

Performance Comparison of Efficient Fiber Kerr Nonlinearity Mitigation Schemes in a Dispersion-Managed Link for 32 GBd 16-QAM Signals

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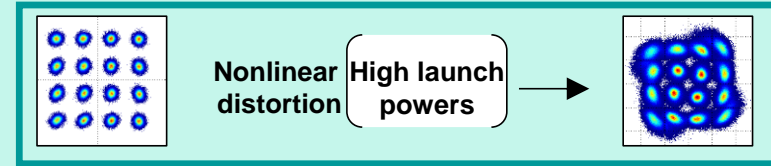
Content

- Motivation for joint optical-digital nonlinearity mitigation
- Experimental setup
- Nonlinearity mitigation architectures
- Results
- Conclusion

Motivation

- Increased transmission capacity and reach
- ▶ Higher-order modulation formats
 - ▶ Higher received OSNR
 - ▶ Higher launch powers

Kerr Nonlinear Distortions !



Digital Nonlinearity Mitigation

State-of-the-art research approaches

- ❑ Digital Backpropagation (DBP)
- ❑ Volterra series nonlinear equalizer

❑ Neural Networks

- Recurrent Neural Network(RNN)
- Reservoir Computing Network (RCN)
- Feedforward Neural Network (FNN)

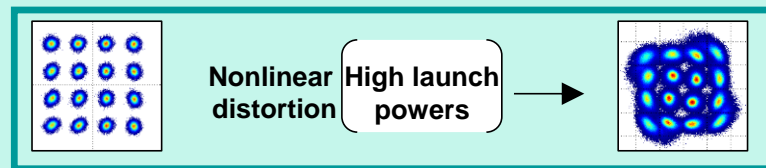
+ Effective to compensate nonlinearities

- Higher Computational Complexity
 - O/E bandwidth limitation

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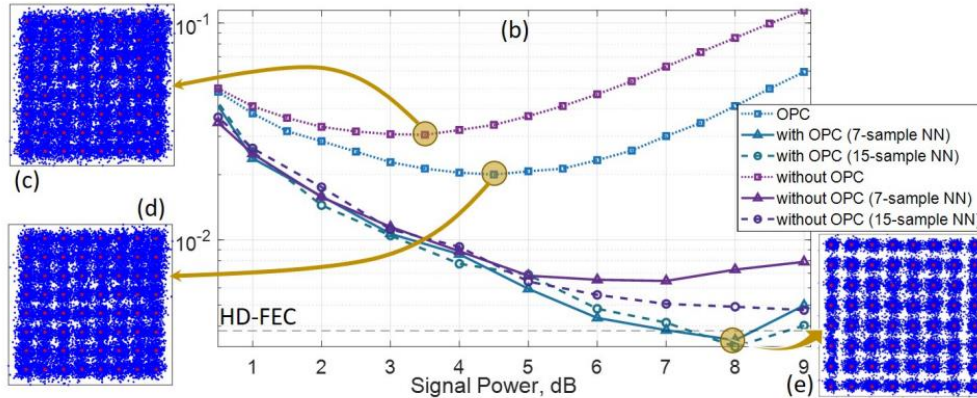
Optical Nonlinearity Mitigation

- Optical Phase conjugation (OPC)
 - + Both inter and intra nonlinearities
 - Strict optical power and dispersion symmetry requirements

Motivation

- Advantages seen in previous research
 - Relax OPC symmetry constraints [1]
 - Improves BER significantly [2,3]

[1] J. C. Cartledge et al., OFC, 2016.



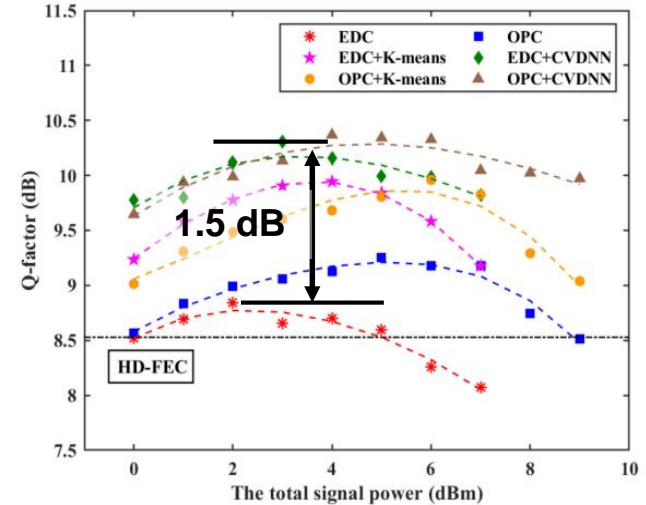
[2] M. Kamalian-Kopae et al., OFC, 2022

28 GBd PDM 64-QAM data signals in
400-km SSMF link

Digital Nonlinearity Mitigation

Optical Nonlinearity Mitigation

Combine
Joint Optical-Digital Nonlinearity Mitigation

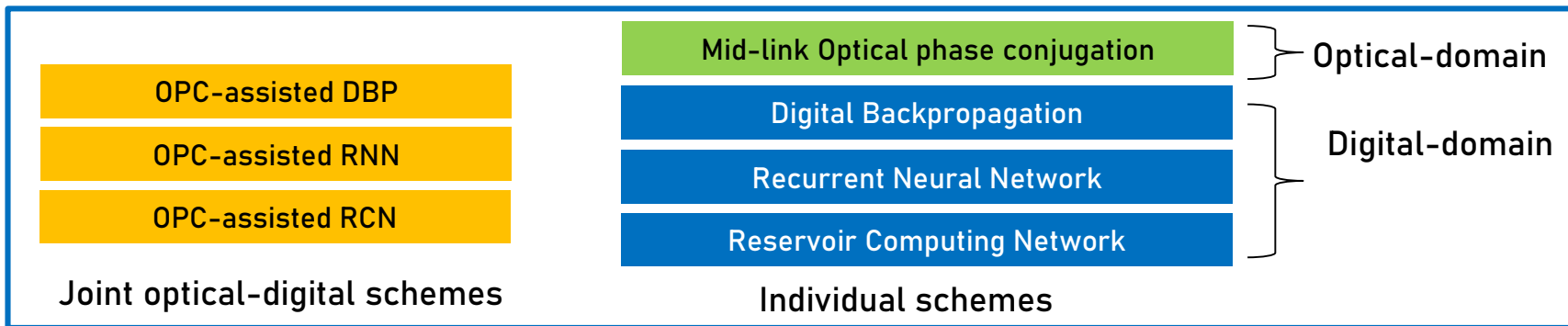


[3] L. Wang et al., IEEE Photonics Journal, 2021.

4x 12.5 GBd single-pol. 64-QAM signal
in 160-km SSMF link

Proposed Approach: Joint Optical-Digital Nonlinearity Mitigation

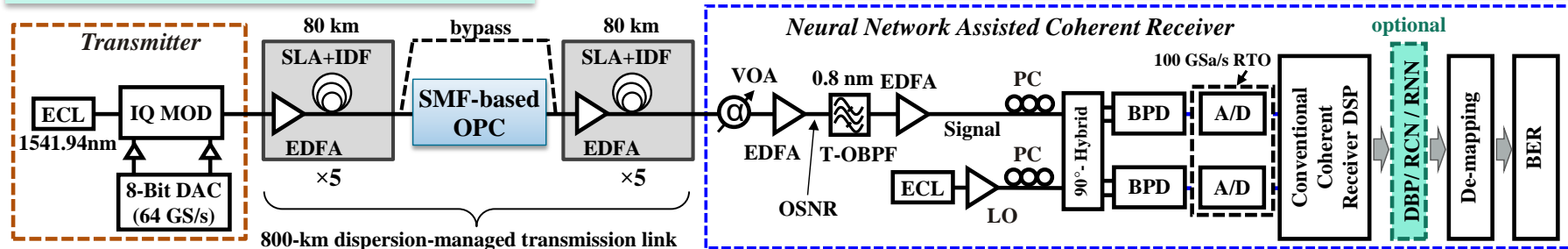
- This talk focuses on:
 - Kerr nonlinearity investigations for longer transmission link
 - Complexity reduction analysis offered by joint OPC-assisted NN schemes
- Nonlinearity mitigation for 1×32GBd single-pol. 16-QAM signals in 800-km dispersion-managed link using following schemes.



- We used a single-pol OPC and compared it to the digital and joint schemes
 - In principle, all the above schemes can work for PDM signals.

Experimental Setup

1×32 GBd single-pol 16-QAM data signal using random sequences

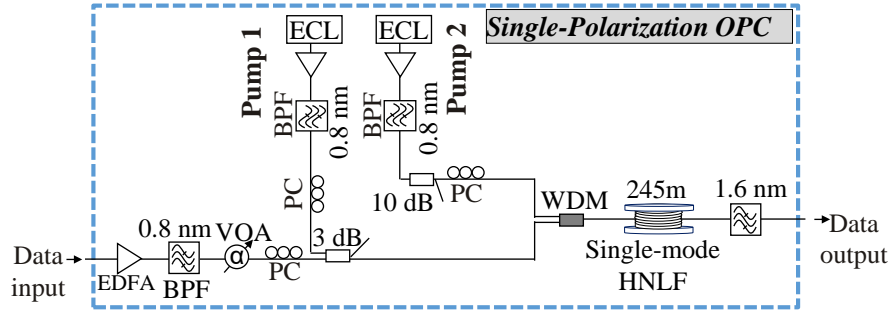


- Coherent receiver
- DSP includes mean error correction, data-aided channel estimation, frequency domain equalization & blind-phase-search phase recovery
- Optional DBP/ RNN/ RCN

- 10x80-km dispersion-managed fiber spans
- Launch powers: -4 dBm to +4 dBm
- Optional mid-link OPC
- Target signal is the b2b measurement (w/o OPC, w/o transmission link) at OSNR 44.8 dB

ECL: external cavity laser, IQ MOD: IQ modulator, DAC: digital-to-analog converter, SLA: super large-area fiber, IDF: inverse dispersion-shifted fiber, VOA: variable optical attenuator, EDFA: Erbium-doped fiber amplifier, T-OBPF: Tuneable optical bandpass filter, PC: polarization controller, BPD: balanced photodiode, A/D: analog-to-digital converter, LO: local oscillator

Optical Phase Conjugation (OPC)



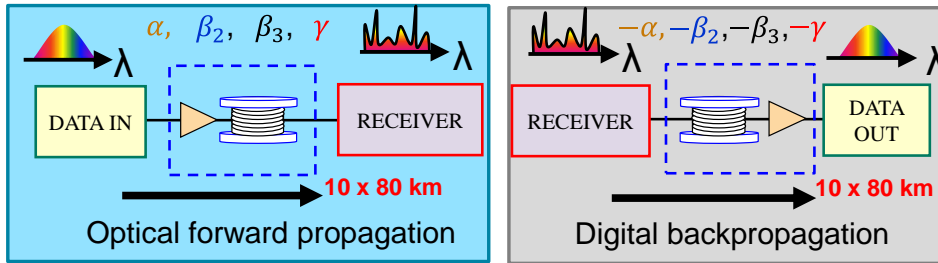
Dual-pump single-polarization OPC

Single-mode fiber based mid-link OPC

- Total power injected into HNLF: +17 dBm
- On-Off conversion efficiency (CE): -20 dB
- OPC insertion loss : ~8 dB
- HNLF nonlinear coefficient. : $9.7 \text{ W}^{-1}\text{km}^{-1}$
- HNLF zero-dispersion wavelength: 1544 nm

HNLF: highly nonlinear fiber, WDM: wavelength-division multiplexing coupler

Digital Backpropagation (DBP)



Digital Backpropagation [1]

$$\frac{\partial A}{\partial z} = \underbrace{-\frac{\alpha}{2}A}_{\text{Loss}} - \underbrace{\frac{i}{2}\beta_2 \frac{\partial^2 A}{\partial t^2}}_{\text{GVD}} + \underbrace{\frac{1}{6}\beta_3 \frac{\partial^3 A}{\partial t^3}}_{\text{TOD}} + \underbrace{i\gamma(|A|^2)A}_{\text{Kerr nonlinearity}}$$

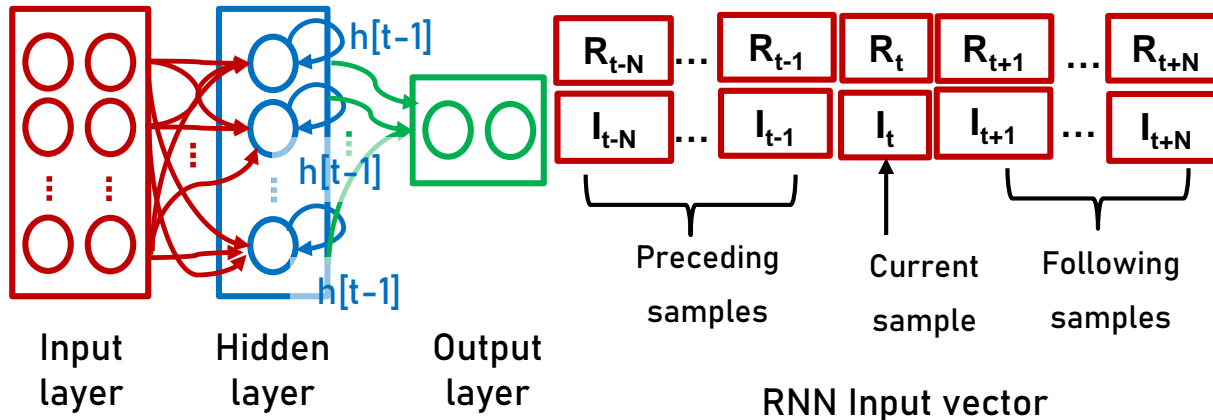
Nonlinear Schrodinger Equation

- Volterra-series transfer function
- Separately modelled SLA and IDF in each span
- Optimized FFT block contains 128 samples
- ASE noise and PMD effect not included in the model

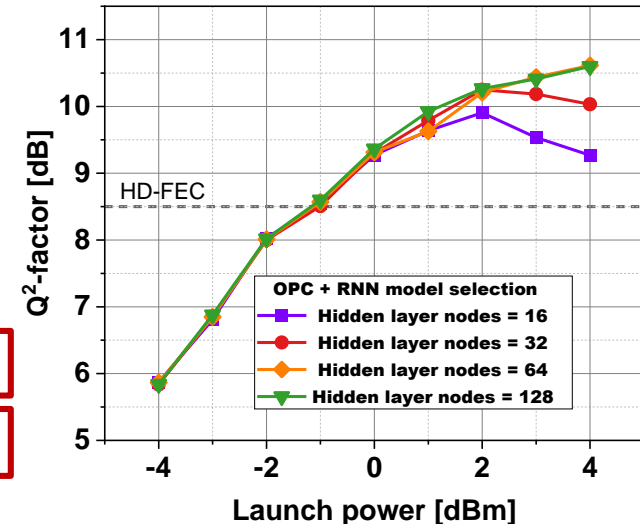
[1] E. Ip et. al., *JLT*, vol. 28, no. 6, 2012.

Recurrent Neural Network (RNN)

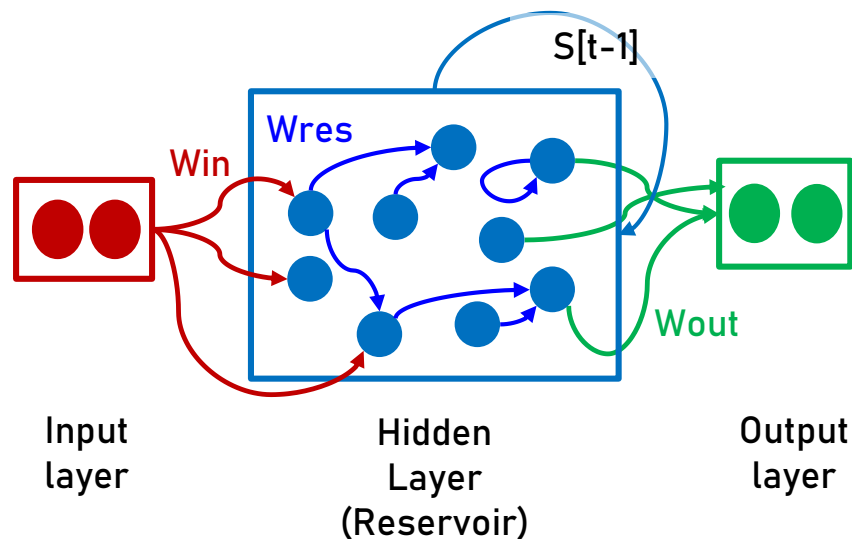
- A time-delayed vector is fed as input to RNN, to capture the long-term dependencies in the signal
- RNN is trained using backpropagation



Optimizing the number of hidden layer neurons for OPC-assisted RNN

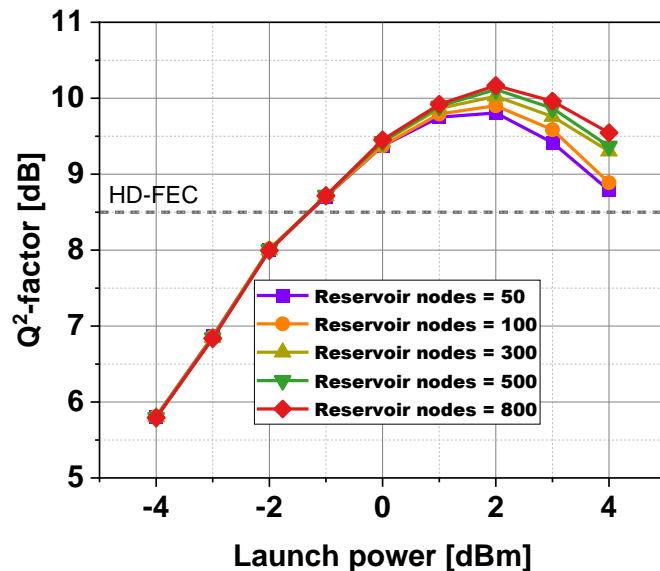


Reservoir Computing Network (RCN)

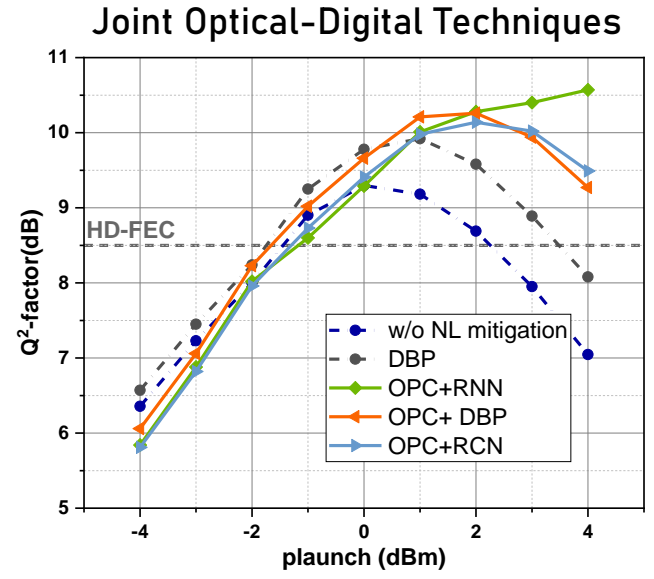
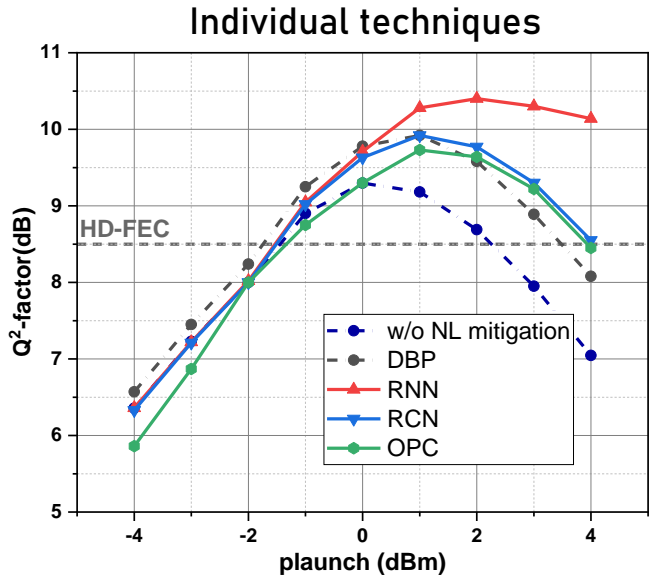


- Reservoir consists of randomly connected neurons with weighted connections
- Only output weights are trained using ridge regression

Optimizing the reservoir size for OPC-assisted RCN



Evaluation Results



Comparative Q²-factor gains (dB)

	DBP-only	RCN-only	RNN-only	OPC+DBP	OPC+RCN	OPC+RNN
Relative to w/o NL mitigation	0.6	0.6	1.1	0.9	0.8	<u>1.3</u>
Relative to DBP-only	-	0	0.4	0.3	0.2	<u>0.7</u>

Reduced Neural Network Computational Complexity

Q ² -factor (dB)	Model	Hidden Layer Size (neurons)	# Real Multiplications [1] (per output sample)
9.9	RCN-only	800	19,200
	OPC+RCN	100	2400
10.4	RNN-only	128	35,584
	OPC+RNN	32	2752

- To achieve the maximum Q²-factor gains as measured for respective individual schemes,
 - OPC+RCN requires **8 times less** complexity than RCN-only
 - OPC+RNN requires approx. **13 times less** complexity than RNN-only

[1] Freire, Pedro et al. (2022). Computational Complexity Evaluation of Neural Network Applications in Signal Processing

Conclusion

- Evaluation of joint optical-digital Kerr nonlinearity mitigation approaches in comparison to individual approaches in an 800-km dispersion-managed transmission link for 32 GBd 16-QAM signals
- Joint techniques outperform individual techniques.
- Joint OPC-assisted NN techniques show capabilities of reducing computational complexity
- Next steps (Joint optical-digital Kerr nonlinearity mitigation schemes):
 - Investigation for WDM PDM signals in a dispersive optical transmission link
 - Power consumption analysis
- The joint optical-digital nonlinearity mitigation scheme has high potential in future optical networks

Fraunhofer Institute for Telecommunications, Heinrich Hertz Institute, HHI

WE PUT SCIENCE INTO ACTION.

Thank you for your attention

Funded by the German
Bundesministerium für Bildung und
Forschung (BMBF) under the 6G-RIC
project with grants 16KISK020K,
16KISK030, and under the CELTIC-NEXT
AI NET PROTECT project with grant
16KIS1282.

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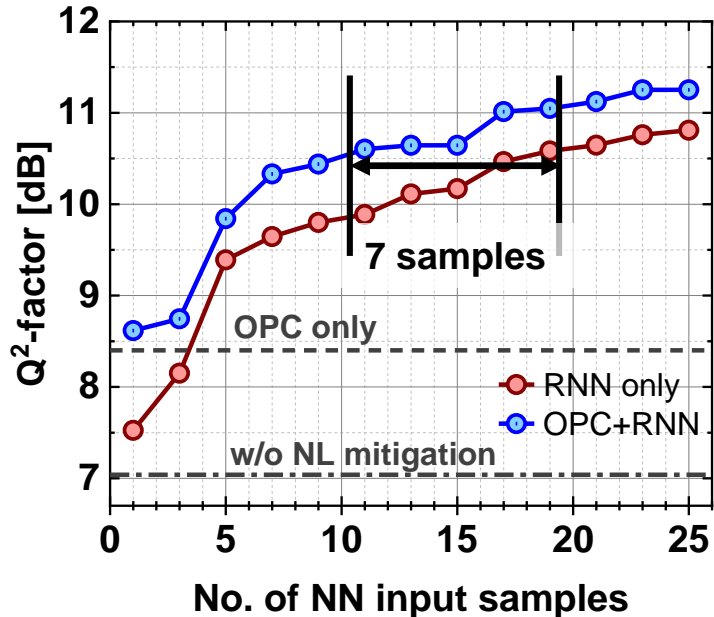
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Backup Slides

RNN Input Vector Reduction Capability

Varying no. of RNN input samples
at a launch of +4 dBm



- Performance increases progressively with the input vector size
- Larger input vector → longer training time
- OPC-assisted RNN can achieve a better improvement margin with fewer number of input samples.