Efficient Training of Volterra Series-based Pre-distortion Filter Using Neural Networks

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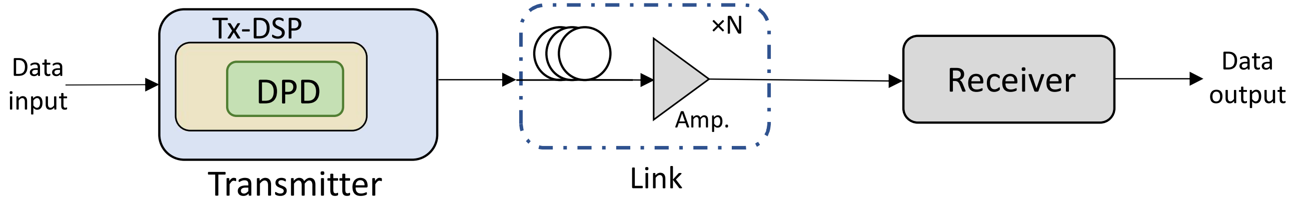
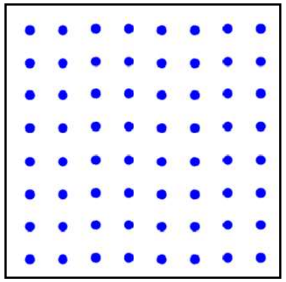
Digital Pre-Distortion (DPD)




64-QAM

Common DPD techniques

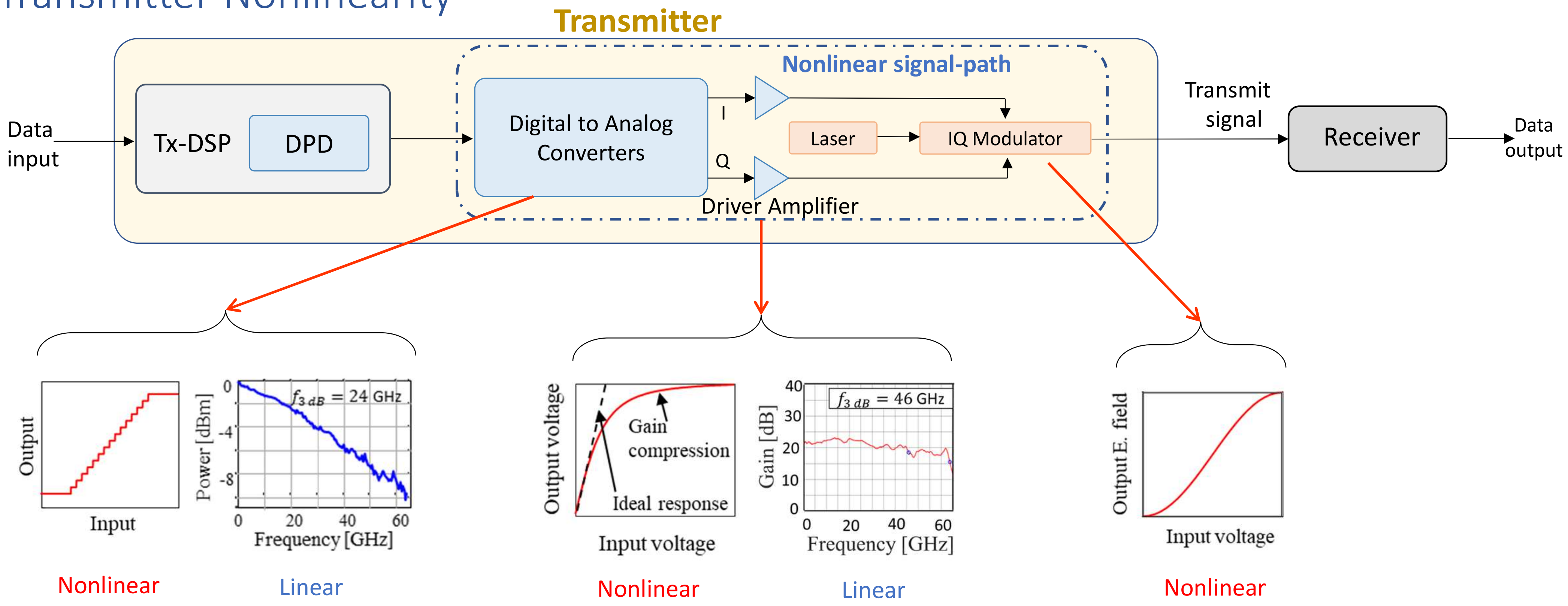
- Linear
- Look-up tables
- Volterra series-based
- Memory polynomials (MPs)
- Generalized MPs
- NN-based

Outline

- Distortions in a Coherent Optical Transmitter
- Volterra series-based DPD and Training
- Proposed Efficient Training of Volterra-DPD
- Simulation Setup and Results
- Conclusion

Coherent Optical Transmitter

Transmitter Nonlinearity

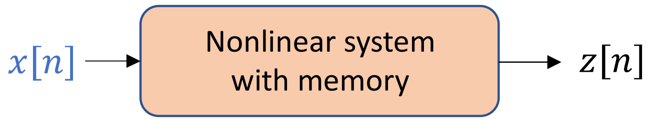


[1] A. Napoli, et al., "Digital pre-compensation techniques enabling high-capacity bandwidth variable transponders", Optics Communications, 409, 52-65, 2018.

[2] P. W. Berenguer, et al., ""Nonlinear digital pre-distortion of transmitter components," Journal of lightwave technology, vol. 34, no. 8, pp. 1739–1745, 2015.

[3] V. Bajaj, et al. ""Deep Neural Network-Based Digital Pre-Distortion for High Baudrate Optical Coherent Transmission," J. Lightwave Technol. 40, 597-606 (2022)

Volterra series-based DPD



$$z[n] = H\, x[n]\ ; \qquad H = \text{Volterra kernels}$$

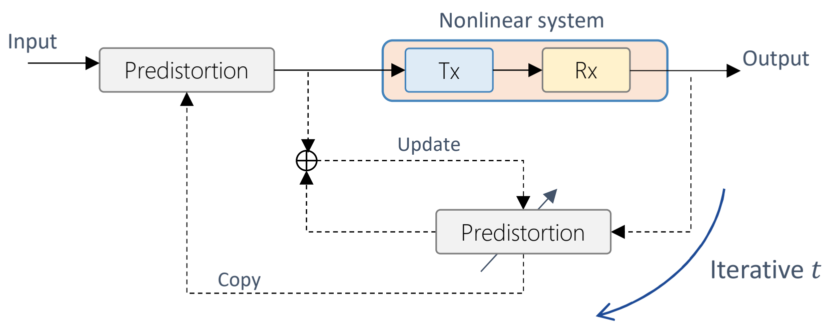
$$z[n] = h_0 + \sum_{\tau_1=-M_1}^{M_1} h_1[\tau_1]x[n-\tau_1] + \sum_{\tau_2=-M_2}^{M_2}\sum_{d_2=0}^{D_2} h_2[\tau_2, d_2]x[n-\tau_2]x[n-\tau_2-d_2] + \ \ldots\, higher\ order\ terms\ \ldots$$

- Volterra series direct extension of the impulse response concept.

Interpretable → Volterra series

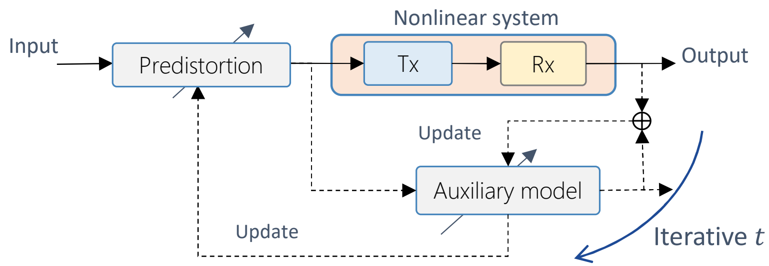
[4] T. Ogunfunmi, “Adaptive nonlinear system identification: The Volterra and Wiener model approaches”. Springer Science & Business Media, 2007.

Training of DPDs



Indirect learning architecture (ILA)

- Simpler [5, 6]
- Noise offset [7]
- Nonlinear operations are not commutative [7]



Direct learning architecture (DLA)

- Pre-inverse
- No Noise offset
- Requires an auxiliary model (differentiable)

Accurate DPD → Direct learning

[5] C. Eun and E. J. Powers, "A new Volterra predistorter based on the indirect learning architecture," IEEE trans. on signal proc., vol. 45, no. 1, pp. 223–227, 1997.

[6] G. Khanna, et al. , "A robust adaptive pre-distortion method for optical communication transmitters," IEEE Photonics Technology Letters, vol. 28, no. 7, 752–755, 2015.

[7] H. Paaso and A. Mammela, "Comparison of direct learning and indirect learning predistortion architectures," in IEEE Int. Symp. on Wireless Comm. systems, 309–313, 2008.

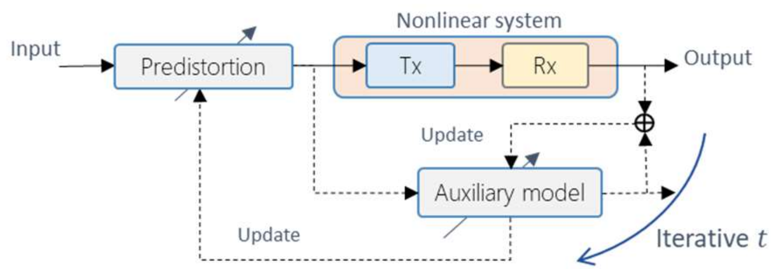
[8] Y. H. Lim, et al., "An adaptive nonlinear prefilter for compensation of distortion in nonlinear systems," IEEE Trans. on Signal Proc., 46, 6, pp. 1726–1730, 1998.

[9] D. Zhou, V. E. DeBrunner, "Novel adaptive nonlinear predistorters based on the direct learning algorithm", IEEE Trans. on Signal Proc., 55, 1, pp. 120–133, 2007.

Training

Direct learning

- Nonlinear Filtered x-LMS
  - Predistortion and Auxiliary model: Volterra series-based
  - Back-propagation to update pre-distortion model is difficult.



Direct learning architecture (DLA)

- Direct learning → NN-based.
  - Modular, back-propagation is easier.

- But NN-based DPDs are kind of black box. Very difficult to interpret.

Simpler direct learning → NN as auxiliary model

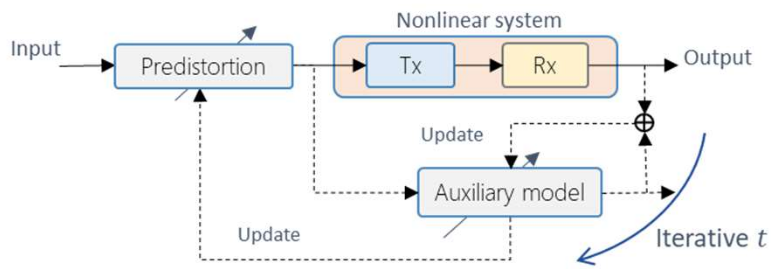
[8] Y. H. Lim, et.al., "An adaptive nonlinear prefilter for compensation of distortion in nonlinear systems", IEEE Transactions on Signal Processing, 46(6):1726–1730, 1998

[10] G. Paryanti, et. al., "A direct learning approach for neural network based pre-distortion for coherent nonlinear optical transmitter", J. Lightw. Technol., 2020.

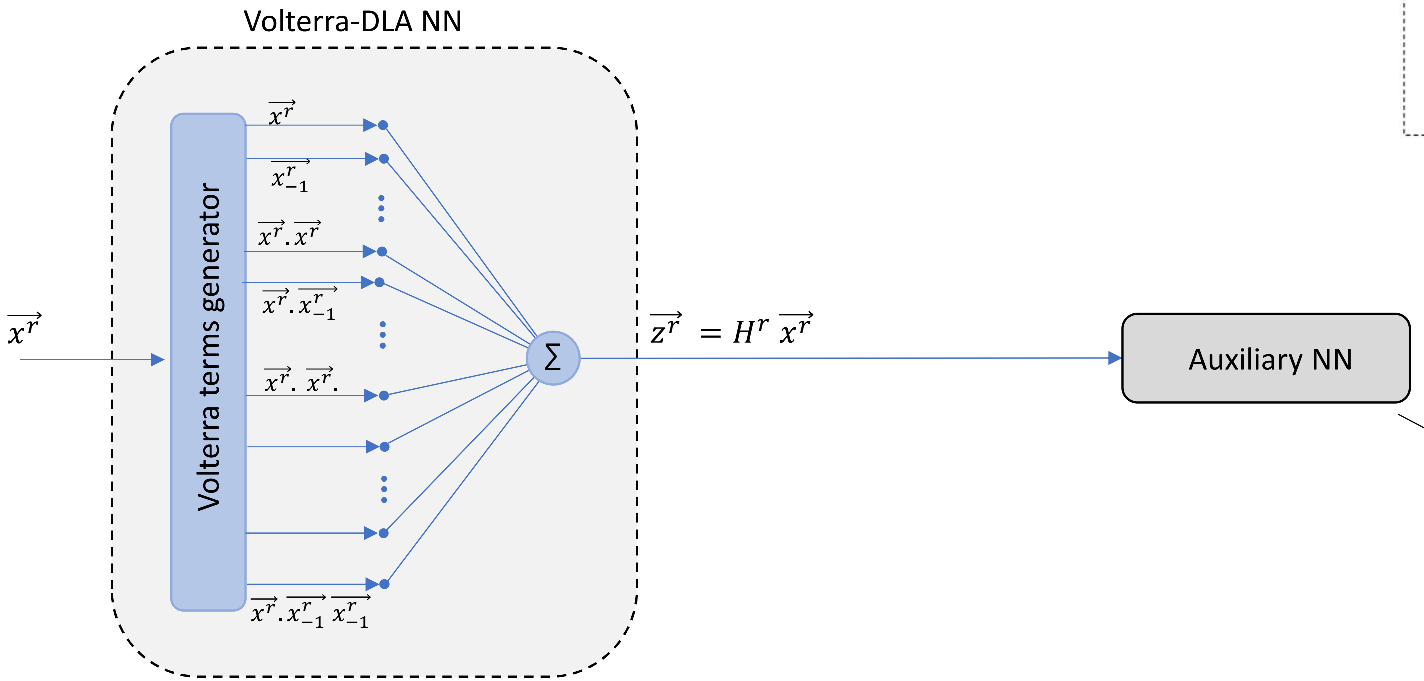
[3] V. Bajaj, et. al. ""Deep Neural Network-Based Digital Pre-Distortion for High Baudrate Optical Coherent Transmission," J. Lightwave Technol. 40, 597-606, 2022

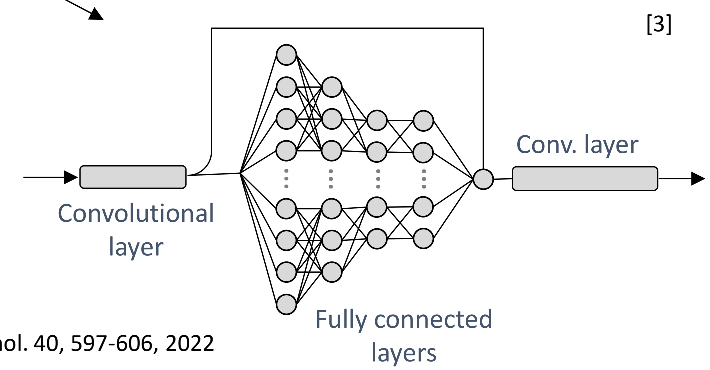
Proposed Volterra-DLA DPD

- Direct learning of Volterra DPD by using neural networks



Direct learning architecture (DLA)





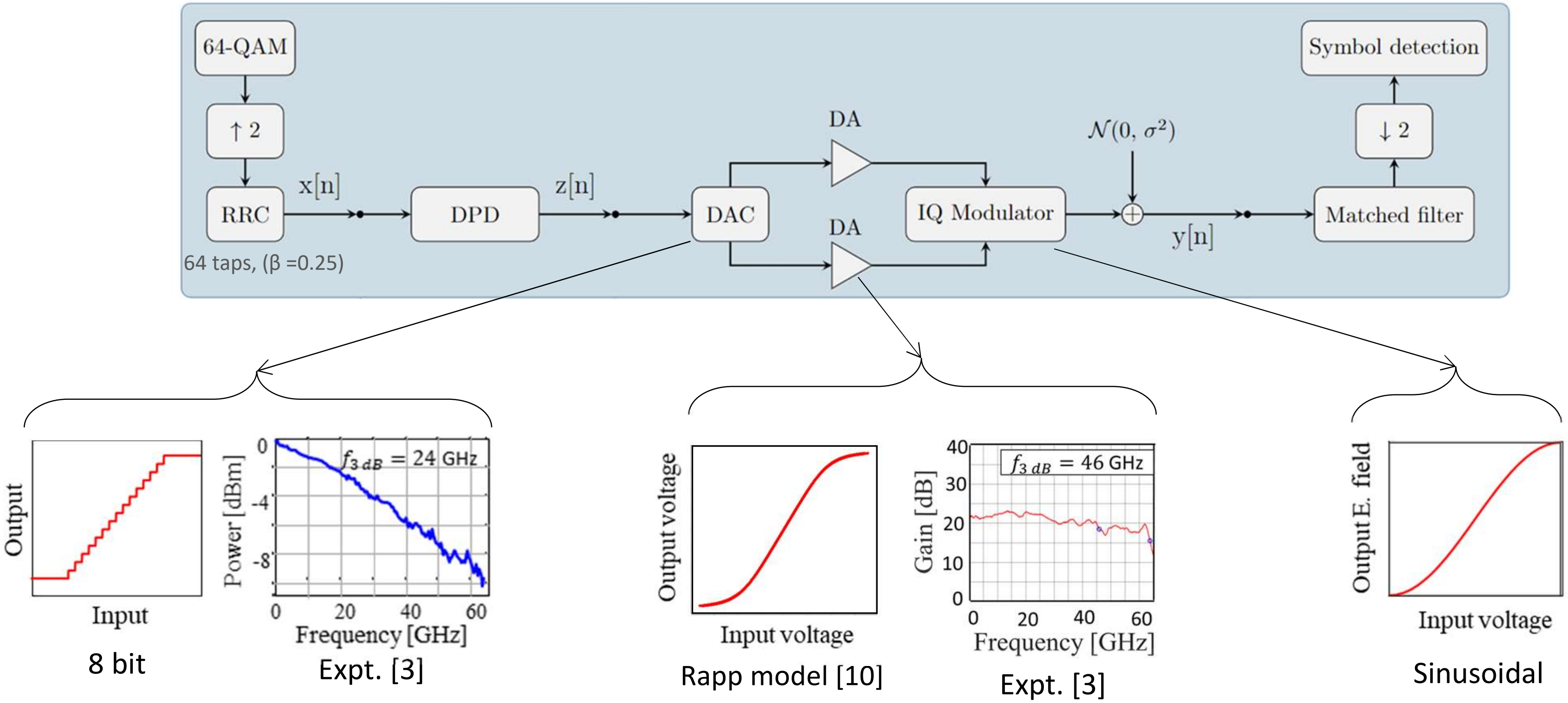
[3]

For Quadrature phase, similar architecture was used.

[3] V. Bajaj, et. al. “"Deep Neural Network-Based Digital Pre-Distortion for High Baudrate Optical Coherent Transmission," J. Lightwave Technol. 40, 597-606, 2022

Simulation setup

64 GBaud, back-to-back conf.



$$Back - Off\ [dB] = -20\log_{10}\left(\frac{V_{rms}}{V_{sat}}\right)$$

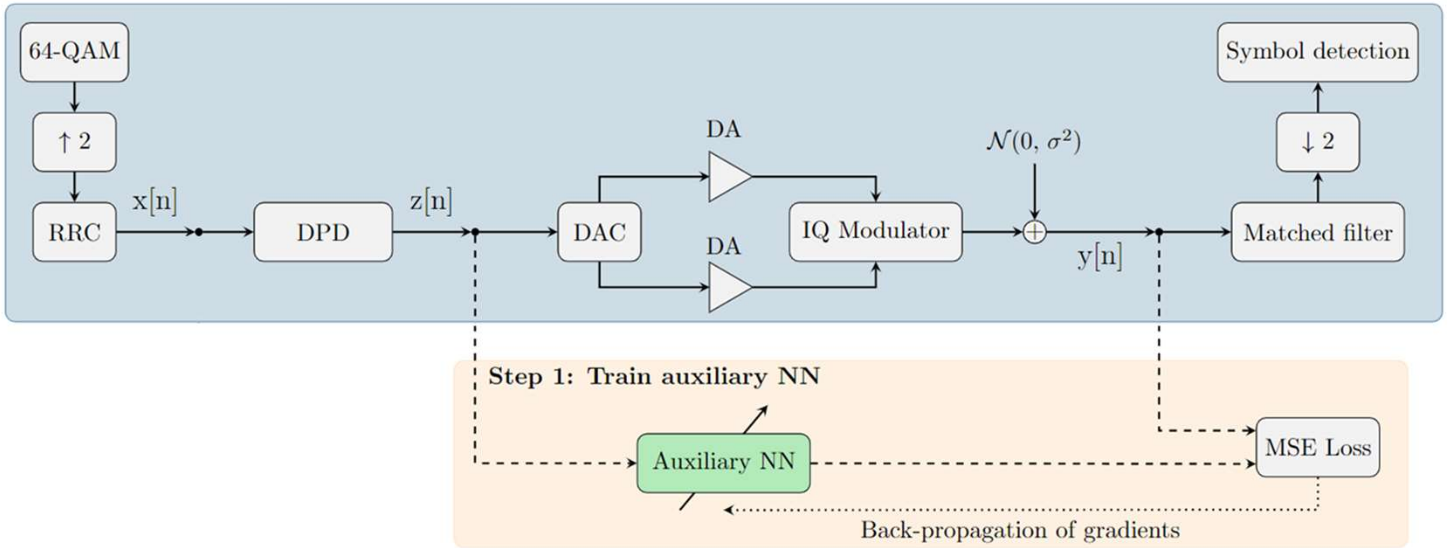
Smaller BO → stronger nonlinearity

	Back-off [dB]
DAC	10
IQ mod	20
DA	7, 5, 3

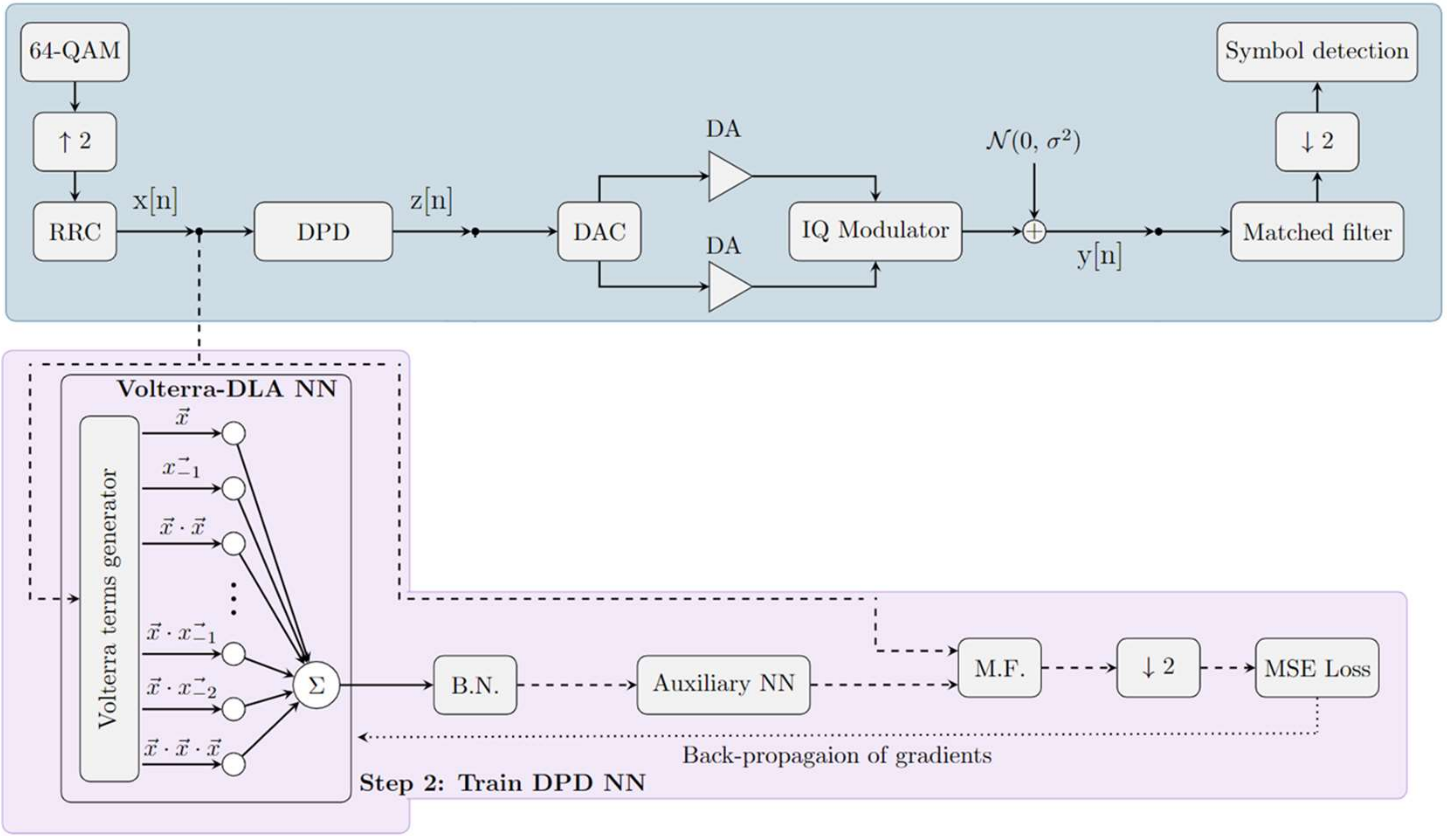
[10] G. Paryanti, et al., “A direct learning approach for neural network based pre-distortion for coherent nonlinear optical transmitter”, J. Lightwave Technol., 2020.

[3] V. Bajaj, et. al. “"Deep Neural Network-Based Digital Pre-Distortion for High Baudrate Optical Coherent Transmission," J. Lightwave Technol. 40, 597-606, 2022

Training Volterra-DLA DPD

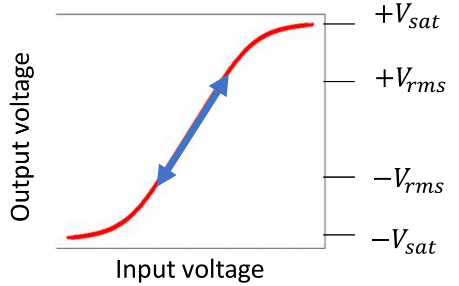


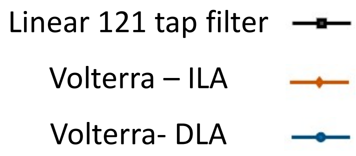
Training Volterra-DLA DPD



Results

Varying DA nonlinearity

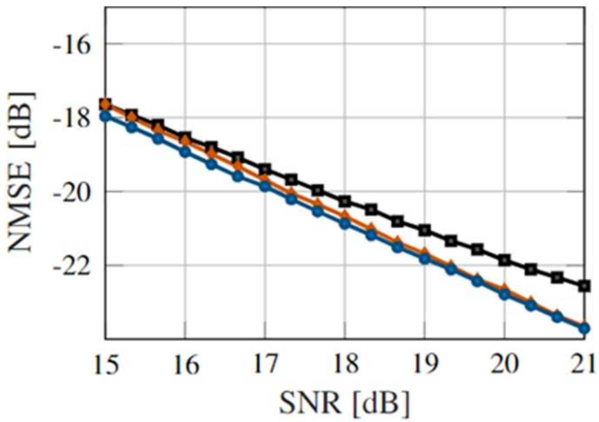




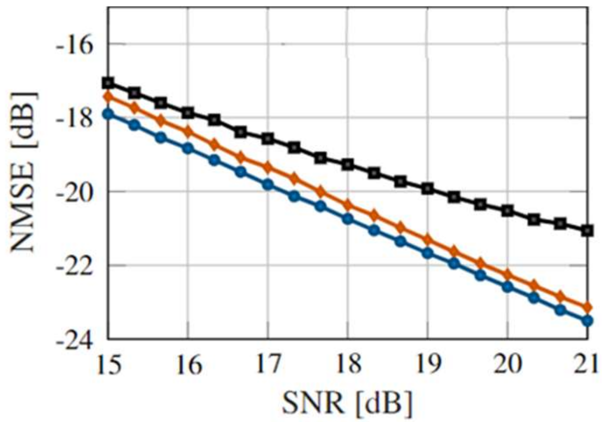
Volterra up to 5th order

Order	Memory	Depths
1st	121	-
3rd	10	4
2nd, 4th ,5th	3	0

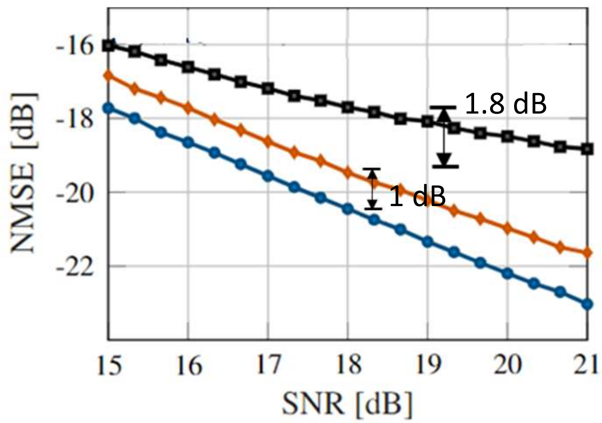
$$Back - Off\ [dB] = -20\log_{10}\left(\frac{V_{rms}}{V_{sat}}\right)$$



BO = 7 dB



BO = 5 dB

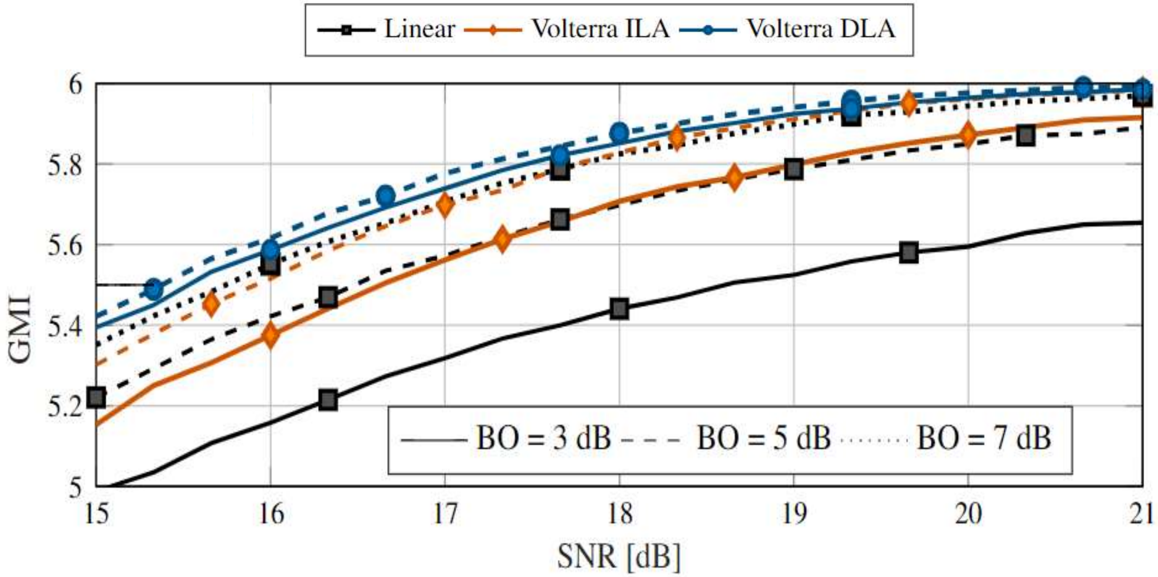


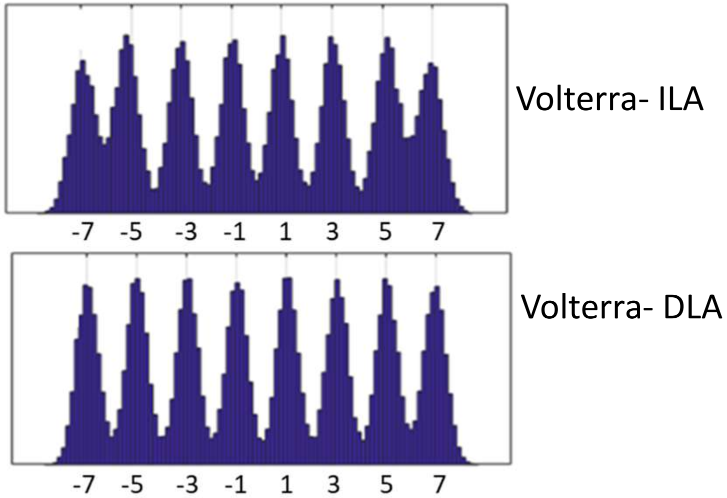
BO = 3 dB

Increasing nonlinearity

Results

GMI and histograms





Histograms of the real part of received signal

Conclusion

- NNs have nice properties to be an auxiliary model
  - Modular, easier back-propagation.
- We proposed an efficient direct learning of Volterra series-based DPD by leveraging advantages of NNs.
- We compared the performance of proposed Volterra-DLA DPD with a Volterra-ILA and a linear DPD for varying nonlinearity condition in simulations.
- The proposed method can be used for training other DPDs like memory polynomials as well.

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