Wideband Time-Domain Digital Backpropagation via Subband Processing and Deep Learning

Christian Häger[1,2] and Henry D. Pfister[2]

[1] Department of Electrical Engineering, Chalmers University of Technology, Gothenburg
[2] Department of Electrical and Computer Engineering, Duke University, Durham

ECOC, Rome, Italy, September 25, 2018

FORCE
FIBER-OPTIC COMMUNICATIONS
RESEARCH CENTER

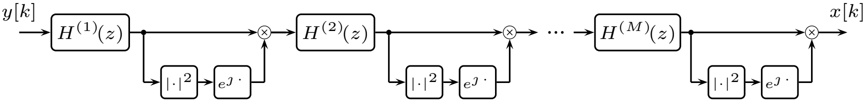
Duke
UNIVERSITY

CHALMERS

Outline

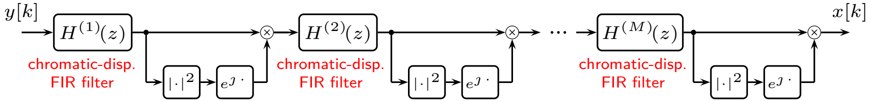
1. Introduction
2. Subband Processing via Filter Banks
3. Proposed DSP Architecture and Deep Learning
4. Results
5. Conclusions

Motivation: Real-Time Digital Backpropagation (DBP)

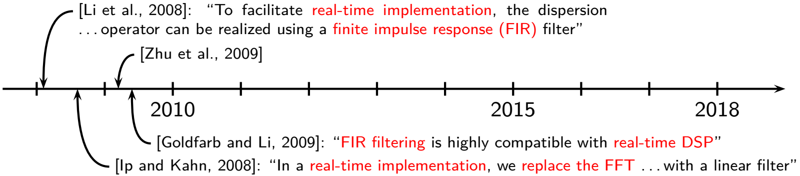


- Real-time DBP based on the split-step Fourier method is widely considered to be impractical due to many FFT/IFFT pairs

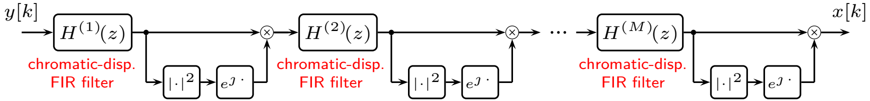
Motivation: Real-Time Digital Backpropagation (DBP)



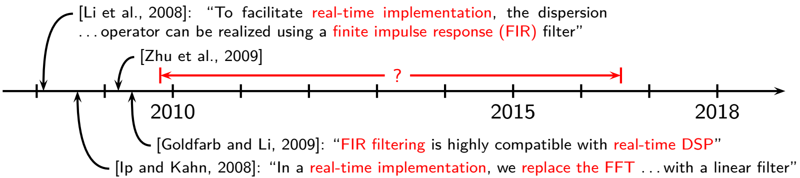
- Real-time DBP based on the split-step Fourier method is widely considered to be impractical due to many FFT/IFFT pairs
- What about finite impulse response (FIR) chromatic-dispersion filters?



Motivation: Real-Time Digital Backpropagation (DBP)



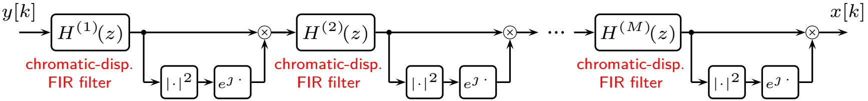
- Real-time DBP based on the split-step Fourier method is widely considered to be impractical due to many FFT/IFFT pairs
- What about finite impulse response (FIR) chromatic-dispersion filters?



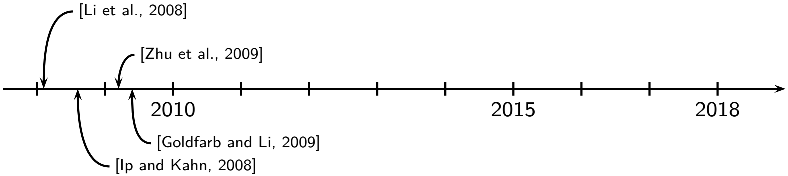
Complexity estimate [Ip and Kahn, 2008]

$> 100\times$ more operations than EDC

Motivation: Real-Time Digital Backpropagation (DBP)



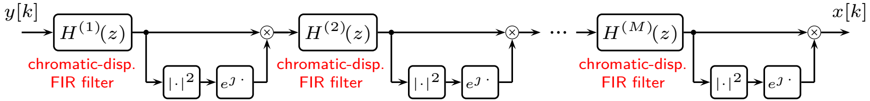
- Real-time DBP based on the split-step Fourier method is widely considered to be impractical due to many FFT/IFFT pairs
- What about finite impulse response (FIR) chromatic-dispersion filters?



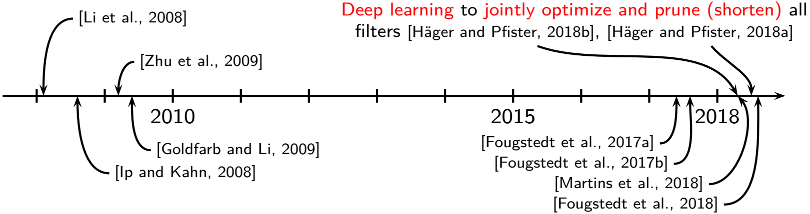
Complexity estimate [Ip and Kahn, 2008]

$> 100\times$ more operations than EDC

Motivation: Real-Time Digital Backpropagation (DBP)



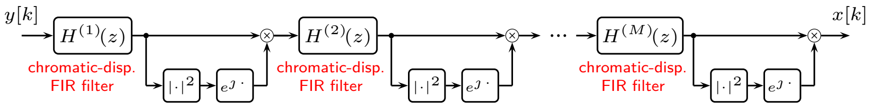
- Real-time DBP based on the split-step Fourier method is widely considered to be impractical due to many FFT/IFFT pairs
- What about finite impulse response (FIR) chromatic-dispersion filters?



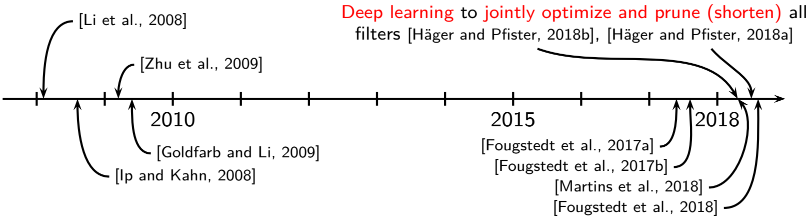
Complexity estimate [Ip and Kahn, 2008]

$> 100\times$ more operations than EDC

Motivation: Real-Time Digital Backpropagation (DBP)



- Real-time DBP based on the split-step Fourier method is widely considered to be impractical due to many FFT/IFFT pairs
- What about finite impulse response (FIR) chromatic-dispersion filters?



Complexity estimate [Ip and Kahn, 2008]

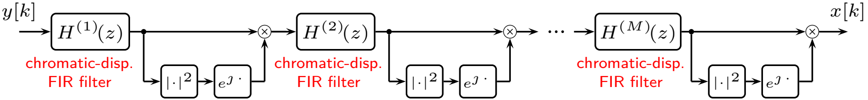
$> 100\times$ more operations than EDC

Our ASIC design* (20 Gbaud, 28 nm):

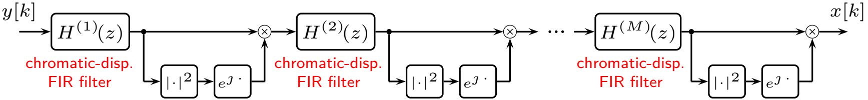
$< 2\times$ power compared to EDC

*C. Fougstedt et al., tomorrow 13:30 in *"DSP Techniques for Cost Effective Transmission"*

This Talk: Wideband Scenarios

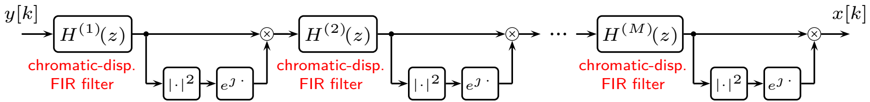


This Talk: Wideband Scenarios



- Complexity depends on overall system memory (total number of filter taps)
- Problem: quadratic dependence of system memory on the bandwidth

This Talk: Wideband Scenarios



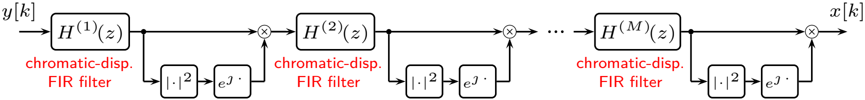
- Complexity depends on overall system memory (total number of filter taps)
- Problem: quadratic dependence of system memory on the bandwidth

Example

- ASIC power estimate* for 2500 km and 20 Gbaud (PM-16-QAM): 9 W
- $5\times$ increase to 96-Gbaud (or superchannel or multiple WDM channels)
- Quadratic scaling: $\approx 25 \times 9$ W $= 225$ W (full DBP)
- Linear scaling: $\approx 5 \times 9$ W $= 45$ W (5 independent receivers)

* C. Fougstedt et al., tomorrow 13:30 in *"DSP Techniques for Cost Effective Transmission"*

This Talk: Wideband Scenarios



- Complexity depends on overall system memory (total number of filter taps)
- Problem: quadratic dependence of system memory on the bandwidth

Example

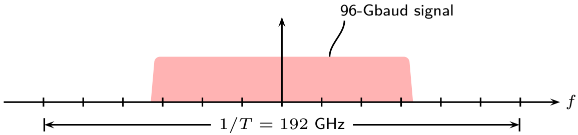
- ASIC power estimate* for 2500 km and 20 Gbaud (PM-16-QAM): 9 W
- $5\times$ increase to 96-Gbaud (or superchannel or multiple WDM channels)
- Quadratic scaling: $\approx 25 \times 9$ W $= 225$ W (full DBP)
- Linear scaling: $\approx 5 \times 9$ W $= 45$ W (5 independent receivers)

Is it possible to scale time-domain DBP gracefully to larger bandwidths?

* C. Fougstedt et al., tomorrow 13:30 in *"DSP Techniques for Cost Effective Transmission"*

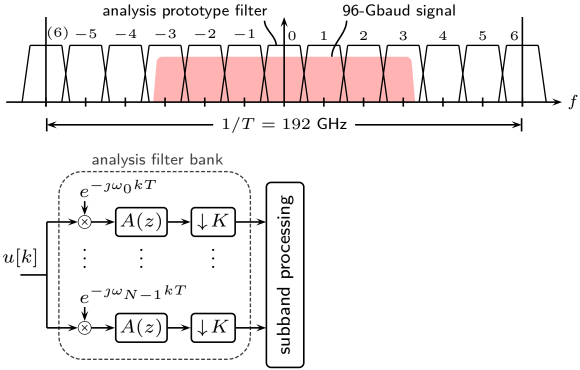
Subband Processing via Filter Banks

See, e.g., [Taylor, 2008], [Ho, 2009], [Slim et al., 2013], [Nazarathy and Tolmachev, 2014] (EDC) and [Mateo et al., 2010], [Ip et al., 2011], [Oyama et al., 2015] (nonlinearity compensation)



Subband Processing via Filter Banks

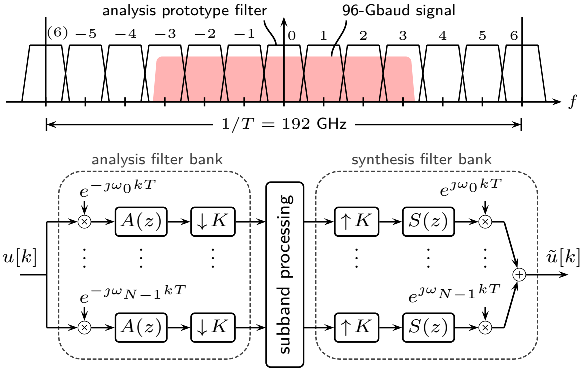
See, e.g., [Taylor, 2008], [Ho, 2009], [Slim et al., 2013], [Nazarathy and Tolmachev, 2014] (EDC) and [Mateo et al., 2010], [Ip et al., 2011], [Oyama et al., 2015] (nonlinearity compensation)



- Split received signal into N parallel signals, then downsample by K

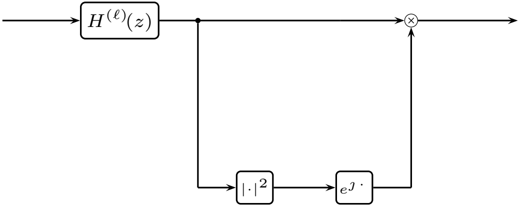
Subband Processing via Filter Banks

See, e.g., [Taylor, 2008], [Ho, 2009], [Slim et al., 2013], [Nazarathy and Tolmachev, 2014] (EDC) and [Mateo et al., 2010], [Ip et al., 2011], [Oyama et al., 2015] (nonlinearity compensation)

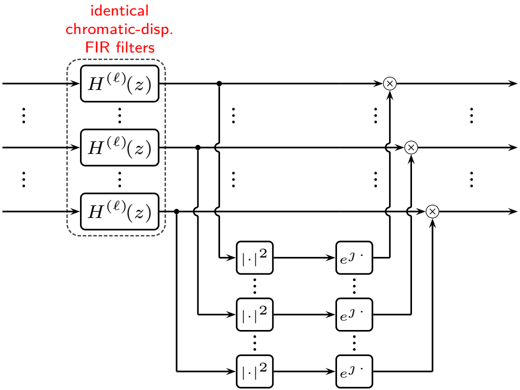


- Split received signal into N parallel signals, then downsample by K
- Synthesis filter bank reassembles the signal after processing

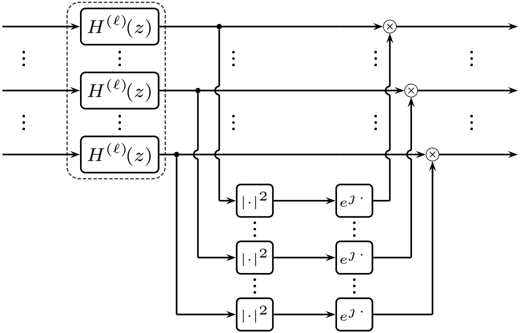
Proposed DSP Architecture (ℓ-th Step)



Proposed DSP Architecture (ℓ-th Step)



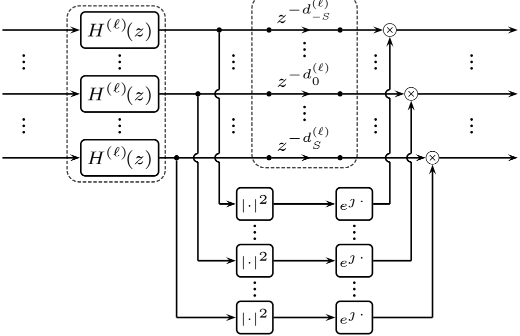
Proposed DSP Architecture (ℓ-th Step)



subband group delay differences depend linearly on propagation distance

$\Longrightarrow$ choose step size such that delays are integer multiples of sampling interval

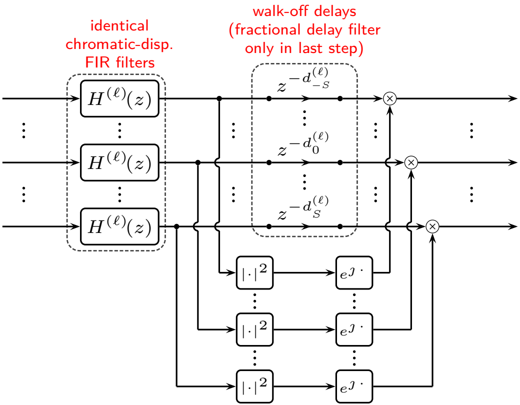
Proposed DSP Architecture (ℓ-th Step)



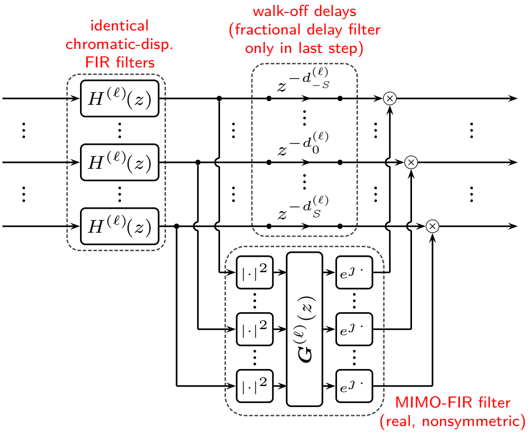
subband group delay differences depend linearly on propagation distance

$\Longrightarrow$ choose step size such that delays are integer multiples of sampling interval

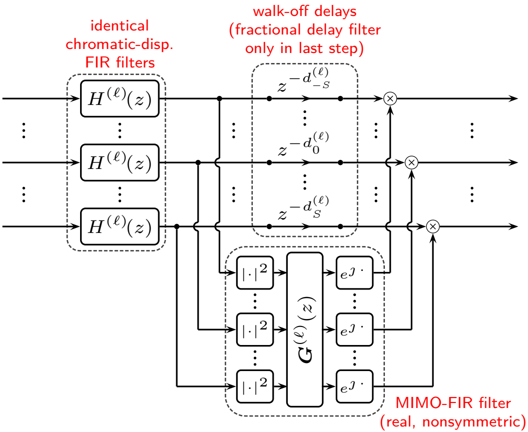
Proposed DSP Architecture (ℓ-th Step)



Proposed DSP Architecture (ℓ-th Step)

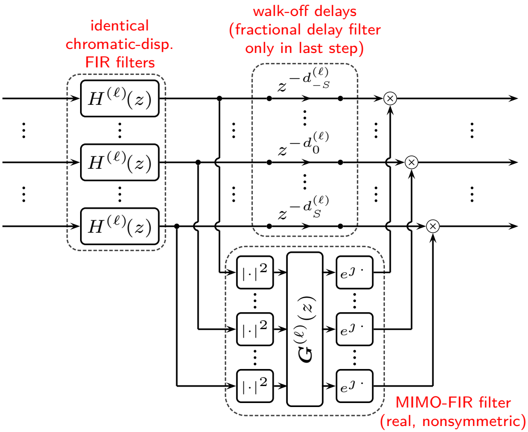


Proposed DSP Architecture (ℓ-th Step)

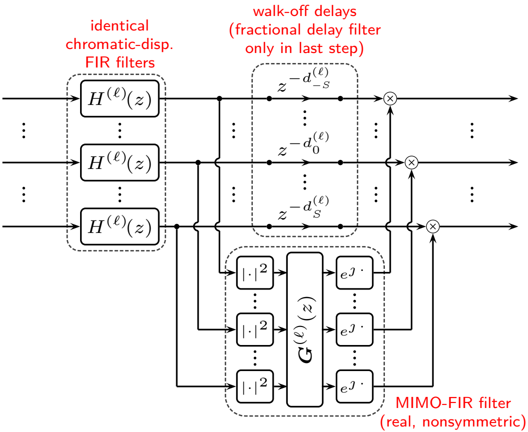


- Hardware-efficient implementation (no FFT/IFFT) of split-step method for coupled NLSEs [Leibrich and Rosenkranz, 2003], see also [Mateo et al., 2010]
- Only accounts for XPM between subbands, but not FWM

Proposed DSP Architecture (ℓ-th Step)

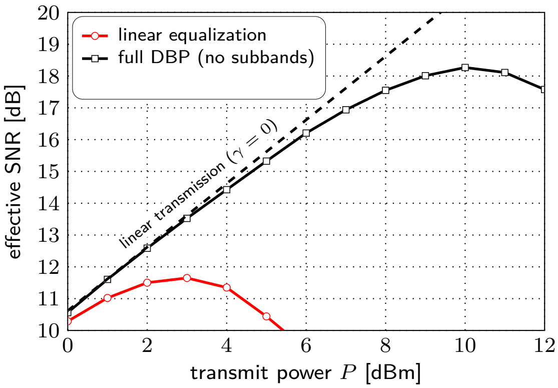


Proposed DSP Architecture (ℓ-th Step)



- "Unrolling" all steps gives a deep, multi-layer computation graph
- Deep learning to jointly optimize filters $H^{(\ell)}(z)$, $\boldsymbol{G}^{(\ell)}(z)$ in all steps by maximizing effective SNR based on stochastic gradient descent
- Iteratively prune (set to 0) the outermost taps to get very short filters

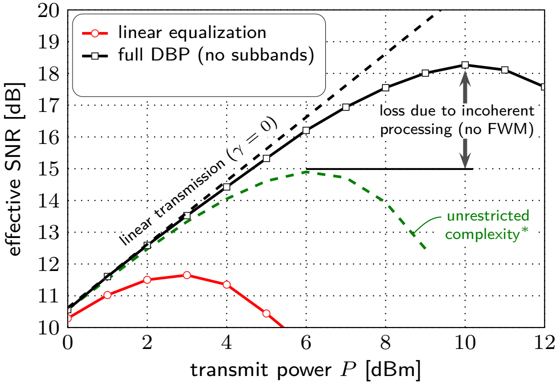
Results ($N = 12$ Subbands for 96 Gbaud)



System parameters:

- 25×100 km fiber
- 96 Gbaud
- Gaussian symbols, single pol.
- RRC pulses (0.1 roll-off)

Results ($N = 12$ Subbands for 96 Gbaud)

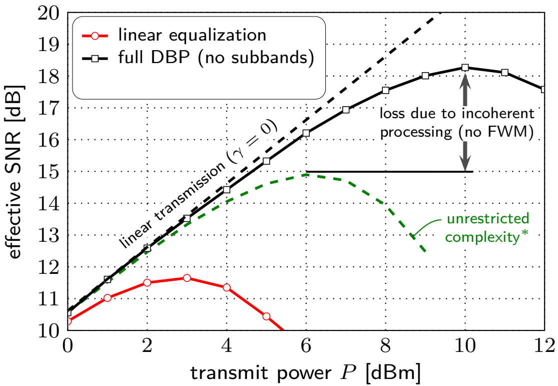


System parameters:

- 25×100 km fiber
- 96 Gbaud
- Gaussian symbols, single pol.
- RRC pulses (0.1 roll-off)

* [Leibrich and Rosenkranz, 2003] FFT/IFFT, no downsampling, 1000 steps/span

Results ($N = 12$ Subbands for 96 Gbaud)



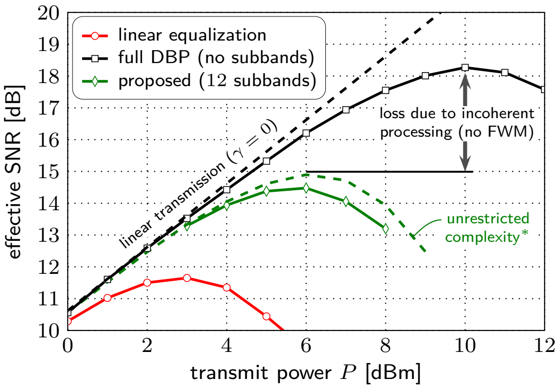
System parameters:

- 25×100 km fiber
- 96 Gbaud
- Gaussian symbols, single pol.
- RRC pulses (0.1 roll-off)

* [Leibrich and Rosenkranz, 2003] FFT/IFFT, no downsampling, 1000 steps/span

- $K = 8$ ($1.5\times$ subband oversampling), 38.2 km step size (2.6 steps/span)

Results ($N = 12$ Subbands for 96 Gbaud)



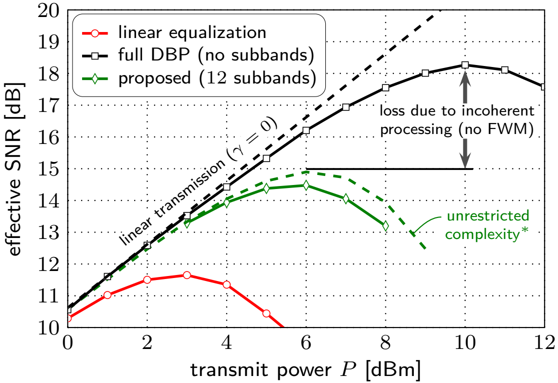
System parameters:

- 25×100 km fiber
- 96 Gbaud
- Gaussian symbols, single pol.
- RRC pulses (0.1 roll-off)

* [Leibrich and Rosenkranz, 2003]
FFT/IFFT, no downsampling,
1000 steps/span

- $K = 8$ ($1.5\times$ subband oversampling), 38.2 km step size (2.6 steps/span)

Results ($N = 12$ Subbands for 96 Gbaud)



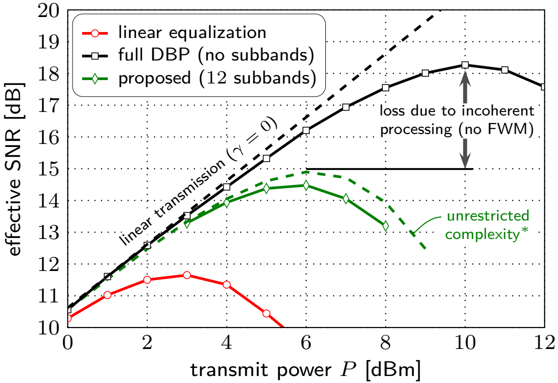
System parameters:

- 25×100 km fiber
- 96 Gbaud
- Gaussian symbols, single pol.
- RRC pulses (0.1 roll-off)

* [Leibrich and Rosenkranz, 2003] FFT/IFFT, no downsampling, 1000 steps/span

- $K = 8$ ($1.5\times$ subband oversampling), 38.2 km step size (2.6 steps/span)
- 7-tap learned filters (16 real mul.), sparse MIMO filters (8 real mul.)

Results ($N = 12$ Subbands for 96 Gbaud)



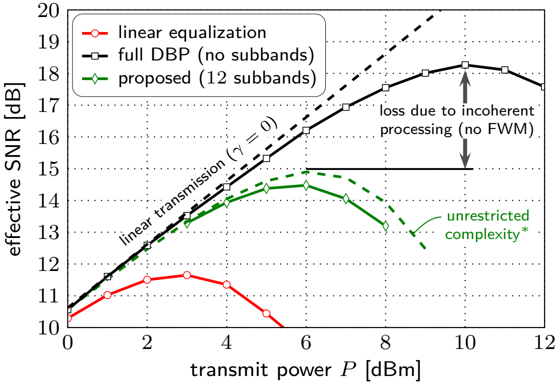
System parameters:

- 25×100 km fiber
- 96 Gbaud
- Gaussian symbols, single pol.
- RRC pulses (0.1 roll-off)

* [Leibrich and Rosenkranz, 2003]
FFT/IFFT, no downsampling,
1000 steps/span

- $K = 8$ ($1.5\times$ subband oversampling), 38.2 km step size (2.6 steps/span)
- 7-tap learned filters (16 real mul.), sparse MIMO filters (8 real mul.)
- $> 4\times$ less real mul. compared to FFT/IFFT [Mateo et al., 2010]

Results ($N = 12$ Subbands for 96 Gbaud)

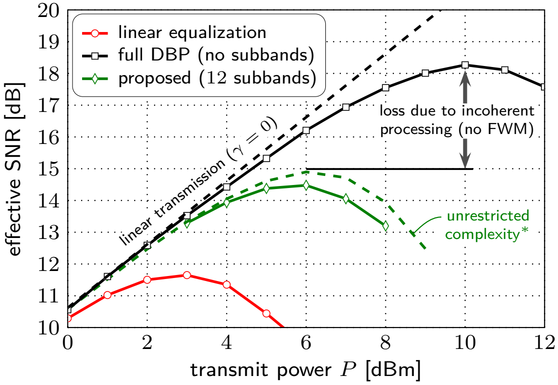


System parameters:

- 25×100 km fiber
- 96 Gbaud
- Gaussian symbols, single pol.
- RRC pulses (0.1 roll-off)

* [Leibrich and Rosenkranz, 2003]
FFT/IFFT, no downsampling,
1000 steps/span

Results ($N = 12$ Subbands for 96 Gbaud)



System parameters:

- 25×100 km fiber
- 96 Gbaud
- Gaussian symbols, single pol.
- RRC pulses (0.1 roll-off)

* [Leibrich and Rosenkranz, 2003]
FFT/IFFT, no downsampling,
1000 steps/span

- $\approx 2 - 3\times$ less complexity compared to full DBP (estimated):
  - Full DBP: ≈ 225 W
  - Subband processing: ≈ 75 W – 113 W
  - Independent receivers: ≈ 45 W

Conclusions and Future Work

Conclusions and Future Work

- Split-step DBP is feasible for real-time DSP using time-domain filtering
- Wideband compensation can be efficient using subband processing
- Deep learning can be used to jointly optimize and prune all FIR filters

Conclusions and Future Work

- Split-step DBP is feasible for real-time DSP using time-domain filtering
- Wideband compensation can be efficient using subband processing
- Deep learning can be used to jointly optimize and prune all FIR filters

- ASIC implementation of subband processing
- Deep learning based on experimental data
- Can we do efficient FWM compensation with subbands?

Conclusions and Future Work

- Split-step DBP is feasible for real-time DSP using time-domain filtering
- Wideband compensation can be efficient using subband processing
- Deep learning can be used to jointly optimize and prune all FIR filters

- ASIC implementation of subband processing
- Deep learning based on experimental data
- Can we do efficient FWM compensation with subbands?

Thank you!

FORCE FIBER-OPTIC COMMUNICATIONS RESEARCH CENTER

Duke UNIVERSITY

References I

Fougstedt, C., Mazur, M., Svensson, L., Eliasson, H., Karlsson, M., and Larsson-Edefors, P. (2017a).
Time-domain digital back propagation: Algorithm and finite-precision implementation aspects.
In *Proc. Optical Fiber Communication Conf. (OFC)*, Los Angeles, CA.

Fougstedt, C., Svensson, L., Mazur, M., Karlsson, M., and Larsson-Edefors, P. (2017b).
Finite-precision optimization of time-domain digital back propagation by inter-symbol interference minimization.
In *Proc. European Conf. Optical Communication*, Gothenburg, Sweden.

Fougstedt, C., Svensson, L., Mazur, M., Karlsson, M., and Larsson-Edefors, P. (2018).
ASIC implementation of time-domain digital back propagation for coherent receivers.
IEEE Photon. Technol. Lett., 30(13):1179–1182.

Goldfarb, G. and Li, G. (2009).
Efficient backward-propagation using wavelet- based filtering for fiber backward-propagation.
Opt. Express, 17(11):814–816.

Häger, C. and Pfister, H. D. (2018a).
Deep learning of the nonlinear Schrödinger equation in fiber-optic communications.
In *Proc. IEEE Int. Symp. Information Theory (ISIT)*, Vail, CO.

Häger, C. and Pfister, H. D. (2018b).
Nonlinear interference mitigation via deep neural networks.
In *Proc. Optical Fiber Communication Conf. (OFC)*, San Diego, CA.

Ho, K.-P. (2009).
Subband equaliser for chromatic dispersion of optical fibre.
Electronics Lett., 45(24):1224–1226.

References II

Ip, E., Bai, N., and Wang, T. (2011).
Complexity versus performance tradeoff for fiber nonlinearity compensation using frequency-shaped, multi-subband backpropagation.
In *Proc. Optical Fiber Communication Conf. (OFC)*, page OThF4, Los Angeles, CA.

Ip, E. and Kahn, J. M. (2008).
Compensation of dispersion and nonlinear impairments using digital backpropagation.
J. Lightw. Technol., 26:3416–3425.

Leibrich, J. and Rosenkranz, W. (2003).
Efficient numerical simulation of multichannel WDM transmission systems limited by XPM.
IEEE Photon. Technol. Lett., 15(3):395–397.

Li, X., Chen, X., Goldfarb, G., Mateo, E., Kim, I., Yaman, F., and Li, G. (2008).
Electronic post-compensation of WDM transmission impairments using coherent detection and digital signal processing.
Opt. Express, 16(2):880–888.

Martins, C. S., Bertignono, L., Nespola, A., Carena, A., Guiomar, F. P., and Pinto, A. N. (2018).
Efficient time-domain DBP using random step-size and multi-band quantization.
In *Proc. Optical Fiber Communication Conf. (OFC)*, San Diego, CA.

Mateo, E. F., Yaman, F., and Li, G. (2010).
Efficient compensation of inter-channel nonlinear effects via digital backward propagation in WDM optical transmission.
Opt. Express, 18(14):15144.

References III

Nazarathy, M. and Tolmachev, A. (2014).
Subbanded DSP architectures based on underdecimated filter banks for coherent OFDM receivers: Overview and recent advances.
IEEE Signal Processing Mag., 31(2):70–81.

Oyama, T., Nakashima, H., Hoshida, T., Tanimura, T., Akiyama, Y., Tao, Z., and Rasmussen, J. C. (2015).
Complexity reduction of perturbation-based nonlinear compensator by sub-band processing.
In *Proc. Optical Fiber Communication Conf. (OFC)*.

Slim, I., Mezghani, A., Baltar, L. G., Qi, J., Hauske, F. N., and Nossek, J. A. (2013).
Delayed single-tap frequency-domain chromatic-dispersion compensation.
IEEE Photon. Technol. Lett., 25(2):167–170.

Taylor, M. G. (2008).
Compact digital dispersion compensation algorithms.
In *Proc. Optical Fiber Communication Conf. (OFC)*, San Diego, CA.

Zhu, L., Li, X., Mateo, E., and Li, G. (2009).
Complementary FIR filter pair for distributed impairment compensation of WDM fiber transmission.
IEEE Photon. Technol. Lett., 21(5):292–294.