_N}, \quad \alpha = -\gamma L_{eff} \frac{N+1}{2}$$



(a) With NLPN (b) After NLPN Compensation

Figure: NLPN compensation of a 16QAM constellation at a launch power 0.17 mW after 40 spans of 40 km fiber, inducing a phase shift $\langle \phi_{NLPN} \rangle = 0.13$ mrad.

[4] Ho, K. P., and J. M. Kahn. Detection technique to mitigate Kerr effect phase noise. No. physics/0211097. 2002.

Outline

1. Introduction & Motivation
   - Optical Communication
   - Improvements to a OOK System
   - Impairments of a Coherent Optical Link
2. Digital Signal Processing
   - Analytical NLPN Compensation
   - Machine Leaning Enabled DSP
3. VPI mQAM Link with ML Assisted Detection
   - NLPN in a Long-Haul Communication Link
   - NLIN in a WDM Communication Link
4. Conclusion
   - Final Remarks

Support Vector Machine SVM

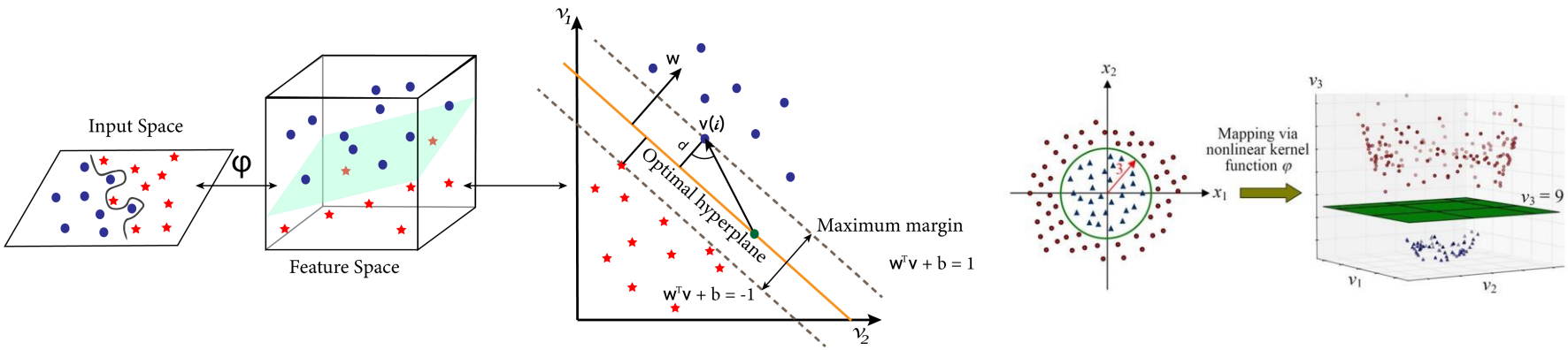


Figure: The two main components of SVM is the margin maximisation algorithm and the implementation of kernels to project onto a higher dimensional space.

[5] N. Khan, Q. Fan, C. Lu and A. P. T. Lau, "An Optical Communication's Perspective on Machine Learning and Its Applications," in Journal of Lightwave Technology, vol. 37, no. 2, pp. 493-516, 15 Jan.15, 2019

Random Forest RF

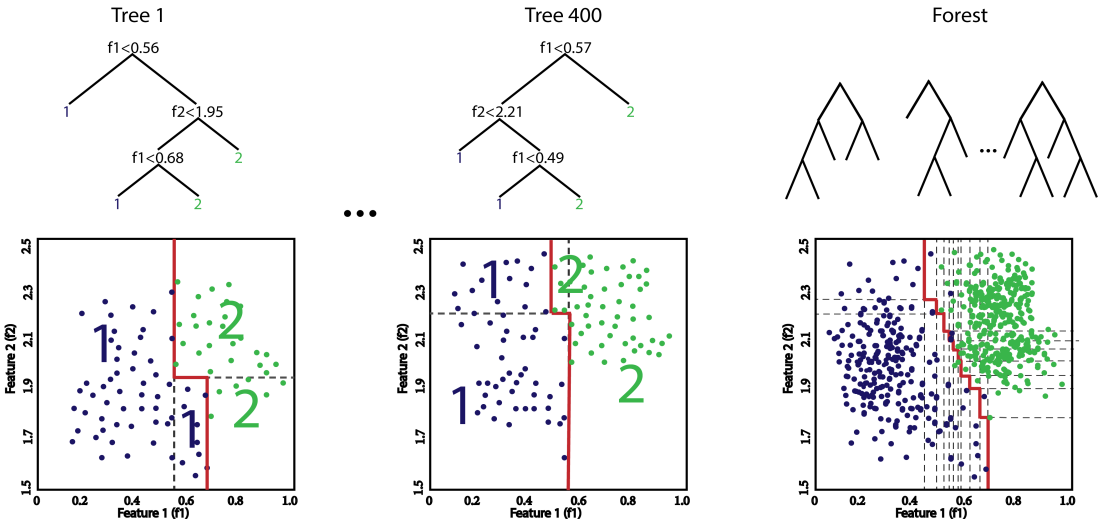
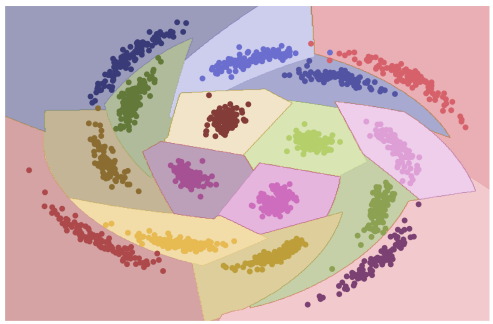


Figure: Random Forest consist of there techniques decision trees, bootstrapping and boosting. Current implementations are fast to optimize and train, but they have a tendency to overfit the training dataset.

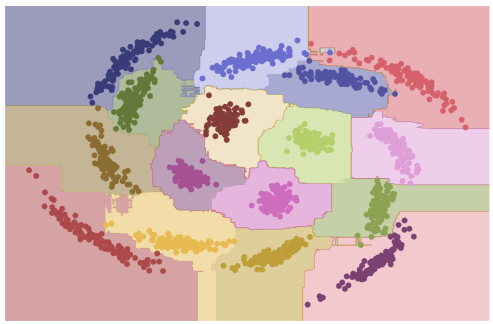
Feurer, M., Klein, A., Eggensperger, K., Springenberg, J. T., Blum, M., & Hutter, F. (2019). Auto-sklearn: efficient and robust automated machine learning. In Automated Machine Learning (pp. 113-134). Springer, Cham.

Nonparameter Based Approach

RF is first implemented by the nonparameter scheme. If RF has a SER larger than a maximum SER the SVM algorithm is computed. The scheme with the smallest SER is the one implemented by the noparameter DSP scheme.



(a) SVM



(b) RF

Figure: Decision regions computed for the same training dataset. The difference in the algorithms can be observed in the smoothness of the determined decision regions.

Outline

1. Introduction & Motivation
   - Optical Communication
   - Improvements to a OOK System
   - Impairments of a Coherent Optical Link
2. Digital Signal Processing
   - Analytical NLPN Compensation
   - Machine Leaning Enabled DSP
3. VPI mQAM Link with ML Assisted Detection
   - NLPN in a Long-Haul Communication Link
   - NLIN in a WDM Communication Link
4. Conclusion
   - Final Remarks

Fiber Link Simulation

128 Gbits/s

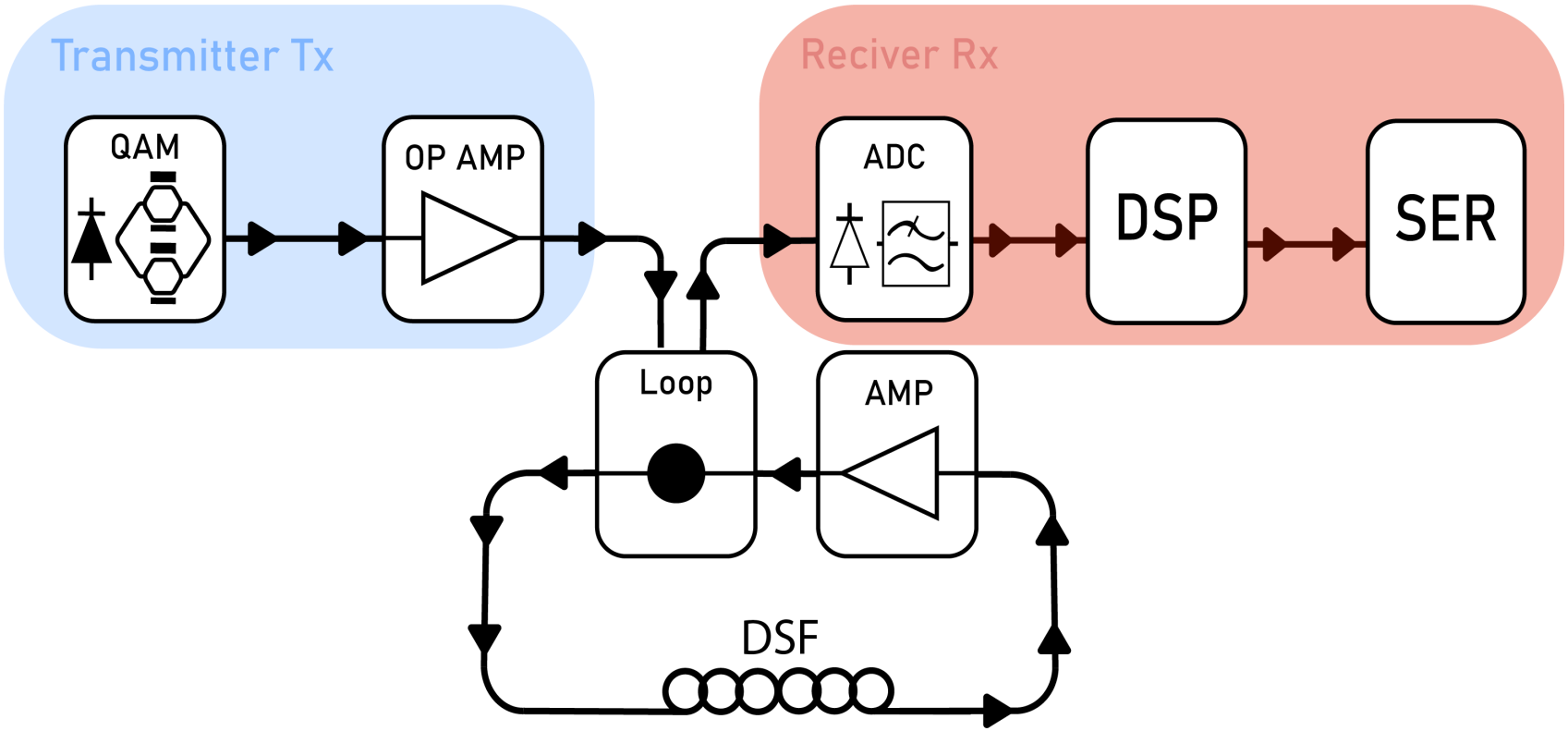


Figure: Nonlinear long-haul fiber link implemented in VPI

Comments on the Simulations

Keep in Mind

- Maximum SER for a reliable detection.

$$SER < 10^{-5}$$

- Number of simulated symbols

$$2^{12} = 4096$$

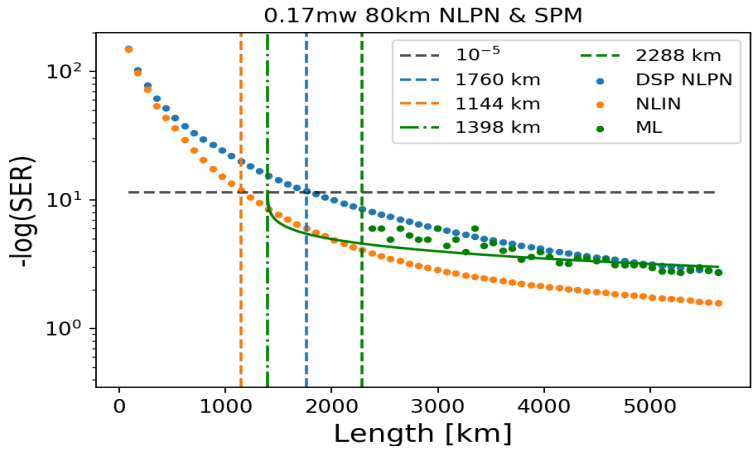
- Making one mistake in the simulation gives a

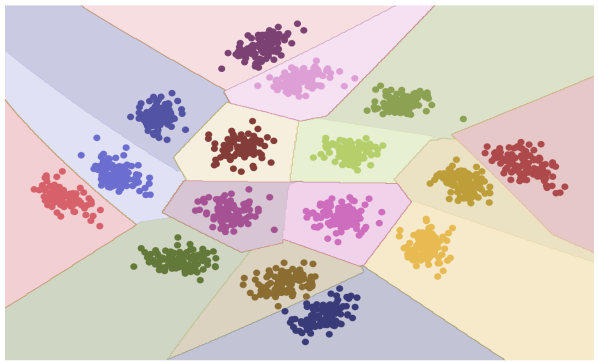
$$SER = 24.4 \cdot 10^{-5}$$

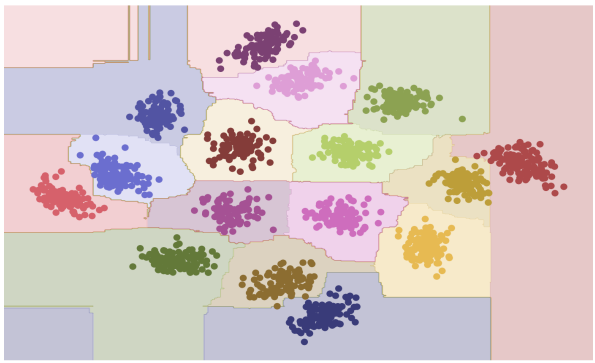
- The SER for all DSP schemes changes exponentially fast.

Detection Scheme 0.17 mW Launch Power

16QAM

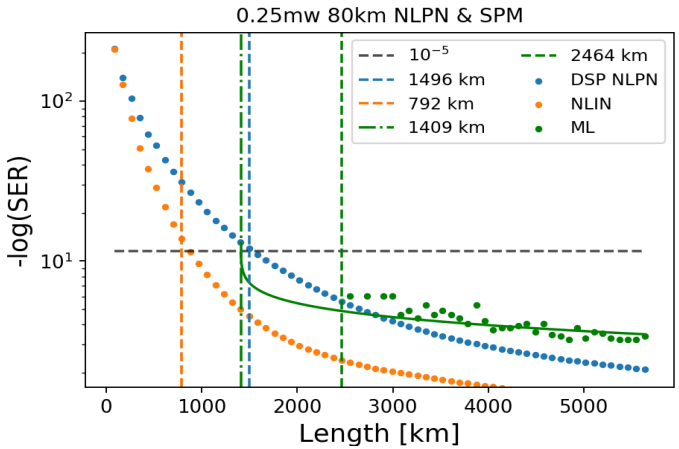


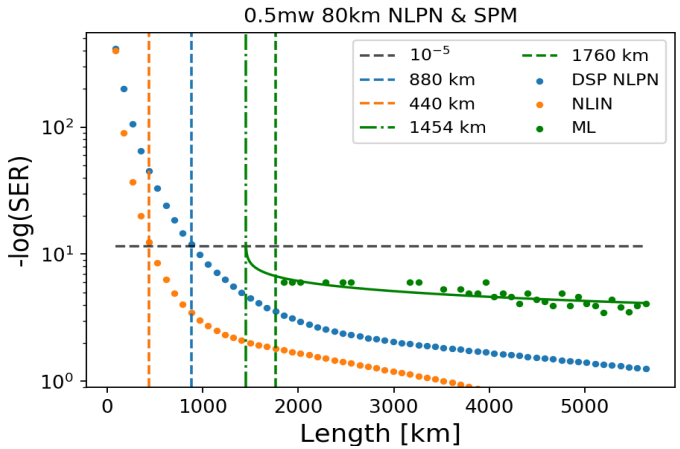


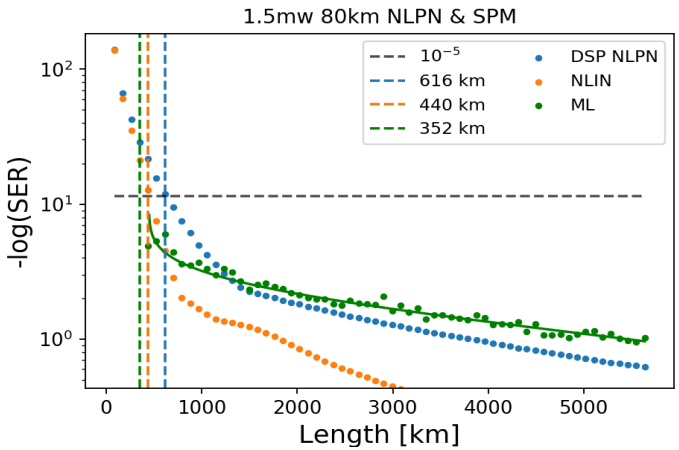


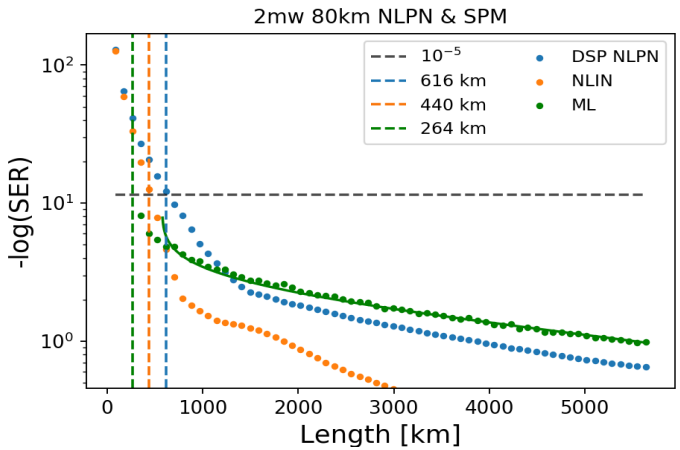
Detection Scheme for Low and High Launch Power

16QAM



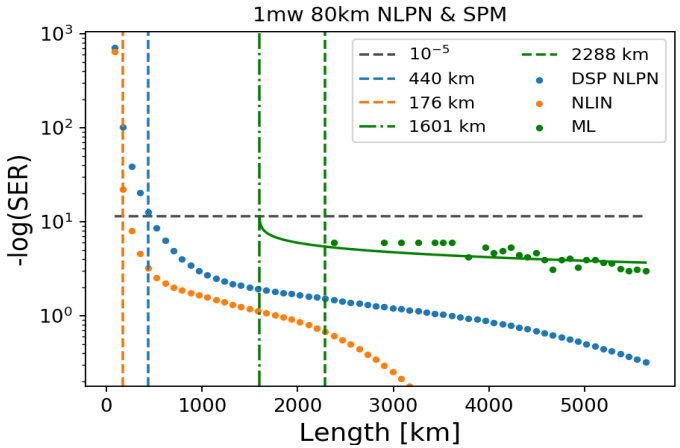


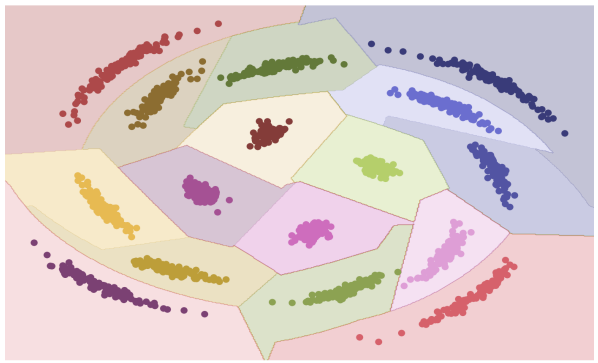


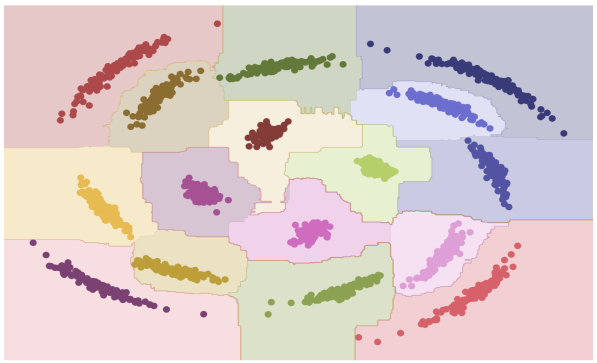


Detection Scheme 1 mW Launch Power

16QAM







Outline

1. Introduction & Motivation
   - Optical Communication
   - Improvements to a OOK System
   - Impairments of a Coherent Optical Link
2. Digital Signal Processing
   - Analytical NLPN Compensation
   - Machine Leaning Enabled DSP
3. VPI mQAM Link with ML Assisted Detection
   - NLPN in a Long-Haul Communication Link
   - NLIN in a WDM Communication Link
4. Conclusion
   - Final Remarks

Fiber Link Simulation

1.2 Tbits/s WDM

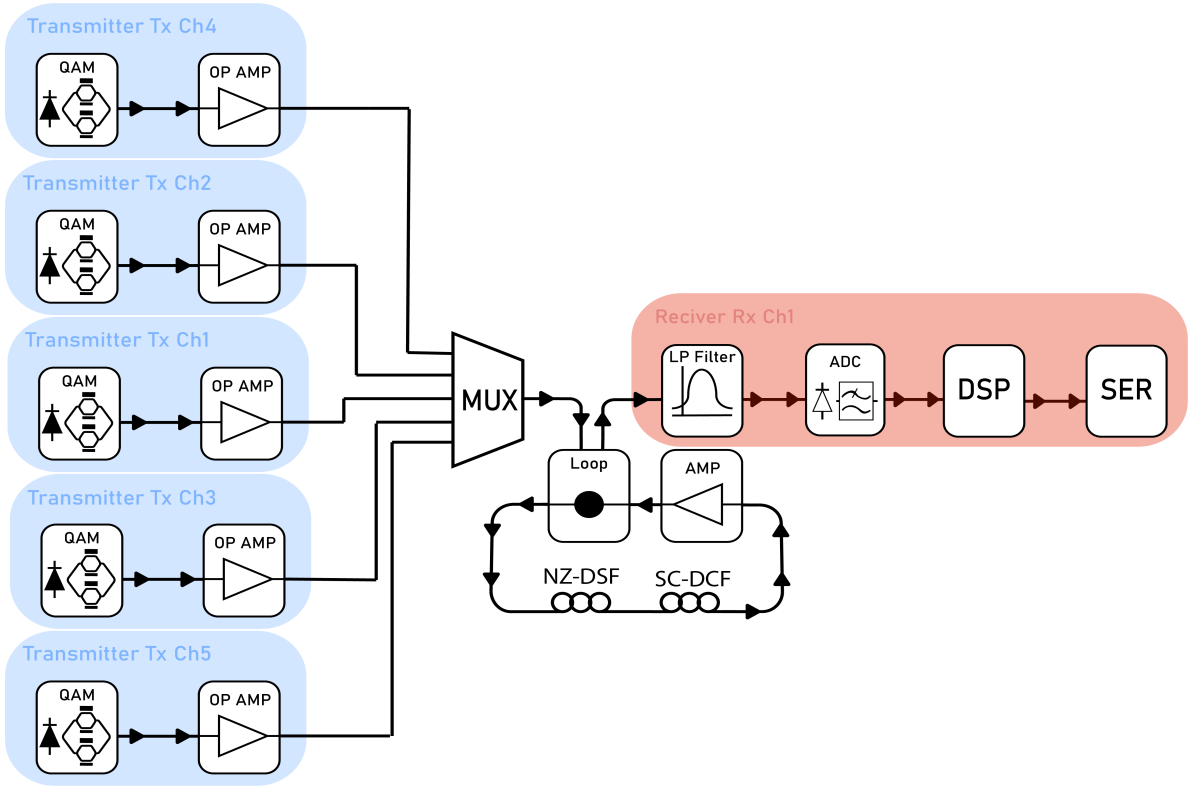
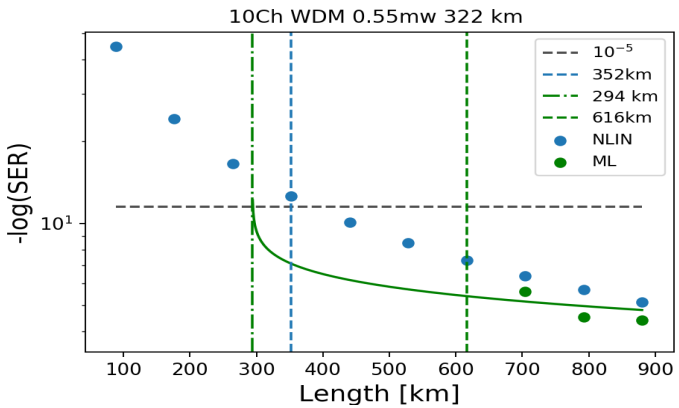
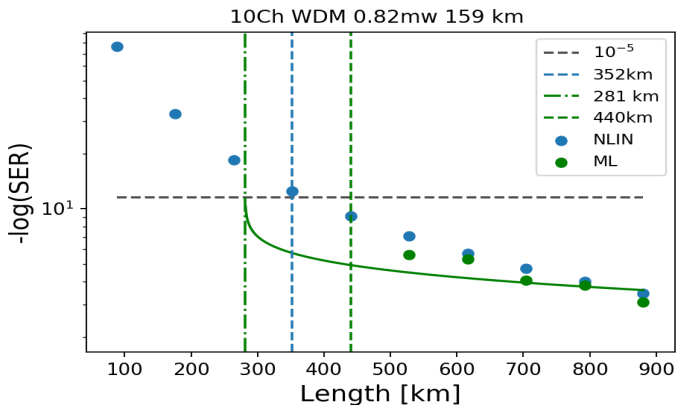


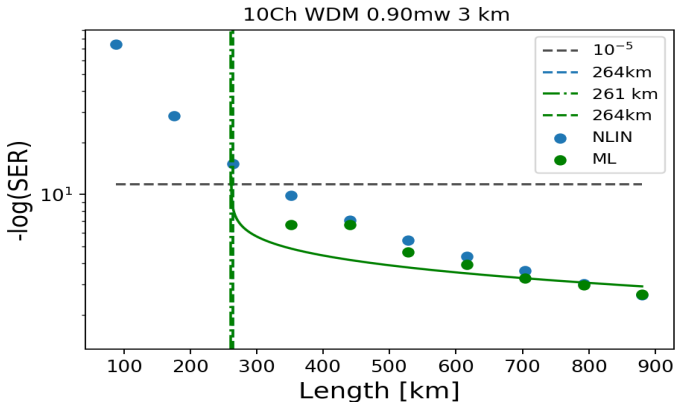
Figure: Nonlinear WDM Fiber Link Implemented in VPI

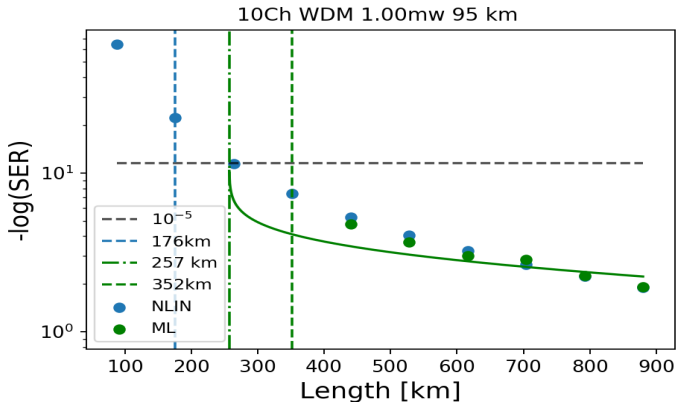
WDM Detection Scheme 0.5 mW - 1 mW Launch Power

16QAM









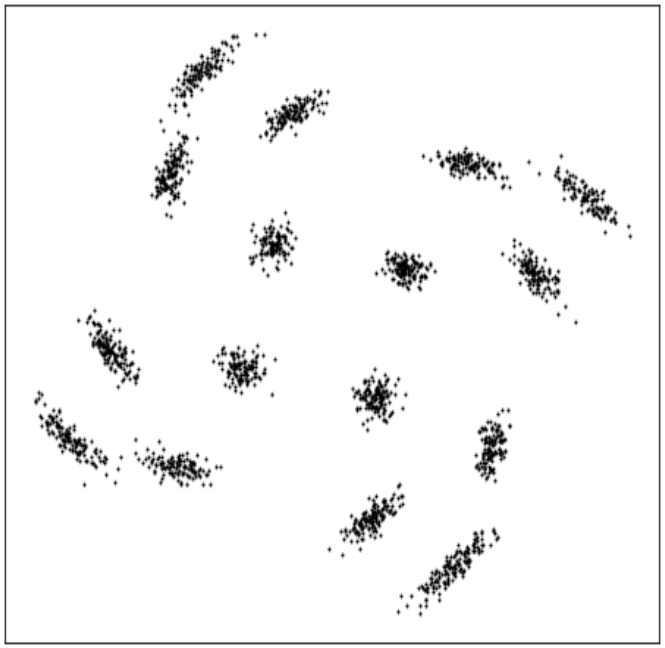
Outline

1. Introduction & Motivation
   - Optical Communication
   - Improvements to a OOK System
   - Impairments of a Coherent Optical Link
2. Digital Signal Processing
   - Analytical NLPN Compensation
   - Machine Leaning Enabled DSP
3. VPI mQAM Link with ML Assisted Detection
   - NLPN in a Long-Haul Communication Link
   - NLIN in a WDM Communication Link
4. Conclusion
   - Final Remarks

Main Remarks

- For a long-haul system there is an improvement in the transmission distance at the optimal launch power.
- The ML DSP can preform at least as good as the analytically derived DSP scheme for relatively high power. Knowledge can be replaced by training.
- For the WDM scheme is hard to determine if there is a clear benefit. XPM is a time dynamic effect and the statistical models implemented can not resolve time dependent effects.
- To determine if there is an improvement in SER it is necessary to increase the amount of symbols used to train the algorithms.

Thank you for listening!



Non-linear Interference Noise (NLIN)

$$E_R = E_{AWGN} e^{-j\phi_{NLIN}}, \quad L_{eff} = \frac{(1 - e^{-\alpha L})}{\alpha}, \quad \gamma = \frac{2\pi \bar{n}_2}{\lambda A_{eff}}$$

- Self Phase Modulation

$$\phi_{\text{SPM}} < \gamma L_{eff} P_{in}$$

- Cross Phase Modulation

$$\phi^i_{\text{XPM}} < \frac{\gamma}{\alpha}(2M - 1) P_{ch}$$

- Nonlinear Phase Noise

$$\phi_{\text{NLPN}} \approx N\gamma L_{eff} P_{in}$$