Digital Nonlinear Equalization

for Long-Haul Optical Transmission Systems

Fernando P. Guiomar

Supervisor: Prof. Armando Humberto Moreira Nolasco Pinto

Department of Electronics, Telecommunications and Informatics, University of Aveiro, Aveiro, Portugal
Instituto de Telecomunicações - Pólo de Aveiro, Portugal

Who am I?

- So many names!
  - **Fernando** Pedro Pereira **Guiomar**

Who am I?

- So many names!
  - **Fernando** Pedro Pereira **Guiomar**
- I did my PhD on Digital Nonlinear Equalization for Optical Transmission Systems
  - Instituto de Telecomunicações and University of Aveiro, Portugal.

Who am I?

- So many names!
  - **Fernando** Pedro Pereira **Guiomar**
- I did my PhD on Digital Nonlinear Equalization for Optical Transmission Systems
  - Instituto de Telecomunicações and University of Aveiro, Portugal.




- Other things I like to do:
  - Football, music, cinema, travelling...

Outline

- Summary of my PhD Thesis Work;
  - Review of Digital Backpropagation;
  - Frequency Domain Volterra Series Nonlinear Equalizer;
  - Time Domain Volterra Series Nonlinear Equalizer;
  - Multi-Carrier Digital Backpropagation.
- Some Open Topics on Nonlinear Equalization;
- The FLEX-ON Project;
  - Main Scientific Objectives;
  - Dissemination and Public Engagement.

Review of Digital Backpropagation

Digital Backpropagation - Operation Principle

- Effective linear+nonlinear compensation requires channel inversion techniques;
  - Signal propagation in the direct fiber direction can be described by:

$$\frac{\partial A_{x/y}}{\partial z} = -\frac{\alpha}{2} A_{x/y} - i\frac{\beta_2}{2}\frac{\partial^2 A_{x/y}}{\partial^2 t} + i\frac{8}{9}\gamma\left(|A_x|^2 + |A_y|^2\right) A_{x/y},$$

E. Ip and J. M. Kahn, ``**Compensation of Dispersion and Nonlinear Impairments Using Digital Backpropagation**'', IEEE/OSA Journal of Lightwave Technology, vol. 26, no. 29, 2008.

Digital Backpropagation - Operation Principle

- Effective linear+nonlinear compensation requires channel inversion techniques;
  - Signal propagation in the reverse fiber direction can be described by:

$$-\frac{\partial A_{x/y}}{\partial z} = +\frac{\alpha}{2}A_{x/y} + i\frac{\beta_2}{2}\frac{\partial^2 A_{x/y}}{\partial^2 t} - i\frac{8}{9}\gamma\left(|A_x|^2 + |A_y|^2\right)A_{x/y},$$

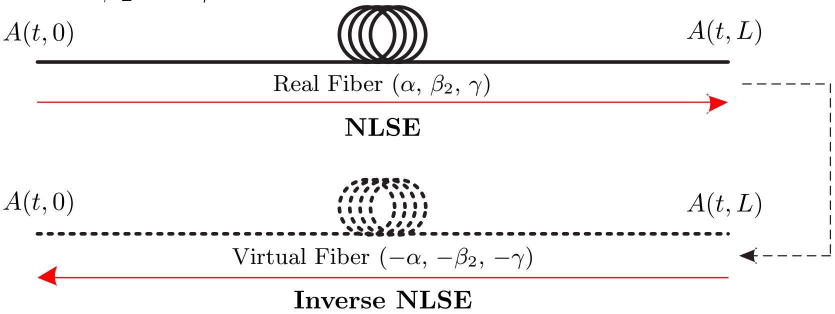
E. Ip and J. M. Kahn, ``**Compensation of Dispersion and Nonlinear Impairments Using Digital Backpropagation**'', IEEE/OSA Journal of Lightwave Technology, vol. 26, no. 29, 2008.

Digital Backpropagation - Operation Principle

- Effective linear+nonlinear compensation requires channel inversion techniques;
  - Signal propagation in the reverse fiber direction can be described by:

$$-\frac{\partial A_{x/y}}{\partial z} = +\frac{\alpha}{2}A_{x/y} + i\frac{\beta_2}{2}\frac{\partial^2 A_{x/y}}{\partial^2 t} - i\frac{8}{9}\gamma\left(|A_x|^2 + |A_y|^2\right)A_{x/y},$$

  - This corresponds to propagate the received signal through a **virtual fiber** with parameters with the opposite sign ($-\alpha$, $-\beta_2$ e $-\gamma$).



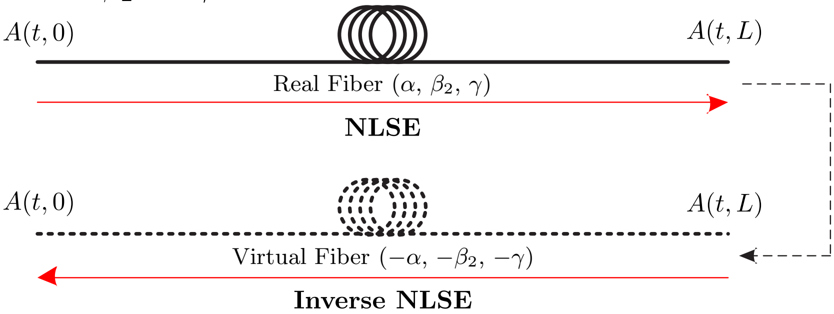
E. Ip and J. M. Kahn, ``**Compensation of Dispersion and Nonlinear Impairments Using Digital Backpropagation**'', IEEE/OSA Journal of Lightwave Technology, vol. 26, no. 29, 2008.

Digital Backpropagation - Operation Principle

- Effective linear+nonlinear compensation requires channel inversion techniques;
  - Signal propagation in the reverse fiber direction can be described by:

$$-\frac{\partial A_{x/y}}{\partial z} = +\frac{\alpha}{2}A_{x/y} + i\frac{\beta_2}{2}\frac{\partial^2 A_{x/y}}{\partial^2 t} - i\frac{8}{9}\gamma\left(|A_x|^2 + |A_y|^2\right)A_{x/y},$$

  - This corresponds to propagate the received signal through a **virtual fiber** with parameters with the opposite sign ($-\alpha$, $-\beta_2$ e $-\gamma$).



  - This method can be digitally applied at the receiver-side for **universal impairment compensation**;

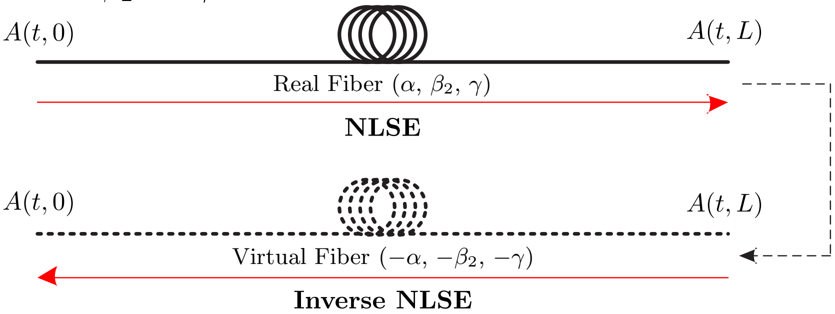
E. Ip and J. M. Kahn, ``**Compensation of Dispersion and Nonlinear Impairments Using Digital Backpropagation**'', IEEE/OSA Journal of Lightwave Technology, vol. 26, no. 29, 2008.

Digital Backpropagation - Operation Principle

- Effective linear+nonlinear compensation requires channel inversion techniques;
  - Signal propagation in the reverse fiber direction can be described by:

$$-\frac{\partial A_{x/y}}{\partial z} = +\frac{\alpha}{2} A_{x/y} + i\frac{\beta_2}{2}\frac{\partial^2 A_{x/y}}{\partial^2 t} - i\frac{8}{9}\gamma\left(|A_x|^2 + |A_y|^2\right) A_{x/y},$$

  - This corresponds to propagate the received signal through a **virtual fiber** with parameters with the opposite sign ($-\alpha$, $-\beta_2$ e $-\gamma$).

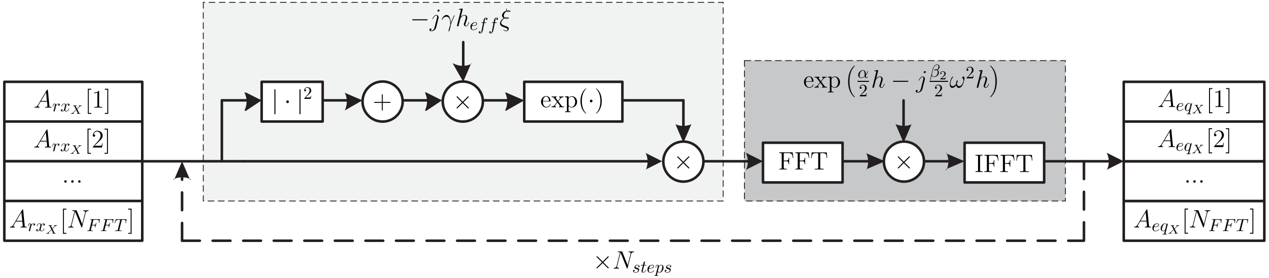


  - This method can be digitally applied at the receiver-side for **universal impairment compensation**;
  - Equalization performance and computational efficiency strongly depend on the numerical method used to apply DBP.

E. Ip and J. M. Kahn, ``**Compensation of Dispersion and Nonlinear Impairments Using Digital Backpropagation**'', IEEE/OSA Journal of Lightwave Technology, vol. 26, no. 29, 2008.

Backpropagation Split-Step Fourier Method

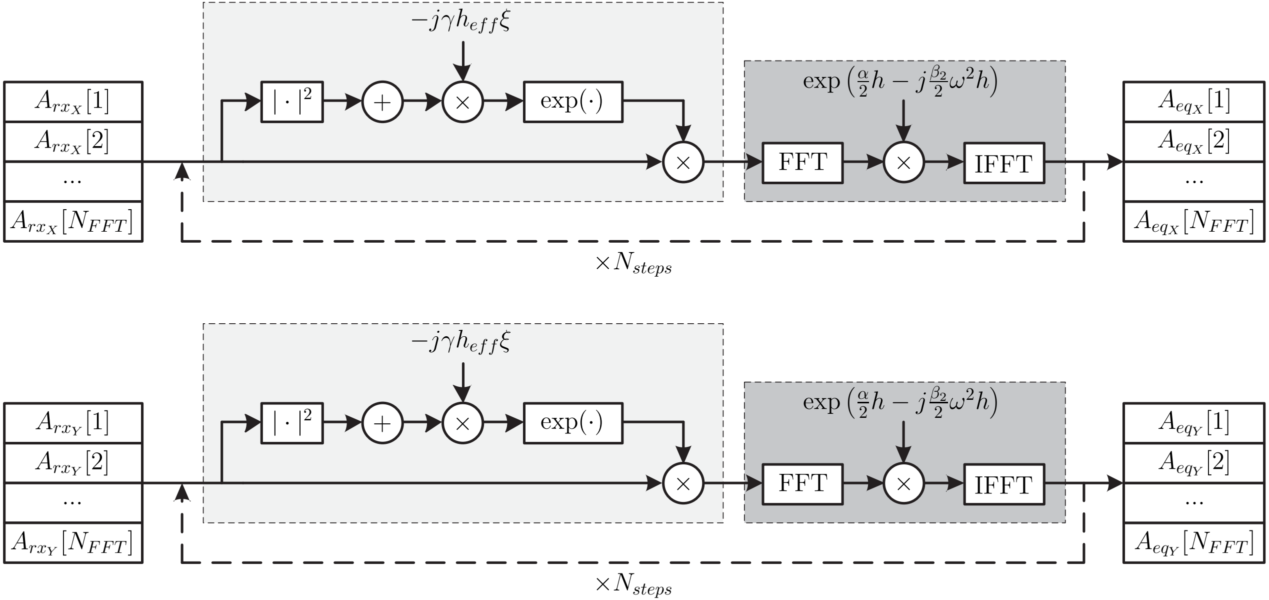
- BP-SSFM has been the most widely used numerical method to solve DBP;



A. N. Pinto, S. B. Amado, N. J. Muga and F. P. Guiomar, ``**Equalization of Fiber Impairments Using High-Speed Digital Signal Processing**,'' *in Proc. ICTON*, Cartagena, Spain, June, 2013. (**invited paper**)

Backpropagation Split-Step Fourier Method

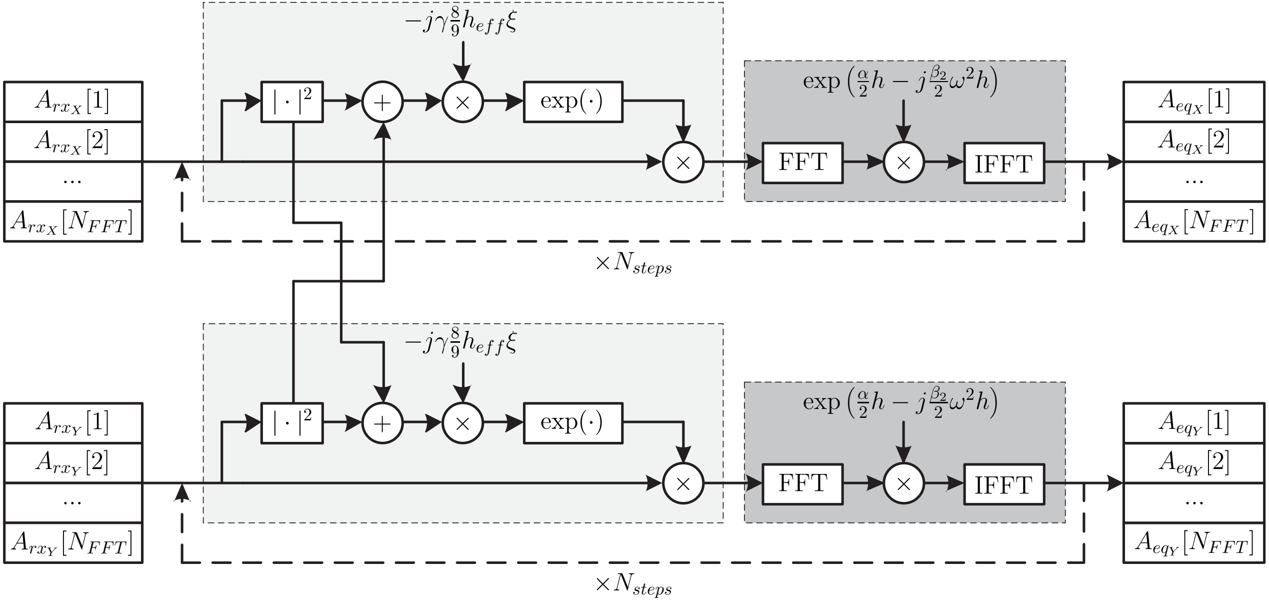
- BP-SSFM has been the most widely used numerical method to solve DBP;



A. N. Pinto, S. B. Amado, N. J. Muga and F. P. Guiomar, ``**Equalization of Fiber Impairments Using High-Speed Digital Signal Processing**,'' *in Proc. ICTON*, Cartagena, Spain, June, 2013. (**invited paper**)

Backpropagation Split-Step Fourier Method

- BP-SSFM has been the most widely used numerical method to solve DBP;



- If spatial and temporal resolutions are sufficiently high, BP-SSFM enables to **fully compensate all the deterministic impairments.**

A. N. Pinto, S. B. Amado, N. J. Muga and F. P. Guiomar, ``**Equalization of Fiber Impairments Using High-Speed Digital Signal Processing**,'' *in Proc. ICTON*, Cartagena, Spain, June, 2013. (**invited paper**)

OPTCOM

Inverse Volterra Series Transfer Function

3.1) Analytical Description

VSTF - Analytical Description

- **DBP alternative**: **third-order Volterra series expansion** of the inverse NLSE in frequency-domain:

$$\tilde{A}_{x/y}(\omega, z-L_s) \approx \underbrace{K_1(\omega, L_s)\tilde{A}_{x/y}(\omega, z)}_{\text{linear term}} + \underbrace{\Gamma(\omega, L_s)\iint K_3(\omega, \omega_j, \omega_k)\tilde{P}(\omega_j, \omega_k, z)\tilde{A}_{x/y}(\omega + \omega_j - \omega_k, z)\partial\omega_j\partial\omega_k}_{\text{3}^{\text{rd}}\text{-order nonlinear term}},$$

F. P. Guiomar, J. D. Reis, A. L. Teixeira and A. N. Pinto, ``**Digital Postcompensation Using Volterra Series Transfer Function**,'' IEEE Photonics Technology Letters, vol.23, no.19, pp.1412-1414, 2011.

VSTF - Analytical Description

- **DBP alternative**: **third-order Volterra series expansion** of the inverse NLSE in frequency-domain:

$$\tilde{A}_{x/y}(\omega, z-L_s) \approx \underbrace{K_1(\omega, L_s)\tilde{A}_{x/y}(\omega, z)}_{\text{linear term}} + \underbrace{\Gamma(\omega, L_s)\iint K_3(\omega, \omega_j, \omega_k)\tilde{P}(\omega_j, \omega_k, z)\tilde{A}_{x/y}(\omega + \omega_j - \omega_k, z)\partial\omega_j\partial\omega_k}_{\text{3}^{\text{rd}}\text{-order nonlinear term}},$$

where $\tilde{P}(\omega_j, \omega_k, z)$ includes the inter-polarization crosstalk,

$$\tilde{P}(\omega_j, \omega_k, z) = \tilde{A}_x(\omega_k, z)\tilde{A}_x^*(\omega_j, z) + \tilde{A}_y(\omega_k, z)\tilde{A}_y^*(\omega_j, z),$$

F. P. Guiomar, J. D. Reis, A. L. Teixeira and A. N. Pinto, ``**Digital Postcompensation Using Volterra Series Transfer Function**,'' IEEE Photonics Technology Letters, vol.23, no.19, pp.1412-1414, 2011.

VSTF - Analytical Description

- **DBP alternative**: **third-order Volterra series expansion** of the inverse NLSE in frequency-domain:

$$\tilde{A}_{x/y}(\omega, z-L_s) \approx \underbrace{K_1(\omega, L_s)\tilde{A}_{x/y}(\omega, z)}_{\text{linear term}} + \underbrace{\Gamma(\omega, L_s)\iint K_3(\omega, \omega_j, \omega_k)\tilde{P}(\omega_j, \omega_k, z)\tilde{A}_{x/y}(\omega + \omega_j - \omega_k, z)\partial\omega_j\partial\omega_k}_{\text{3}^{\text{rd}}\text{-order nonlinear term}},$$

where $\tilde{P}(\omega_j, \omega_k, z)$ includes the inter-polarization crosstalk,

$$\tilde{P}(\omega_j, \omega_k, z) = \tilde{A}_x(\omega_k, z)\tilde{A}_x^*(\omega_j, z) + \tilde{A}_y(\omega_k, z)\tilde{A}_y^*(\omega_j, z),$$

$K_1(\omega, z)$ is the inverse linear kernel,

$$K_1(\omega, z) = \exp\left(\frac{\alpha}{2}L_s - i\frac{\beta_2}{2}\omega^2 z\right),$$

F. P. Guiomar, J. D. Reis, A. L. Teixeira and A. N. Pinto, ``**Digital Postcompensation Using Volterra Series Transfer Function**,'' IEEE Photonics Technology Letters, vol.23, no.19, pp.1412-1414, 2011.

VSTF - Analytical Description

- **DBP alternative**: **third-order Volterra series expansion** of the inverse NLSE in frequency-domain:

$$\tilde{A}_{x/y}(\omega, z-L_s) \approx \underbrace{K_1(\omega, L_s)\tilde{A}_{x/y}(\omega, z)}_{\text{linear term}} + \underbrace{\Gamma(\omega, L_s)\iint K_3(\omega, \omega_j, \omega_k)\tilde{P}(\omega_j, \omega_k, z)\tilde{A}_{x/y}(\omega + \omega_j - \omega_k, z)\partial\omega_j\partial\omega_k}_{3^{\text{rd}}\text{-order nonlinear term}},$$

where $\tilde{P}(\omega_j, \omega_k, z)$ includes the inter-polarization crosstalk,

$$\tilde{P}(\omega_j, \omega_k, z) = \tilde{A}_x(\omega_k, z)\tilde{A}_x^*(\omega_j, z) + \tilde{A}_y(\omega_k, z)\tilde{A}_y^*(\omega_j, z),$$

$K_1(\omega, z)$ is the inverse linear kernel,

$$K_1(\omega, z) = \exp\left(\frac{\alpha}{2}L_s - i\frac{\beta_2}{2}\omega^2 z\right),$$

$K_3(\omega, \omega_j, \omega_k)$ is the inverse nonlinear kernel,

$$K_3(\omega, \omega_j, \omega_k) = \frac{1 - \exp\left(\alpha L_s - i\beta_2(\omega_k - \omega)(\omega_k - \omega_j)L_s\right)}{-\alpha + i\beta_2(\omega_k - \omega)(\omega_k - \omega_j)},$$

and $\Gamma(\omega, z)$ is a one-dimensional frequency-dependent nonlinear term,

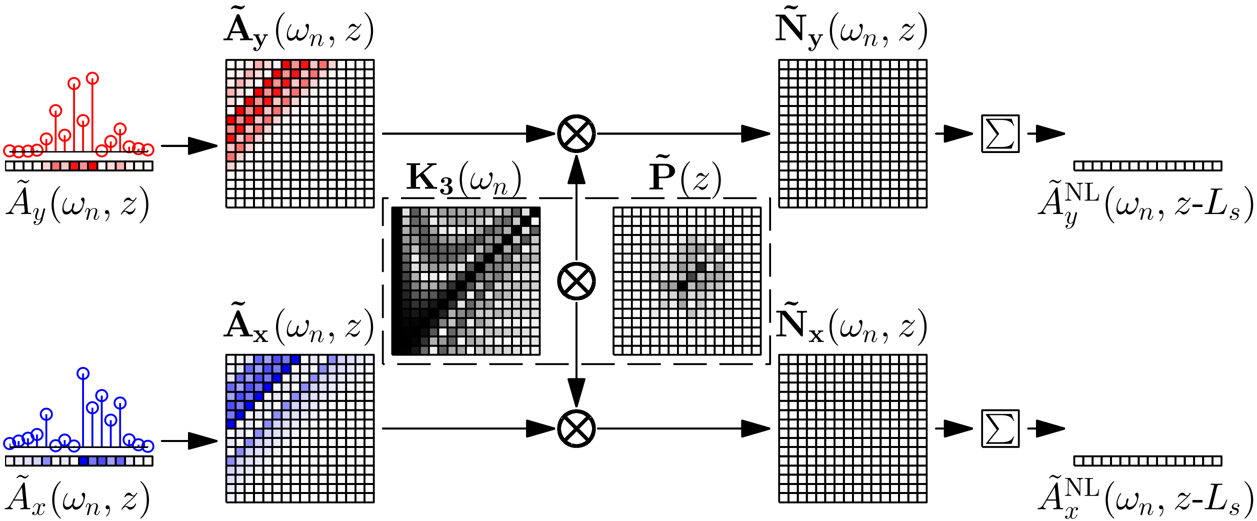
$$\Gamma(\omega, z) = -i\xi\frac{8}{9}\gamma K_1(\omega, z).$$

F. P. Guiomar, J. D. Reis, A. L. Teixeira and A. N. Pinto, ``**Digital Postcompensation Using Volterra Series Transfer Function**,'' IEEE Photonics Technology Letters, vol.23, no.19, pp.1412-1414, 2011.

VSNE - 2D Representation

- The Volterra series nonlinear equalizer in frequency domain is based on an entry-wise product of $N \times N$ matrices:

$$\tilde{\mathbf{N}}_{\mathbf{x/y}}(\omega_n, z) = \mathbf{K_3}(\omega_n) \circ \tilde{\mathbf{P}}(z) \circ \tilde{\mathbf{A}}_{\mathbf{x/y}}(\omega_n, z)$$



- **Highly parallel** implementation, but with $O(N^2)$ complexity per processed sample.

F. P. Guiomar, J. D. Reis, A. L. Teixeira and A. N. Pinto, ``**Mitigation of intra-channel nonlinearities using a frequency-domain Volterra series equalizer**,'' Optics Express, vol.20, no.2, pp.1360-1369, 2012.

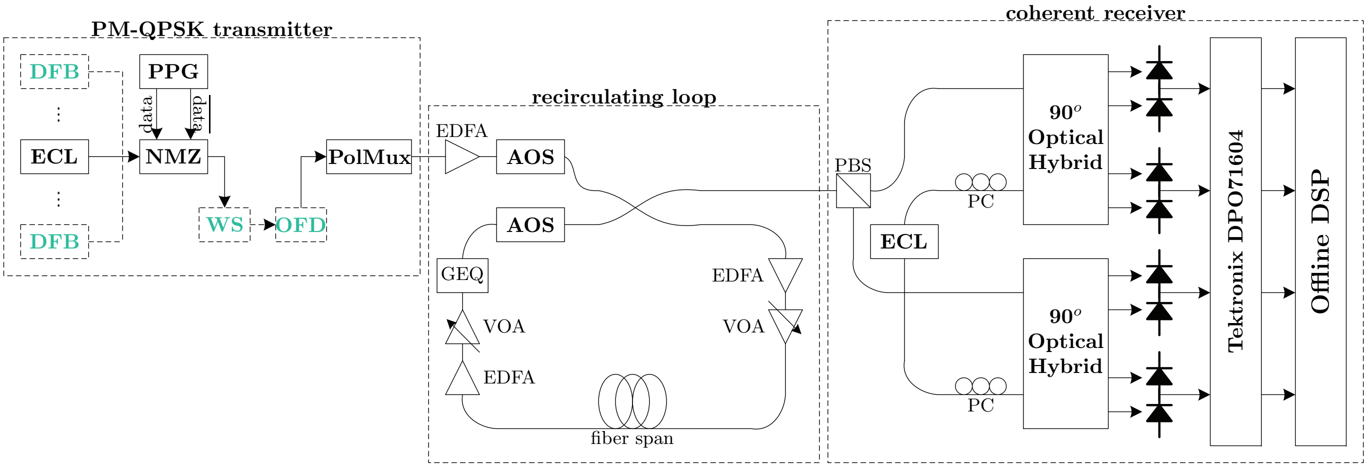
OPTCOM

Inverse Volterra Series Transfer Function

3.2) Experimental Results

VSNE - Experimental Setup

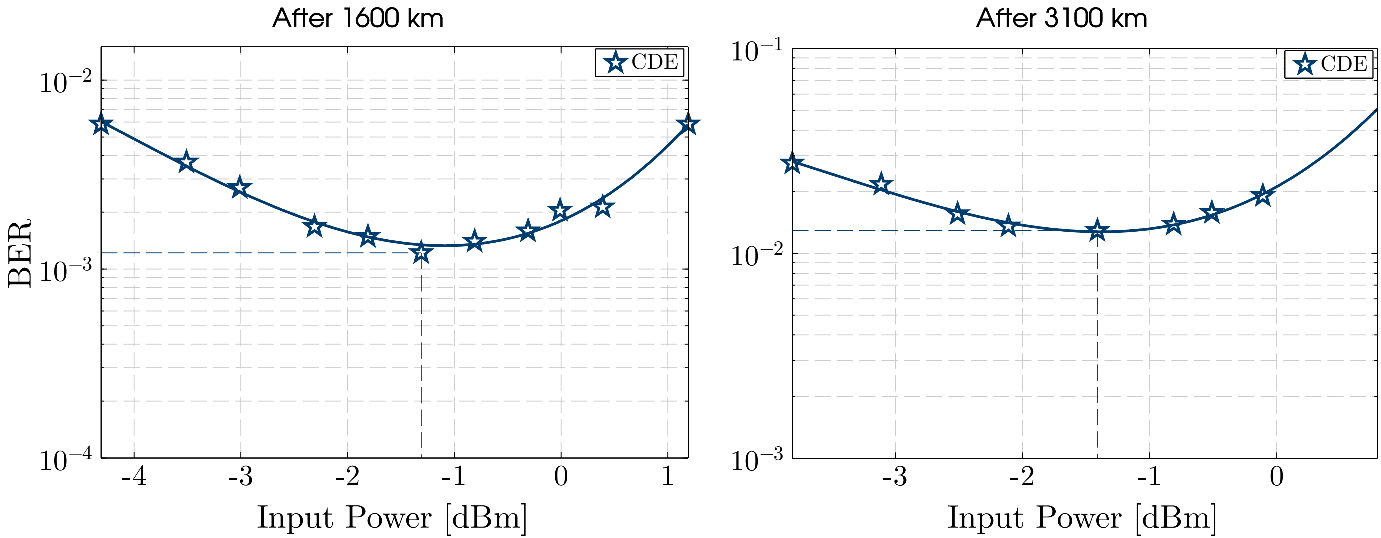
- Experimental setup of a **100G PM-QPSK experiment**, carried out in collaboration with Politecnico di Torino, Italy, in the framework of the EURO-FOS project:



- Main features:
  - Single-channel PM-QPSK @ 120 Gb/s;
  - Optical Nyquist pulse shaping;
  - Propagation over **NZDSF** spans with 100 km each;
  - Sampling @ 50 Gsa/s - ∼**1.6 samples per symbol**.

F. P. Guiomar et al, ``**Experimental demonstration of a frequency-domain Volterra series nonlinear equalizer in polarization-multiplexed transmission**,'' *in Proc. ECOC*, paper Th.1.D.1, Amsterdam, September, 2012.

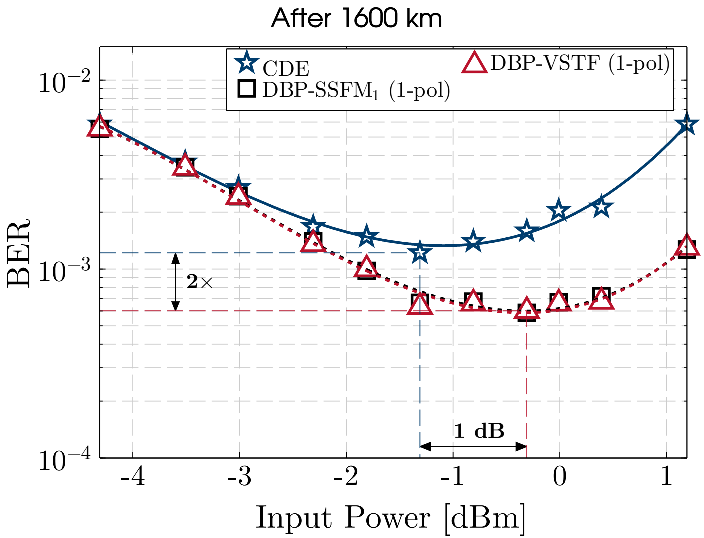
- Single-channel 120 Gb/s PM-QPSK transmission over an NZDSF link:

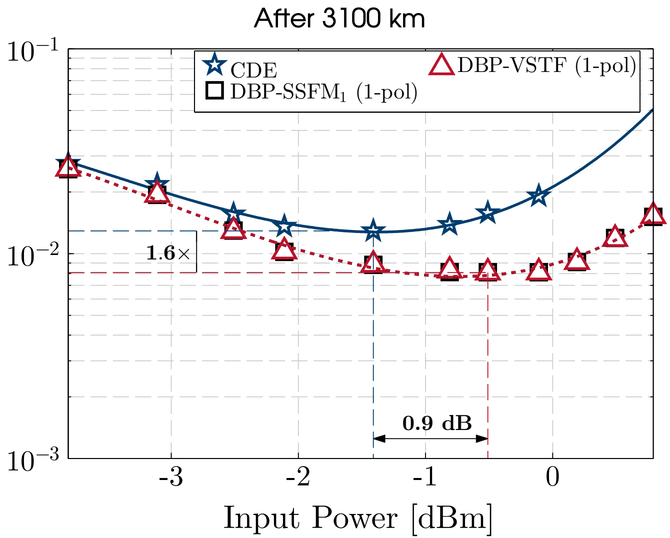


F. P. Guiomar et al, ``**Experimental demonstration of a frequency-domain Volterra series nonlinear equalizer in polarization-multiplexed transmission**,'' Optics Express, vol.21, no.1, pp.276--288, 2013.

VSNE - Experimental Results @ 100G PM-QPSK

- Single-channel 120 Gb/s PM-QPSK transmission over an NZDSF link:



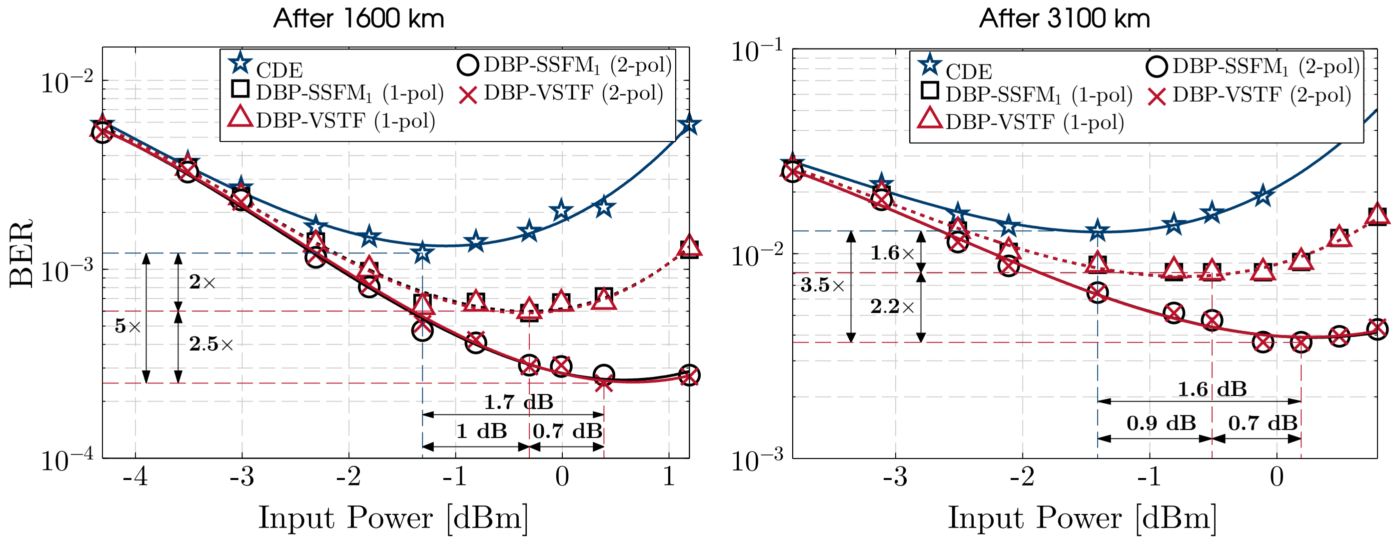


  - The single-polarization DBP-SSFM and DBP-VSTF increase the nonlinear tolerance by ∼**1 dB**;

F. P. Guiomar et al, ``**Experimental demonstration of a frequency-domain Volterra series nonlinear equalizer in polarization-multiplexed transmission**,'' Optics Express, vol.21, no.1, pp.276--288, 2013.

VSNE - Experimental Results @ 100G PM-QPSK

- Single-channel 120 Gb/s PM-QPSK transmission over an NZDSF link:

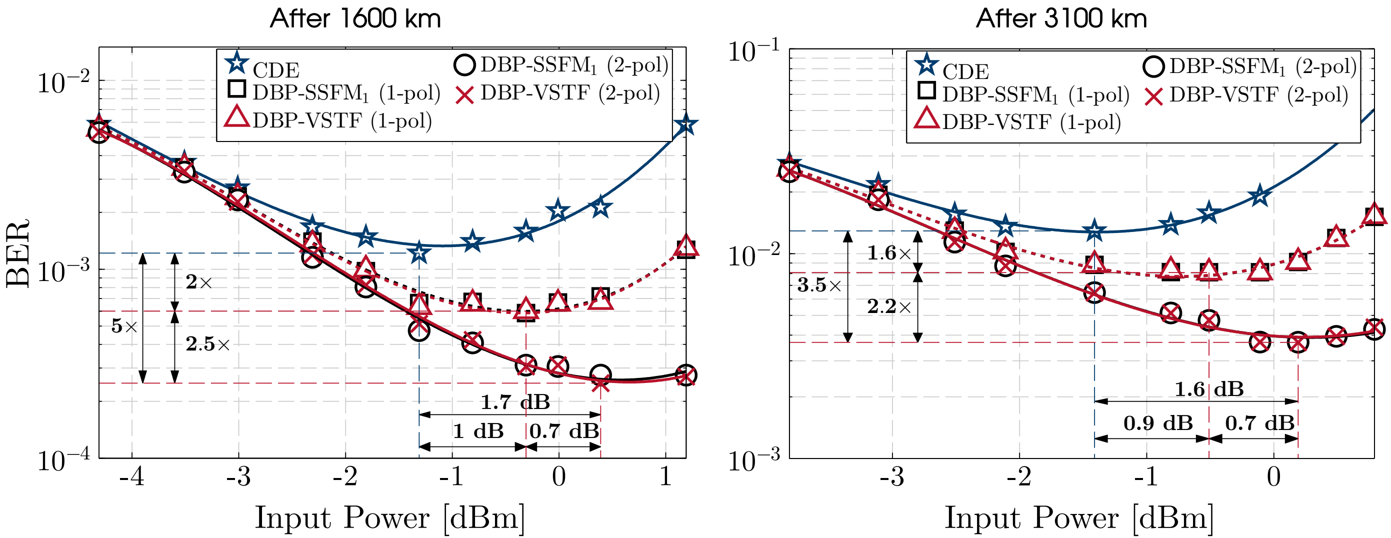


- The single-polarization DBP-SSFM and DBP-VSTF increase the nonlinear tolerance by $\sim$**1 dB**;
- Another **0.7 dB** is obtained by the dual-polarization models, with **negligible added complexity**;
- The DBP-SSFM and DBP-VSTF are shown to yield **similar accuracy**.

F. P. Guiomar et al, ``**Experimental demonstration of a frequency-domain Volterra series nonlinear equalizer in polarization-multiplexed transmission**,'' Optics Express, vol.21, no.1, pp.276--288, 2013.

VSNE - Experimental Results @ 100G PM-QPSK

- Single-channel 120 Gb/s PM-QPSK transmission over an NZDSF link:



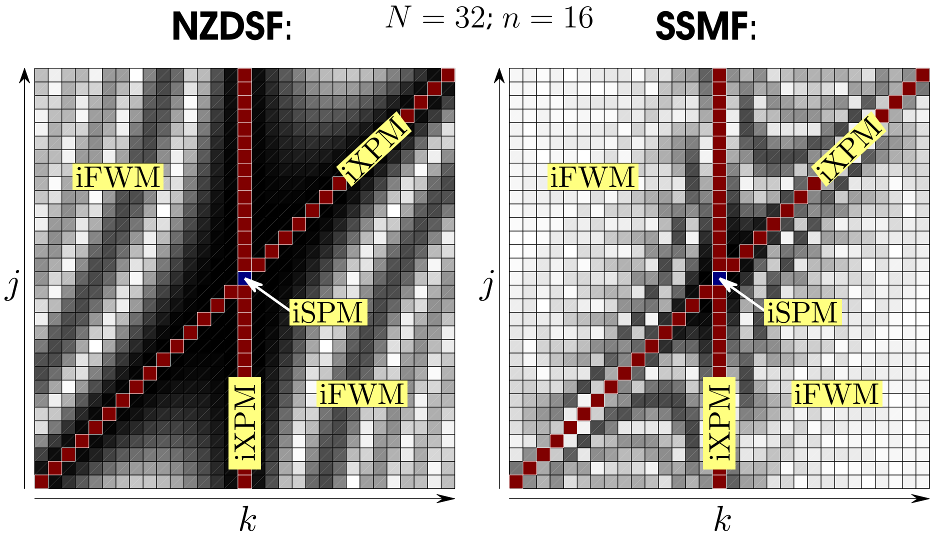
- The single-polarization DBP-SSFM and DBP-VSTF increase the nonlinear tolerance by ∼**1 dB**;
- Another **0.7 dB** is obtained by the dual-polarization models, with **negligible added complexity**;
- The DBP-SSFM and DBP-VSTF are shown to yield **similar accuracy**.
- But, **can we reduce the complexity of the DBP-VSTF?**

F. P. Guiomar et al, ``**Experimental demonstration of a frequency-domain Volterra series nonlinear equalizer in polarization-multiplexed transmission**,'' Optics Express, vol.21, no.1, pp.276--288, 2013.

Frequency Domain VSNE

4.1) Analytical Description

VSNE - 3rd Order Kernel



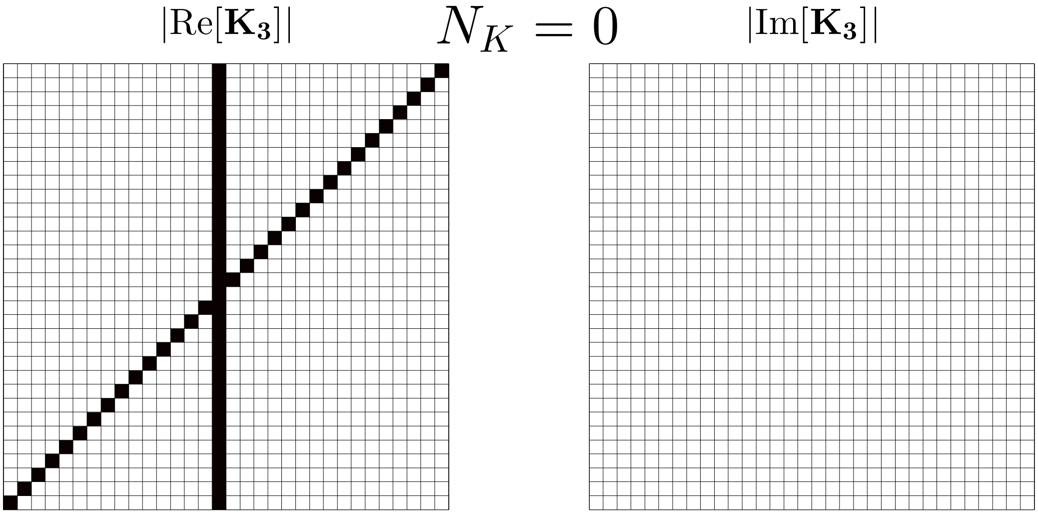
iSPM $\rightarrow j = k = n$;
iXPM $\rightarrow j = k \neq n$;
$\rightarrow k = n \neq j$;
iFWM $\rightarrow$ otherwise

- Interesting **symmetries** can be exploited to avoid replication of operations;
  - Some of the symmetries are also shared with the $\tilde{\mathbf{A}}_{\mathbf{x/y}}$ matrices.
- The $\mathbf{K_3}$ pattern strongly depends on the accumulated dispersion;
- The real part of $\mathbf{K_3}$ is maximum at the **iXPM+iSPM contribution**.

F. P. Guiomar et al, ``**Simplified Volterra Series Nonlinear Equalizer by Intra-Channel Cross-Phase Modulation Oriented Pruning**,'' *in Proc. ECOC*, paper We.3.C.6, London, September, 2013.

VSNE - Symmetric Reconstruction

- Starting from the iXPM contribution (main diagonal + n-th column), the K_3 kernel can be reconstructed from its symmetric column/diagonal pairs:

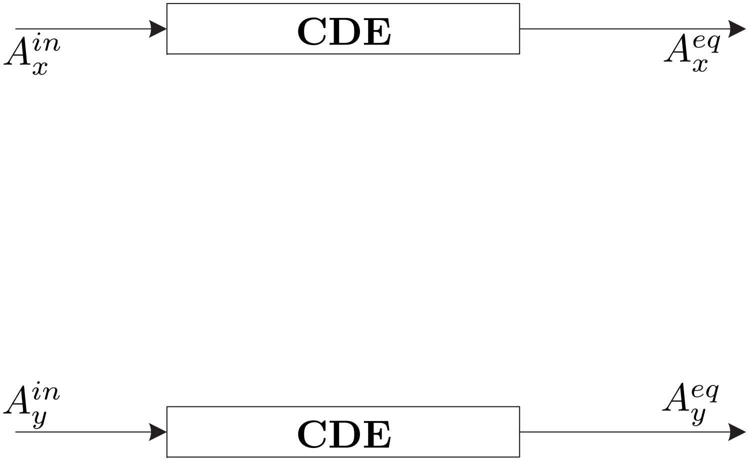


- The full VSNE kernel is then **decomposed into a set of N_K parallel frequency-domain filters**;
  - **symVSNE**: complexity is reduced from $O(N^2)$ **to** $O(N_k N)$;
- **simVSNE**: constant-coefficient approximation, **numerical complexity is** $O(N_k)$.

F. P. Guiomar and A. N. Pinto, ``**Simplified Volterra Series Nonlinear Equalizer for Polarization-Multiplexed Coherent Optical Systems**,'' IEEE/OSA Journal of Lightwave Technology, vol. 31, no. 23, pp. 3879--3891, 2013.

Backpropagation using VSNE-based Equalizers

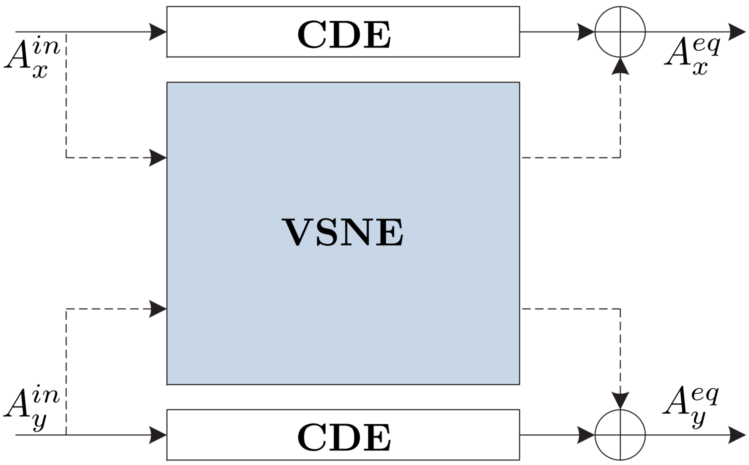
- DBP implementation using CDE and VSNE for linear and nonlinear compensation:



F. P. Guiomar et al, ``**Volterra-based Digital Backpropagation: Performance and Complexity Assessment**'', *in Proc. SPPCom*, Boston, 2015. (**invited paper**)

Backpropagation using VSNE-based Equalizers

- DBP implementation using CDE and VSNE for linear and nonlinear compensation:

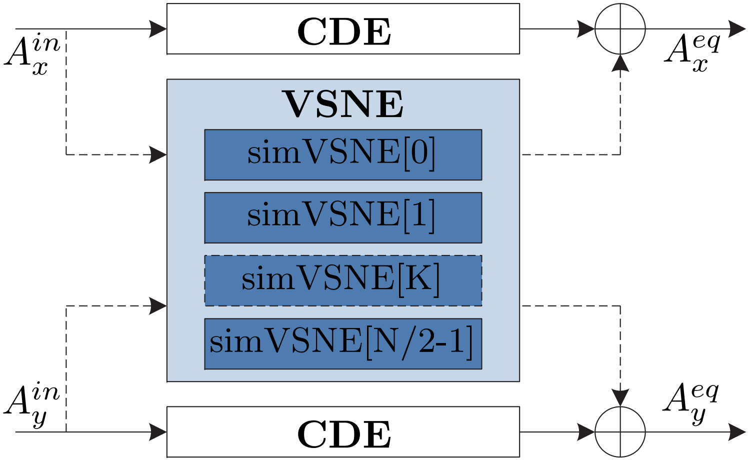


- The VSNE module is **applied in parallel** with CDE;
  - The performance is improved by perturbing the CDE output with a **nonlinear error signal**.

F. P. Guiomar et al, ``**Volterra-based Digital Backpropagation: Performance and Complexity Assessment**'', *in Proc. SPPCom*, Boston, 2015. (**invited paper**)

Backpropagation using VSNE-based Equalizers

- DBP implementation using CDE and VSNE for linear and nonlinear compensation:



- The VSNE module is **applied in parallel** with CDE;
  - The performance is improved by perturbing the CDE output with a **nonlinear error signal**.
- The VSNE can be subdivided into a set of N_k parallel **simVSNE equalizers**.
  - Nonlinear equalization becomes an highly granular **add-on**;
  - Easier trade-off between performance and complexity, depending on the DSP resources.

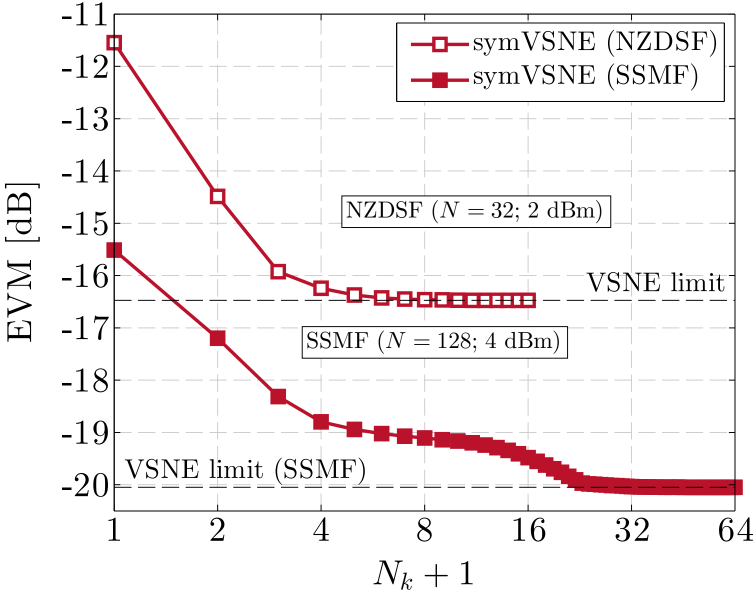
F. P. Guiomar et al, ``**Volterra-based Digital Backpropagation: Performance and Complexity Assessment**'', *in Proc. SPPCom*, Boston, 2015. (**invited paper**)

Frequency Domain VSNE

4.2) Simulation and Experimental Results

simVSNE - Filter Dimension and Computational Effort

- Simulation results for a 20×80 km 224 Gb/s PM-16QAM transmission system:



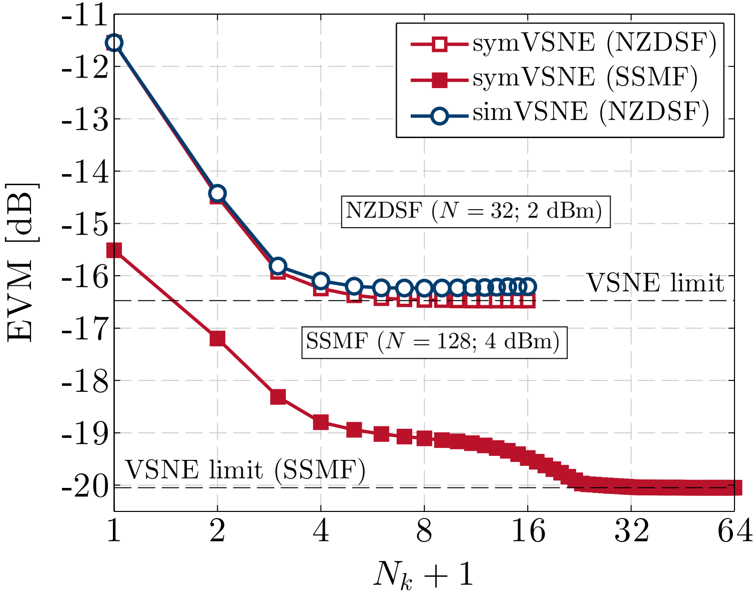
Number of CMs per sample:

N_k	symVSNE		simVSNE	
	$N = 32$	$N = 128$	$N = 32$	$N = 128$
1	6	6	6	6
2	134.9	519	17.6	17.9
3	247.6	1015.2	28.9	29.7
4	346.3	1495.8	39.7	41.4

F. P. Guiomar et al, ``**Simplified Volterra Series Nonlinear Equalizer by Intra-Channel Cross-Phase Modulation Oriented Pruning**'', *in Proc. ECOC*, paper We.3.C.6, London, 2013.

simVSNE - Filter Dimension and Computational Effort

- Simulation results for a 20×80 km 224 Gb/s PM-16QAM transmission system:



Number of CMs per sample:

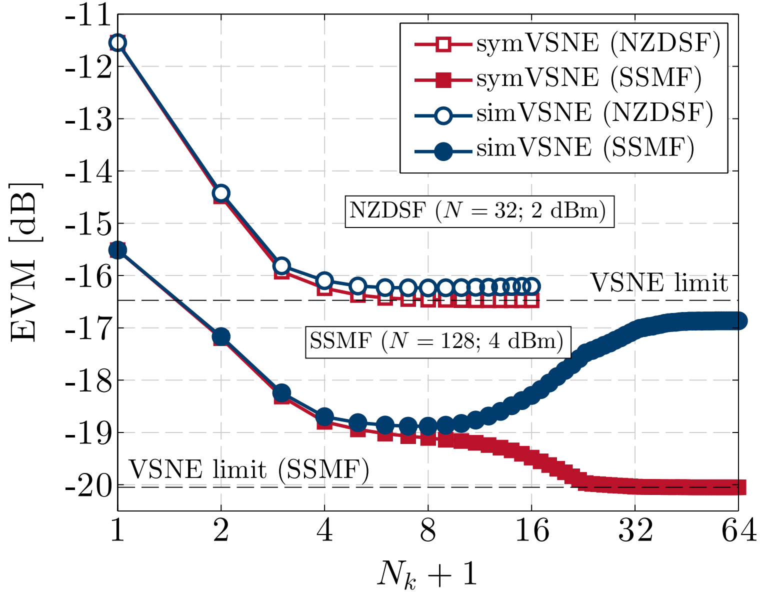
N_k	symVSNE		simVSNE	
	$N = 32$	$N = 128$	$N = 32$	$N = 128$
1	6	6	6	6
2	134.9	519	17.6	17.9
3	247.6	1015.2	28.9	29.7
4	346.3	1495.8	39.7	41.4

- The simVSNE error is negligible for low-dispersion fibers;

F. P. Guiomar et al, ``**Simplified Volterra Series Nonlinear Equalizer by Intra-Channel Cross-Phase Modulation Oriented Pruning**'', *in Proc. ECOC*, paper We.3.C.6, London, 2013.

simVSNE - Filter Dimension and Computational Effort

- Simulation results for a 20×80 km 224 Gb/s PM-16QAM transmission system:



Number of CMs per sample:

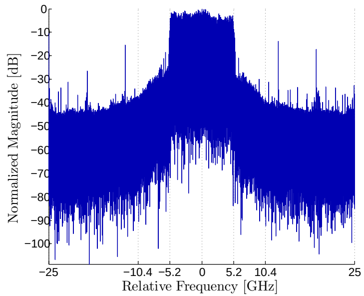
N_k	symVSNE		simVSNE	
	$N = 32$	$N = 128$	$N = 32$	$N = 128$
1	6	6	6	6
2	134.9	519	17.6	17.9
3	247.6	1015.2	28.9	29.7
4	346.3	1495.8	39.7	41.4

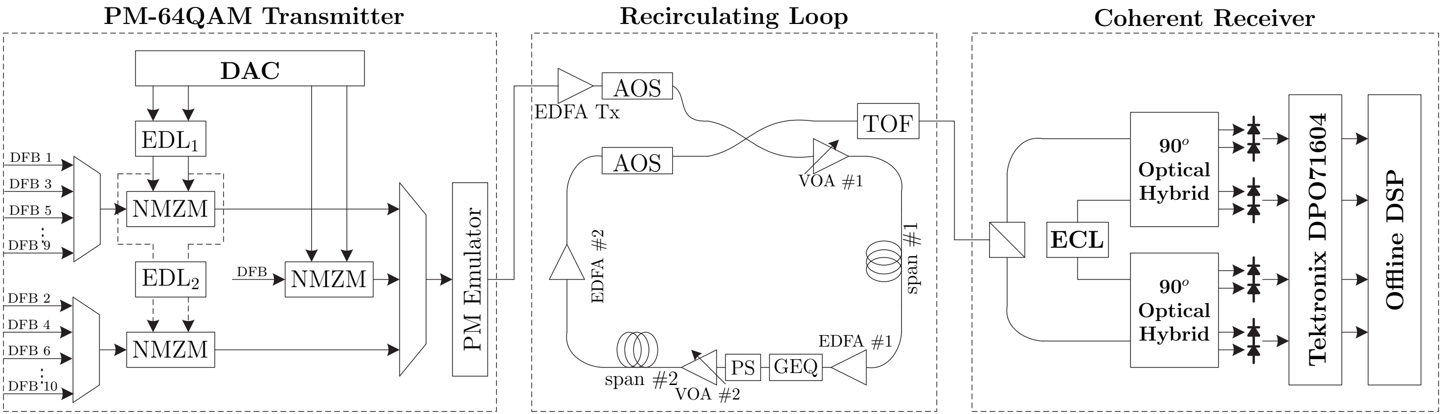
- The simVSNE error is negligible for low-dispersion fibers;
- With large β_2 the iXPM-like regions in the VSNE kernel tend to become **narrower**;
- Still, **for small** N_k, the constant-coefficient assumption remains valid!

F. P. Guiomar et al, ``**Simplified Volterra Series Nonlinear Equalizer by Intra-Channel Cross-Phase Modulation Oriented Pruning**'', *in Proc. ECOC*, paper We.3.C.6, London, 2013.

OPTCOM

- **100G PM-64QAM transmission system** implemented in collaboration **Politecnico di Torino** and **Istituto Superiore Mario Boella**, Italy:
  - **124.8 Gb/s PM-64QAM** signal;
  - Recirculating loop composed of 2×54.44 km of PSCF (150 μm^2);
  - **10 WDM channels** spaced by 50 GHz;
  - Digital Nyquist pulse shaping.

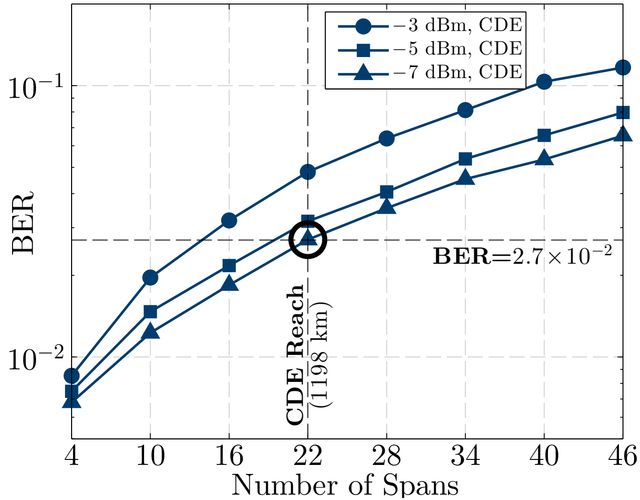


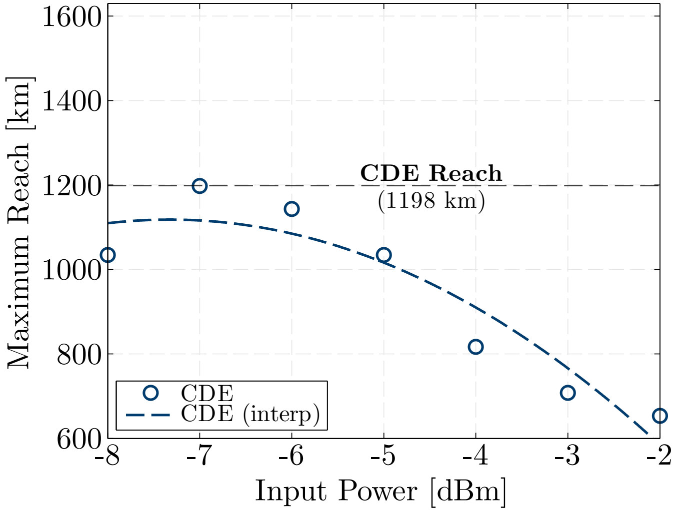


A. Nespola *et al*, **"1306-km 20x124.8-Gb/s PM-64QAM Transmission over PSCF with Net SEDP 11,300 (b.km)/s/Hz using 1.15 samp/symb DAC"**, Opt. Express, vol.22, no.2, 2014.

simVSNE - Experimental Demonstration

- BER performance of 124.8 Gb/s PM-64QAM after linear and nonlinear equalization:

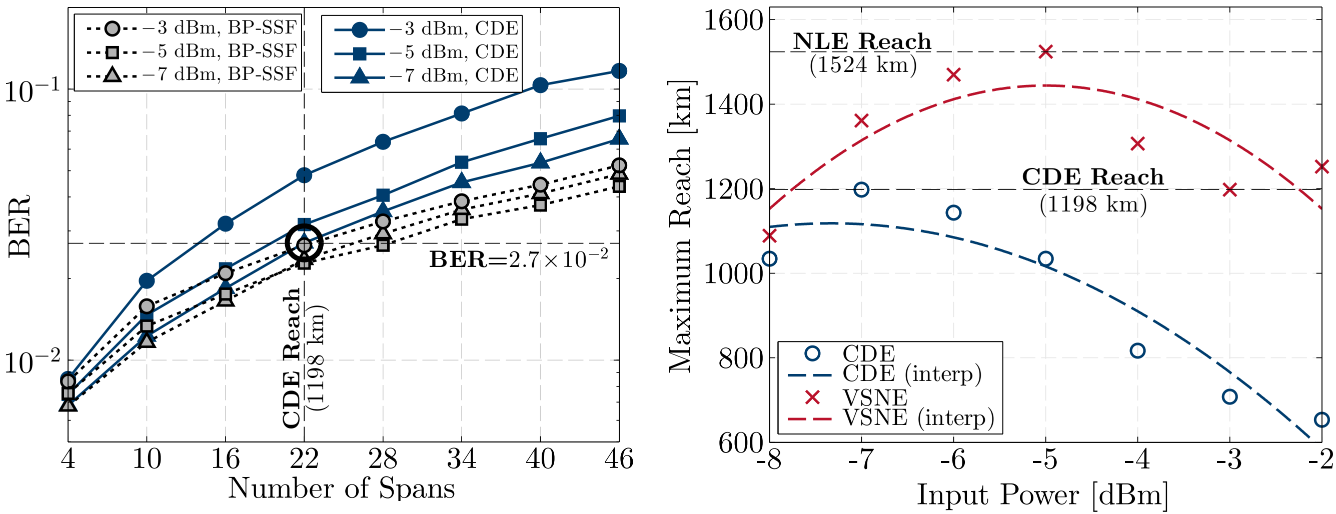




F. P. Guiomar et al, ``**Transmission of PM-64QAM over 1524 km of PSCF using Fully-Blind Equalization and Volterra-Based Nonlinear Mitigation**'', *in Proc. ECOC*, paper We.3.3.3, Cannes, September, 2014.

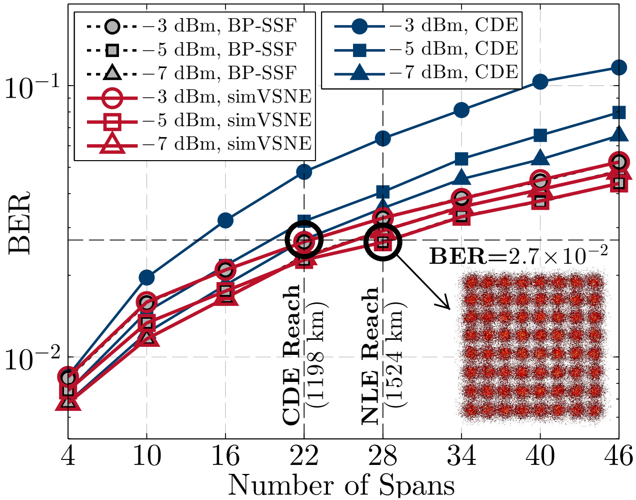
simVSNE - Experimental Demonstration

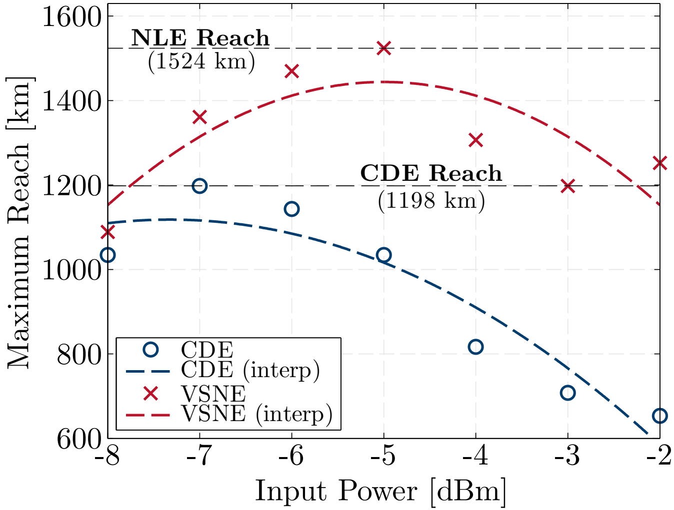
- BER performance of 124.8 Gb/s PM-64QAM after linear and nonlinear equalization:



F. P. Guiomar et al, ``**Transmission of PM-64QAM over 1524 km of PSCF using Fully-Blind Equalization and Volterra-Based Nonlinear Mitigation**'', *in Proc. ECOC*, paper We.3.3.3, Cannes, September, 2014.

- BER performance of 124.8 Gb/s PM-64QAM after linear and nonlinear equalization:





- The simVSNE is able to match the BP-SSF maximum performance (1 span per step);
- Maximum reach is increased from **1198 km** to **1524 km** (**27% increase**);
- Optimum power in increased from **-7 dBm** to **-5 dBm** (**2 dB increase in nonlinear tolerance**).

F. P. Guiomar et al, ``**Transmission of PM-64QAM over 1524 km of PSCF using Fully-Blind Equalization and Volterra-Based Nonlinear Mitigation**'', *in Proc. ECOC*, paper We.3.3.3, Cannes, September, 2014.

simVSNE - Computational Effort

- Computational effort comparison between BP-SSF, symVSNE and simVSNE:

N_{steps}	N	**SSF**	symVSNE		simVSNE	
		N_{CMs}	N_k	N_{CMs}	N_k	N_{CMs}
28	64	523	4	6113	4	772
14	**64**	**266**	4	3063	4	392
7	64	--	5	1794	5	238
4	128	--	8	3316	8	213
3	128	--	9	2709	--	--
2	256	--	15	6164	--	--
1	256	--	19	3658	--	--

- The SSF method requires a minimum of **14 steps**, yielding **266 CMs**;

F. P. Guiomar et al, ``**Fully-Blind Linear and Nonlinear Equalization for 100 G PM-64QAM Optical Systems**'', *IEEE/OSA JLT*, vol. 33, no. 7, pp. 1265--1274, 2015. (**invited paper**)

simVSNE - Computational Effort

- Computational effort comparison between BP-SSF, symVSNE and simVSNE:

N_{steps}	N	SSF	symVSNE		simVSNE	
		N_{CMs}	N_k	N_{CMs}	N_k	N_{CMs}
28	64	523	4	6113	4	772
14	**64**	**266**	4	3063	4	392
7	64	--	5	1794	5	238
4	128	--	8	3316	8	213
3	128	--	9	2709	--	--
2	256	--	15	6164	--	--
1	**256**	--	**19**	**3658**	--	--

  - The SSF method requires a minimum of **14 steps**, yielding **266 CMs**;
  - The symVSNE can be applied with only **1 step**, but incurs higher complexity;

F. P. Guiomar et al, ``**Fully-Blind Linear and Nonlinear Equalization for 100 G PM-64QAM Optical Systems**'', *IEEE/OSA JLT*, vol. 33, no. 7, pp. 1265--1274, 2015. (**invited paper**)

simVSNE - Computational Effort

- Computational effort comparison between BP-SSF, symVSNE and simVSNE:

N_{steps}	N	**SSF**	**symVSNE**		**simVSNE**	
		N_{CMs}	N_k	N_{CMs}	N_k	N_{CMs}
28	64	523	4	6113	4	772
14	**64**	**266**	4	3063	4	392
7	64	--	5	1794	5	238
4	**128**	--	8	3316	**8**	**213**
3	128	--	9	2709	--	--
2	256	--	15	6164	--	--
1	256	--	19	3658	--	--

- The SSF method requires a minimum of **14 steps**, yielding **266 CMs**;
- The symVSNE can be applied with only **1 step**, but incurs higher complexity;
- The simVSNE provides an optimized balance between latency and complexity:
  - ∗ **4 steps** and **213 CMs**.

F. P. Guiomar et al, ``**Fully-Blind Linear and Nonlinear Equalization for 100 G PM-64QAM Optical Systems**'', *IEEE/OSA JLT*, vol. 33, no. 7, pp. 1265--1274, 2015. (**invited paper**)

OPTCOM

Time Domain VSNE

5.1) Analytical Description

Time Domain VSNE - Analytical Formulation

- **Frequency-domain iXPM filter** - **simVSNE**$[0]$:

$$\tilde{A}^{\mathrm{iXPM}}_{x/y}(\omega_n) = \kappa\left[\tilde{A}^{\mathrm{CD}}_{x/y}(\omega_n)\left(2\sum_{k=1}^{N}|\tilde{A}_{x/y}(\omega_k)|^2 + \sum_{k=1}^{N}|\tilde{A}_{y/x}(\omega_k)|^2 - \tilde{\chi}(\omega_n)\right) + \tilde{A}^{\mathrm{CD}}_{y/x}(\omega_n)\sum_{k=1}^{N}\tilde{A}_{x/y}(\omega_k)\tilde{A}^{*}_{y/x}(\omega_k)\right],$$

F. P. Guiomar, S. B. Amado, C. S. Martins and A. N. Pinto, ``**Time Domain Volterra-Based Digital Backpropagation for Coherent Optical Systems**'', IEEE/OSA Journal of Lightwave Technology, vol. 33, no. 15, pp. 1265--1274, 2015.

Time Domain VSNE - Analytical Formulation

- **Frequency-domain iXPM filter** - **simVSNE**$[0]$:

$$\tilde{A}^{\text{iXPM}}_{x/y}(\omega_n) = \kappa \left[\tilde{A}^{\text{CD}}_{x/y}(\omega_n) \left(2 \sum_{k=1}^{N} |\tilde{A}_{x/y}(\omega_k)|^2 + \sum_{k=1}^{N} |\tilde{A}_{y/x}(\omega_k)|^2 - \tilde{\chi}(\omega_n) \right) + \tilde{A}^{\text{CD}}_{y/x}(\omega_n) \sum_{k=1}^{N} \tilde{A}_{x/y}(\omega_k) \tilde{A}^{*}_{y/x}(\omega_k) \right],$$

- Applying an inverse Fourier transform, we obtain a **time-domain equivalent**:

$$A^{\text{iXPM}}_{x/y}(t_n) = \kappa \left[A^{\text{CD}}_{x/y}(t_n) \left(2P_{x/y}(t_n) + P_{y/x}(t_n) \right) + A^{\text{CD}}_{y/x}(t_n) P_{xy/yx}(t_n) - \chi_{x/y}(t_n) \right],$$

$$P_{x/y}(t_n) = \frac{1}{N_{\text{NLE}}} \sum_{k \in \text{K}} \left| A_{x/y}(t_k) \right|^2, \qquad P_{xy}(t_n) = \frac{1}{N_{\text{NLE}}} \sum_{k \in \text{K}} A_x(t_k) A^{*}_y(t_k), \qquad P_{yx}(t_n) = P^{*}_{xy}(t_n),$$

F. P. Guiomar, S. B. Amado, C. S. Martins and A. N. Pinto, ``**Time Domain Volterra-Based Digital Backpropagation for Coherent Optical Systems**'', IEEE/OSA Journal of Lightwave Technology, vol. 33, no. 15, pp. 1265--1274, 2015.

Time Domain VSNE - Analytical Formulation

- **Frequency-domain iXPM filter** - **simVSNE**$[0]$:

$$\tilde{A}^{\mathrm{iXPM}}_{x/y}(\omega_n) = \kappa \left[\tilde{A}^{\mathrm{CD}}_{x/y}(\omega_n) \left(2 \sum_{k=1}^{N} |\tilde{A}_{x/y}(\omega_k)|^2 + \sum_{k=1}^{N} |\tilde{A}_{y/x}(\omega_k)|^2 - \tilde{\chi}(\omega_n) \right) + \tilde{A}^{\mathrm{CD}}_{y/x}(\omega_n) \sum_{k=1}^{N} \tilde{A}_{x/y}(\omega_k) \tilde{A}^{*}_{y/x}(\omega_k) \right],$$

- Applying an inverse Fourier transform, we obtain a **time-domain equivalent**:

$$A^{\mathrm{iXPM}}_{x/y}(t_n) = \kappa \left[A^{\mathrm{CD}}_{x/y}(t_n) \left(2P_{x/y}(t_n) + P_{y/x}(t_n) \right) + A^{\mathrm{CD}}_{y/x}(t_n) P_{xy/yx}(t_n) - \chi_{x/y}(t_n) \right],$$

$$P_{x/y}(t_n) = \frac{1}{N_{\mathrm{NLE}}} \sum_{k \in \mathrm{K}} \left| A_{x/y}(t_k) \right|^2, \qquad P_{xy}(t_n) = \frac{1}{N_{\mathrm{NLE}}} \sum_{k \in \mathrm{K}} A_x(t_k) A_y^{*}(t_k), \qquad P_{yx}(t_n) = P^{*}_{xy}(t_n),$$

  - where the summation (weighting) interval, K, is of **adjustable width**, N_{NLE},

$$\mathrm{K} = \left\{ k : \; n - \left\lceil \frac{N_{\mathrm{NLE}}}{2} \right\rceil + 1 \leq k \leq n + \left\lfloor \frac{N_{\mathrm{NLE}}}{2} \right\rfloor \right\}$$

F. P. Guiomar, S. B. Amado, C. S. Martins and A. N. Pinto, ``**Time Domain Volterra-Based Digital Backpropagation for Coherent Optical Systems**'', IEEE/OSA Journal of Lightwave Technology, vol. 33, no. 15, pp. 1265--1274, 2015.

OPTCOM

Time Domain VSNE - Analytical Formulation

- **Frequency-domain iXPM filter** - **simVSNE**$[0]$:

$$\tilde{A}^{\mathrm{iXPM}}_{x/y}(\omega_n) = \kappa \left[\tilde{A}^{\mathrm{CD}}_{x/y}(\omega_n) \left(2 \sum_{k=1}^{N} |\tilde{A}_{x/y}(\omega_k)|^2 + \sum_{k=1}^{N} |\tilde{A}_{y/x}(\omega_k)|^2 - \tilde{\chi}(\omega_n) \right) + \tilde{A}^{\mathrm{CD}}_{y/x}(\omega_n) \sum_{k=1}^{N} \tilde{A}_{x/y}(\omega_k) \tilde{A}^{*}_{y/x}(\omega_k) \right],$$

- Applying an inverse Fourier transform, we obtain a **time-domain equivalent**:

$$A^{\mathrm{iXPM}}_{x/y}(t_n) = \kappa \left[A^{\mathrm{CD}}_{x/y}(t_n) \left(2P_{x/y}(t_n) + P_{y/x}(t_n) \right) + A^{\mathrm{CD}}_{y/x}(t_n) P_{xy/yx}(t_n) - \chi_{x/y}(t_n) \right],$$

$$P_{x/y}(t_n) = \frac{1}{N_{\mathrm{NLE}}} \sum_{k \in \mathrm{K}} \left| A_{x/y}(t_k) \right|^2, \qquad P_{xy}(t_n) = \frac{1}{N_{\mathrm{NLE}}} \sum_{k \in \mathrm{K}} A_x(t_k) A^{*}_y(t_k), \qquad P_{yx}(t_n) = P^{*}_{xy}(t_n),$$

  - where the summation (weighting) interval, K, is of **adjustable width**, N_{NLE},

$$\mathrm{K} = \left\{ k : \; n - \left\lceil \frac{N_{\mathrm{NLE}}}{2} \right\rceil + 1 \leq k \leq n + \left\lfloor \frac{N_{\mathrm{NLE}}}{2} \right\rfloor \right\}$$

- An identical procedure can be done for the remaining simVSNE$\{K\}$ filters, yielding the **weighted VSNE (W-VSNE) filter array**.

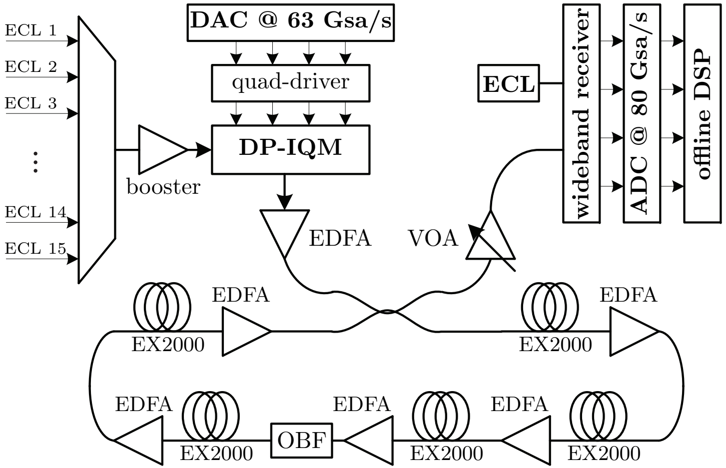
F. P. Guiomar, S. B. Amado, C. S. Martins and A. N. Pinto, ``**Time Domain Volterra-Based Digital Backpropagation for Coherent Optical Systems**'', IEEE/OSA Journal of Lightwave Technology, vol. 33, no. 15, pp. 1265--1274, 2015.

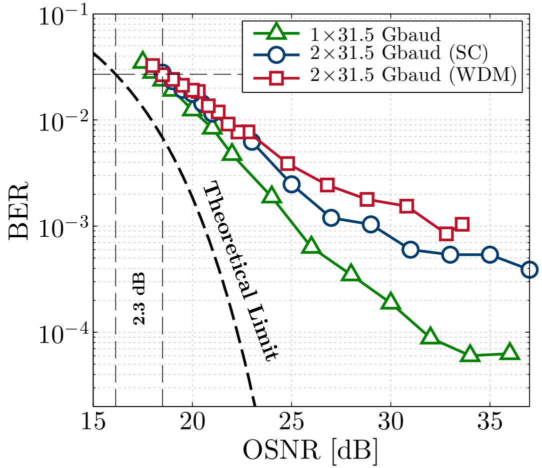
Time Domain VSNE

5.2) Experimental Results

Weighted VSNE - Laboratorial Setup

- Laboratorial setup of a **ultra-long-haul 400G PM-16QAM transmission system** implemented in collaborations CPqD, Campinas, Brazil:



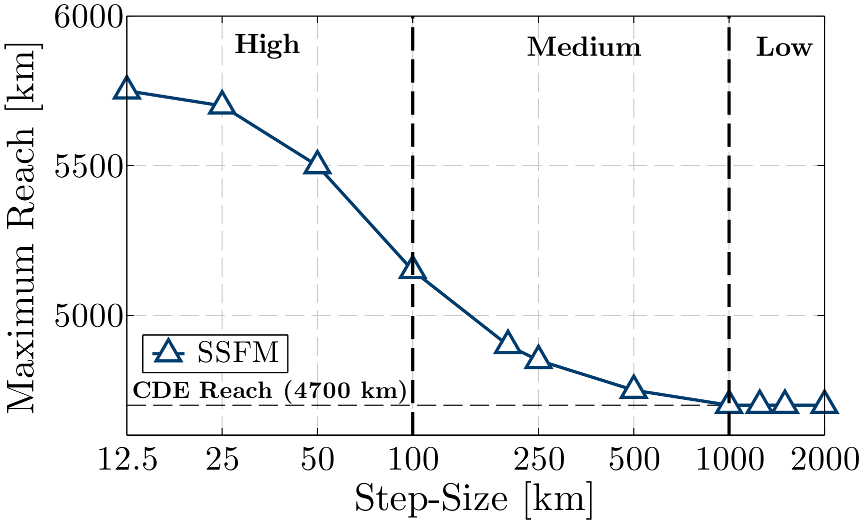


- **2×32 Gbaud PM-16QAM** signal;
- Propagation over a recirculating loop composed of **5×ULA (112 μm^2) spans** with 50 km each;
- **5 WDM superchannels** spaced by **75 GHz**;
- Digital Nyquist pulse shaping.

S. B. Amado, F. P. Guiomar, et al, ``**Experimental Demonstration of the Parallel Split-Step Method in Ultra-Long-Haul 400G Transmission**,'' *in Proc. ECOC*, paper Th.2.6.2, Valencia, October, 2015.

Weighted VSNE - Experimental Results

- Estimated maximum reach as a function of the DBP step-size:

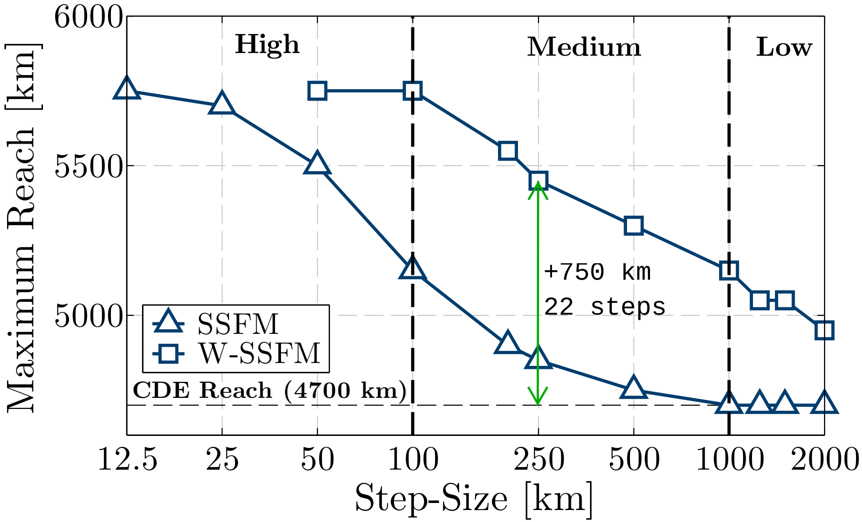


  - The standard SSFM is **not adequate** for low-complexity DBP.

S. B. Amado, F. P. Guiomar, et al, ``**Low Complexity Advanced DBP Techniques for Ultra-Long-Haul 400G Transmission Systems**,'' submitted to IEEE/OSA JLT, 2015. (**invited paper**)

Weighted VSNE - Experimental Results

- Estimated maximum reach as a function of the DBP step-size:

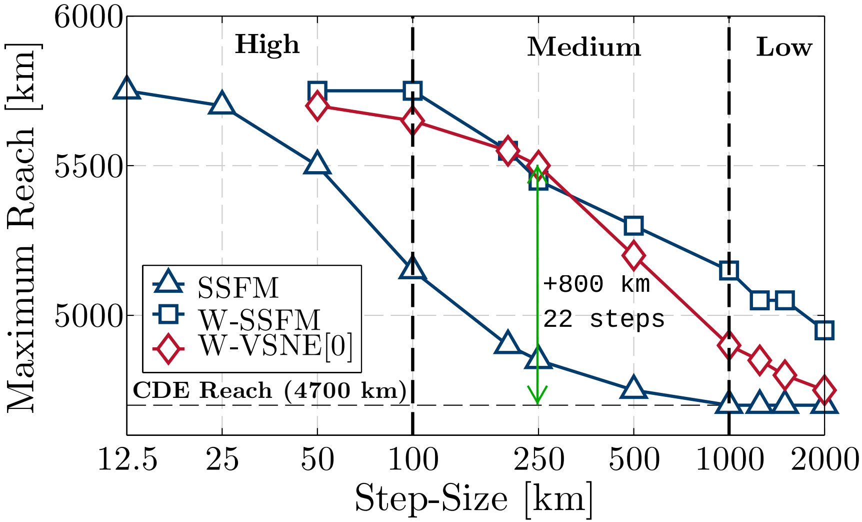


  - The standard SSFM is **not adequate** for low-complexity DBP.
  - The W-SSFM shows a significantly increased tolerance to large step-sizes;

S. B. Amado, F. P. Guiomar, et al, ``**Low Complexity Advanced DBP Techniques for Ultra-Long-Haul 400G Transmission Systems**,'' submitted to IEEE/OSA JLT, 2015. (**invited paper**)

Weighted VSNE - Experimental Results

- Estimated maximum reach as a function of the DBP step-size:

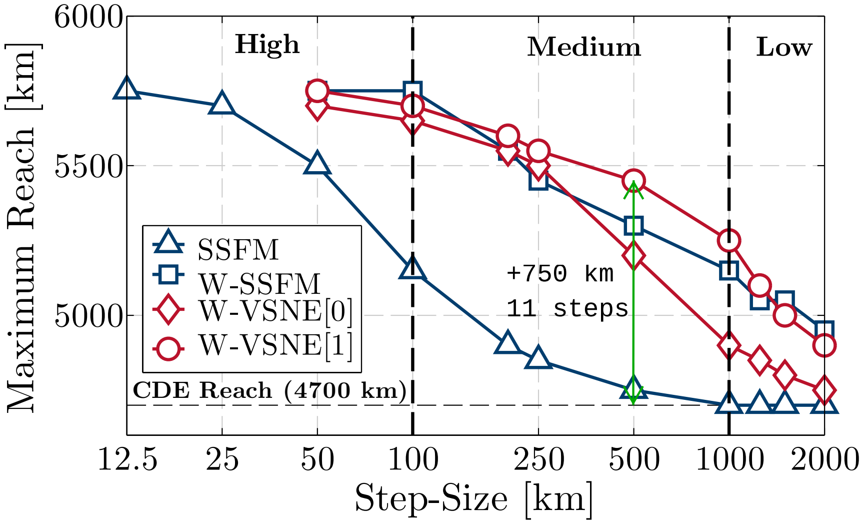


  - The standard SSFM is **not adequate** for low-complexity DBP.
  - The W-SSFM shows a significantly increased tolerance to large step-sizes;

S. B. Amado, F. P. Guiomar, et al, ``**Low Complexity Advanced DBP Techniques for Ultra-Long-Haul 400G Transmission Systems**,'' submitted to IEEE/OSA JLT, 2015. (**invited paper**)

Weighted VSNE - Experimental Results

- Estimated maximum reach as a function of the DBP step-size:

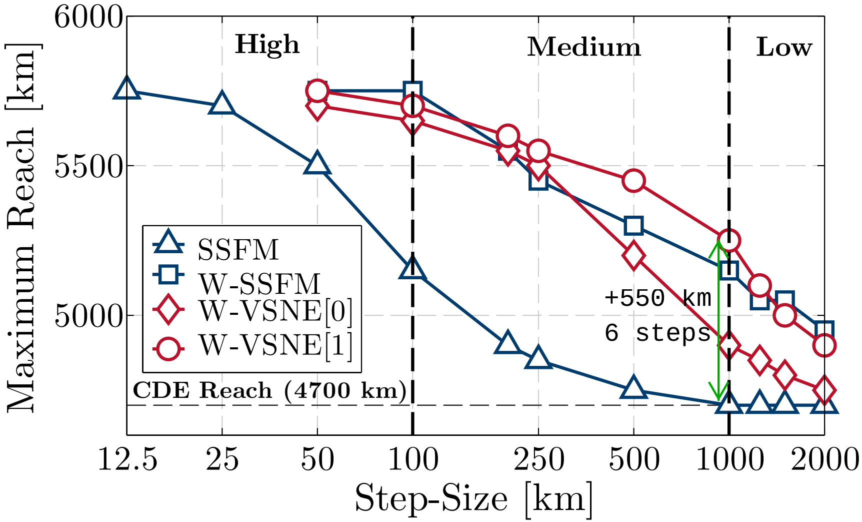


  - The standard SSFM is **not adequate** for low-complexity DBP.
  - The W-SSFM shows a significantly increased tolerance to large step-sizes;
  - The W-VSNE[1] outperforms the W-SSFM in the medium performance region;

S. B. Amado, F. P. Guiomar, et al, ``**Low Complexity Advanced DBP Techniques for Ultra-Long-Haul 400G Transmission Systems**,'' submitted to IEEE/OSA JLT, 2015. (**invited paper**)

Weighted VSNE - Experimental Results

- Estimated maximum reach as a function of the DBP step-size:



  - The standard SSFM is **not adequate** for low-complexity DBP.
  - The W-SSFM shows a significantly increased tolerance to large step-sizes;
  - The W-VSNE[1] outperforms the W-SSFM in the medium performance region;
  - Even with a step-size of 1000 km (**6 steps in total**) the W-VSNE[1] enables to extended the signal reach by **550 km**.

S. B. Amado, F. P. Guiomar, et al, ``**Low Complexity Advanced DBP Techniques for Ultra-Long-Haul 400G Transmission Systems**,'' submitted to IEEE/OSA JLT, 2015. (**invited paper**)

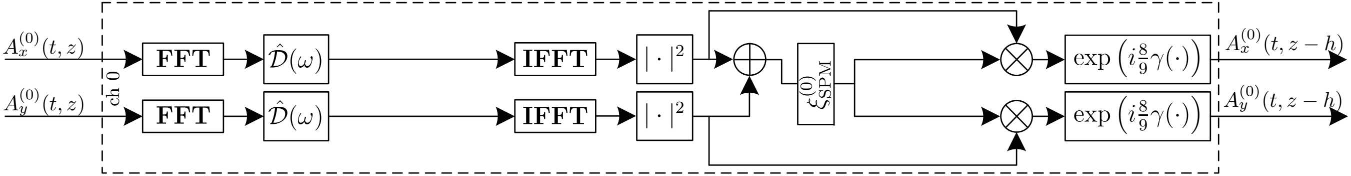
OPTCOM

Multi-Carrier Digital Backpropagation

6.1) Numerical Implementation

Coupled Equations DBP - Numerical Implementation

- Numerical implementation of the CE-DBP approach using the asymmetric SSFM:

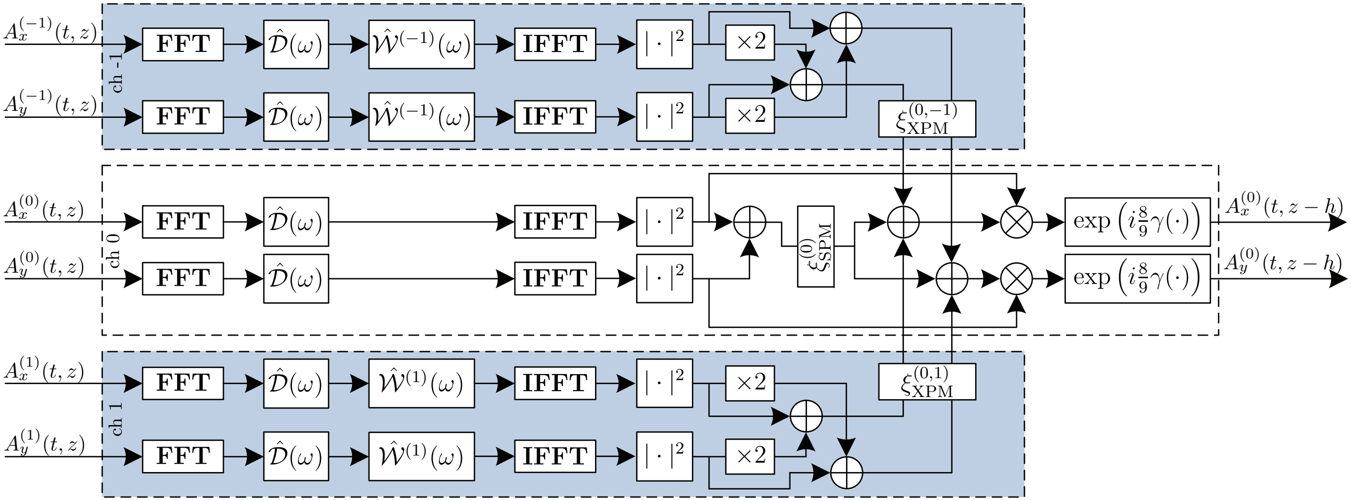


- **SPM** is compensated by the standard SSFM over each subcarrier;

F. P. Guiomar et al, ``**Multi-Carrier Digital Backpropagation for 400G Optical Superchannels**,'' to be submitted to IEEE/OSA JLT, 2015. (**invited paper**)

Coupled Equations DBP - Numerical Implementation

- Numerical implementation of the CE-DBP approach using the asymmetric SSFM:

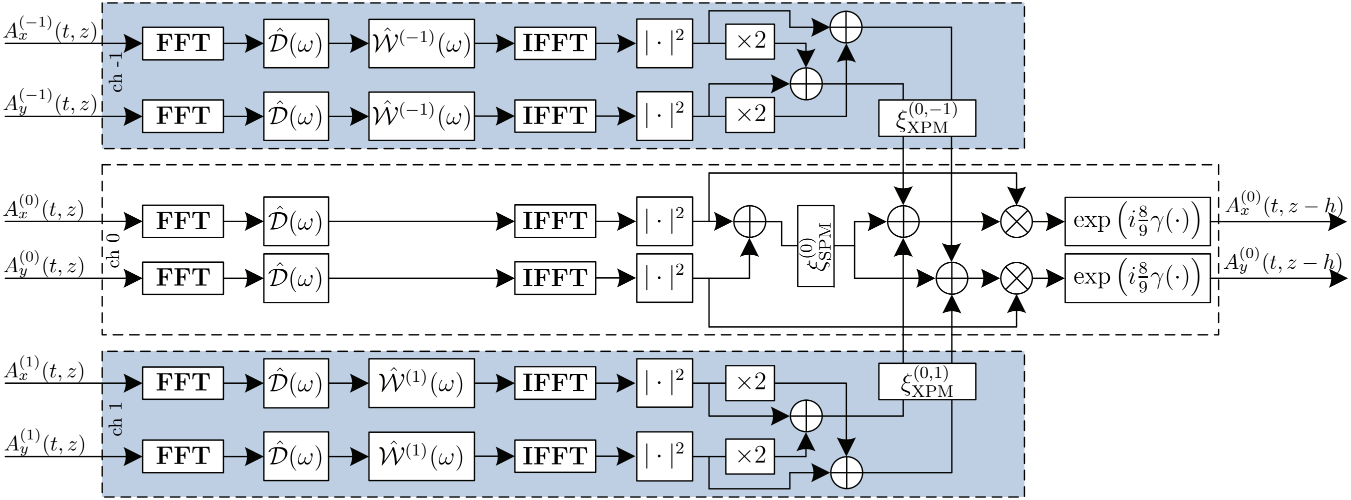


- **SPM** is compensated by the standard SSFM over each subcarrier;
- **XPM** is compensated by introducing **coupling terms** in the nonlinear step;
  - ∗ A new operator, $\hat{\mathcal{W}}^{(m)}(\omega)$, is responsible for the **walk-off effect** between subcarriers.

F. P. Guiomar et al, ``**Multi-Carrier Digital Backpropagation for 400G Optical Superchannels**,'' to be submitted to IEEE/OSA JLT, 2015. (**invited paper**)

Coupled Equations DBP - Numerical Implementation

- Numerical implementation of the CE-DBP approach using the asymmetric SSFM:



- **SPM** is compensated by the standard SSFM over each subcarrier;
- **XPM** is compensated by introducing **coupling terms** in the nonlinear step;
  - ∗ A new operator, $\hat{\mathcal{W}}^{(m)}(\omega)$, is responsible for the **walk-off effect** between subcarriers.
- Complexity is **similar** to that of intra-channel compensation of each subcarrier.

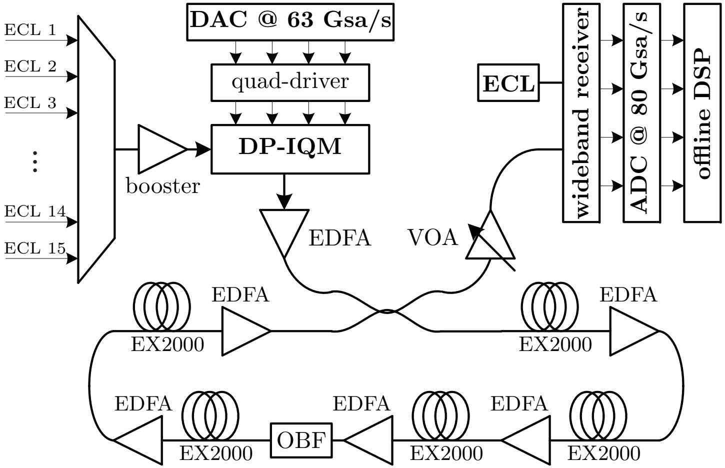
F. P. Guiomar et al, ``**Multi-Carrier Digital Backpropagation for 400G Optical Superchannels**,'' to be submitted to IEEE/OSA JLT, 2015. (**invited paper**)

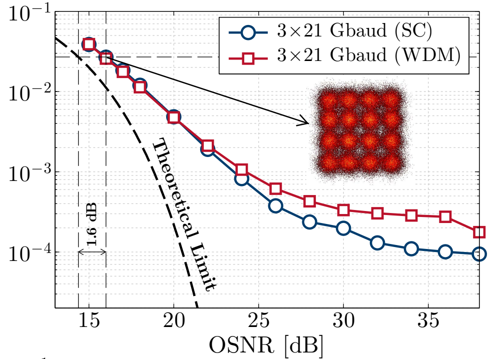
Multi-Carrier Digital Backpropagation

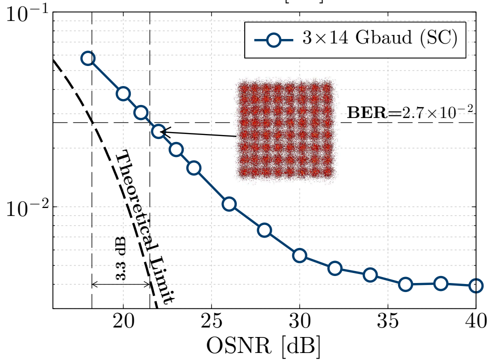
6.2) Experimental Results

Multi-Carrier DBP - Laboratorial Setup

- Laboratorial setup for **metro** and **ultra-long-haul** 400G PM-16QAM transmission system implemented in collaborations CPqD, Campinas, Brazil:





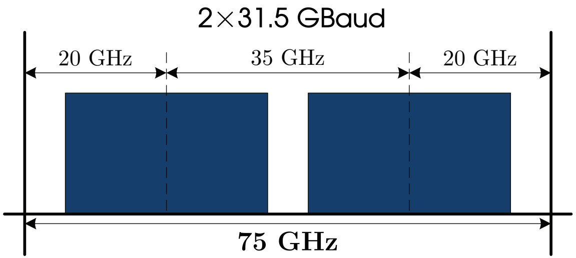


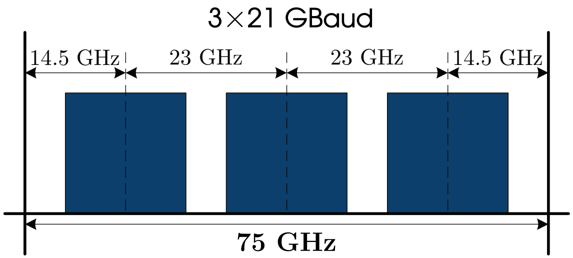
- ULH - 2×32 Gbaud and 3×21 Gbaud **PM-16QAM** signal;
  - ∗ 5 WDM superchannels in a 75 GHz slot - 5.33 b/s/Hz;
- Metro - 3×14 Gbaud **PM-64QAM** signal;
  - ∗ 1 superchannel in a 50 GHz slot - 8 b/s/Hz;

F. P. Guiomar, et al, "**Ultra-Long-Haul 400G Superchannel Transmission with Multi-Carrier Nonlinear Equalization**," *in Proc. ECOC*, paper Th.2.2.4, Valencia, September, 2015.

400G Superchannel Configurations

- Superchannel configurations for PM-16QAM:



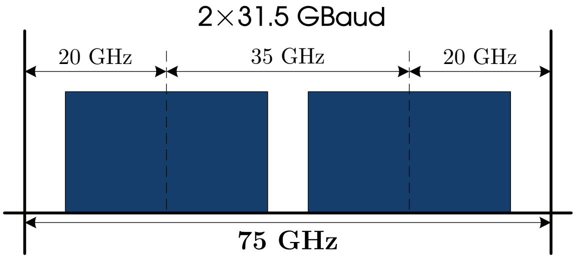


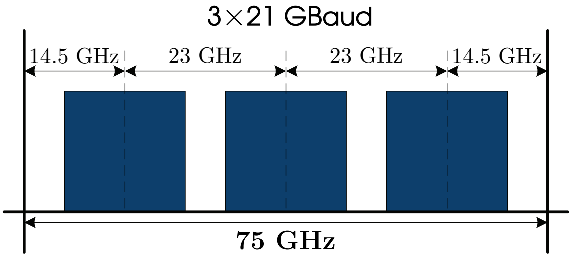
  - Net spectral efficiency of 5.33 b/s/Hz;
  - Designed for **long-haul and ultra-long-haul applications**.

F. P. Guiomar et al, ``**Multi-Carrier Digital Backpropagation for 400G Optical Superchannels**,'' to be submitted to IEEE/OSA JLT, 2015. (**invited paper**)

400G Superchannel Configurations

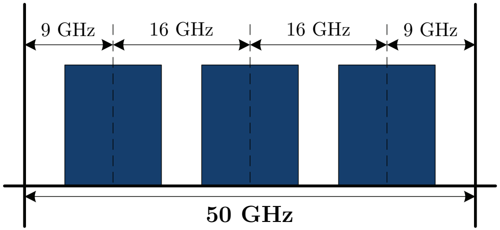
- Superchannel configurations for PM-16QAM:





  - Net spectral efficiency of 5.33 b/s/Hz;
  - Designed for **long-haul and ultra-long-haul applications**.

- Superchannel configuration for PM-64QAM - 3 × 14 GBaud:

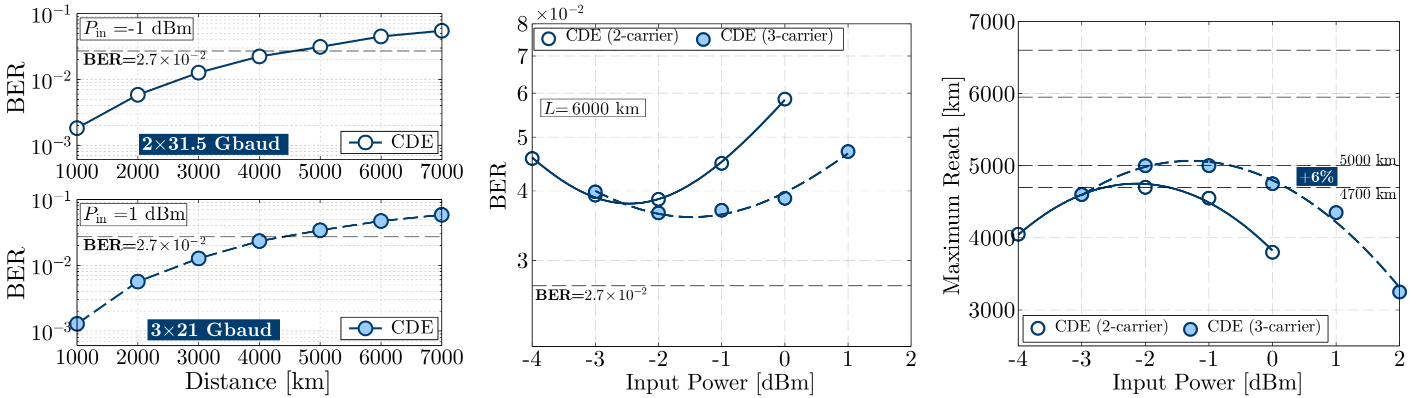


  - Net spectral efficiency of **8 b/s/Hz**;
  - Designed for **metro and long-haul applications** with high spectral efficiency.

F. P. Guiomar et al, ``**Multi-Carrier Digital Backpropagation for 400G Optical Superchannels**,'' to be submitted to IEEE/OSA JLT, 2015. (**invited paper**)

DBP Impact on ULH 400G Performance

- Ultra-long-haul 400G propagation performance:

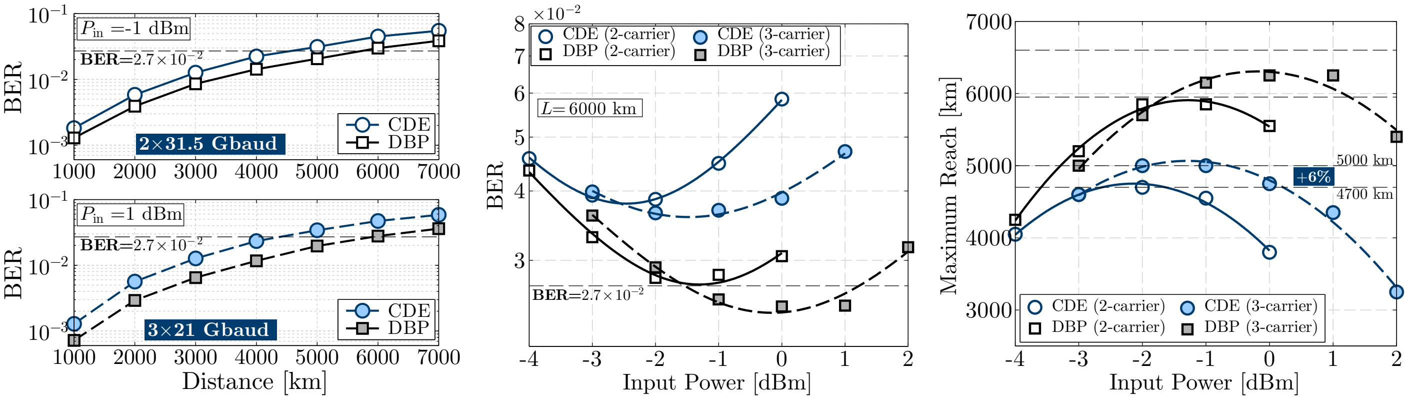


- **after CDE**, triple-carrier 400G provides an increased reach of approximately **6%**;
  - good agreement with previous works based on simulation and EGN model predictions;

F. P. Guiomar, et al, ``**Ultra-Long-Haul 400G Superchannel Transmission with Multi-Carrier Nonlinear Equalization,**'' *in Proc. ECOC*, paper Th.2.2.4, Valencia, September, 2015.

DBP Impact on ULH 400G Performance

- Ultra-long-haul 400G propagation performance:

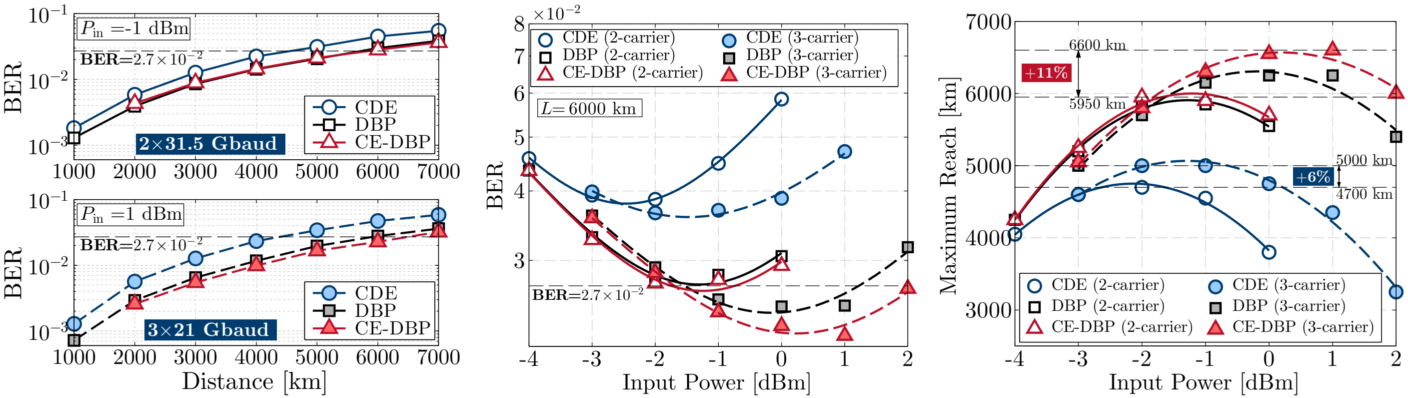


- **after CDE**, triple-carrier 400G provides an increased reach of approximately **6%**;
  - good agreement with previous works based on simulation and EGN model predictions;

F. P. Guiomar, et al, ``**Ultra-Long-Haul 400G Superchannel Transmission with Multi-Carrier Nonlinear Equalization,**'' *in Proc. ECOC*, paper Th.2.2.4, Valencia, September, 2015.

DBP Impact on ULH 400G Performance

- Ultra-long-haul 400G propagation performance:

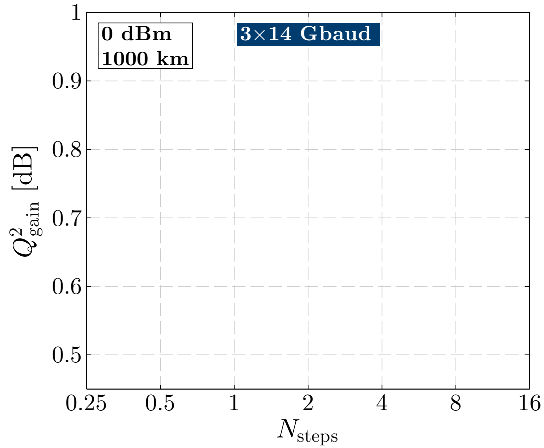


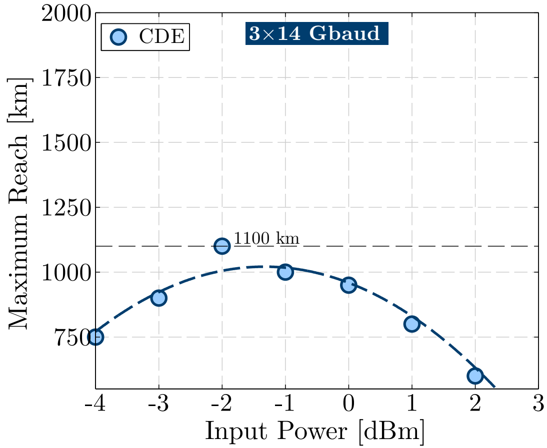
- **after CDE**, triple-carrier 400G provides an increased reach of approximately **6%**;
  - good agreement with previous works based on simulation and EGN model predictions;
- **after CE-DBP**, the reach improvement provided by the triple-carrier 400G is now of **11%**;
  - CE-DBP performance improves with increasing number of backpropagated subcarriers.
- The overall reach enhancement over CDE is of 1250 km (26%) and **1600 km (32%)** for the dual- and **triple-carrier** 400G superchannels, respectively.

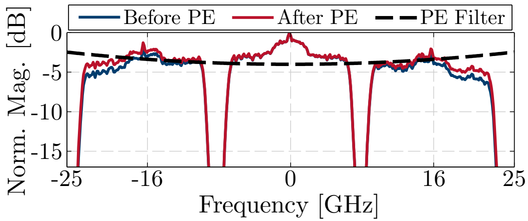
F. P. Guiomar, et al, ``**Ultra-Long-Haul 400G Superchannel Transmission with Multi-Carrier Nonlinear Equalization**,'' *in Proc. ECOC*, paper Th.2.2.4, Valencia, September, 2015.

MC-DBP: Experimental Results for PM-64QAM

- DBP optimization and performance of 400G superchannels based on PM-64QAM:





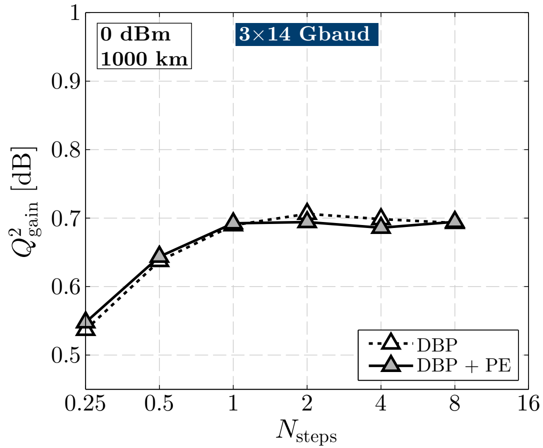


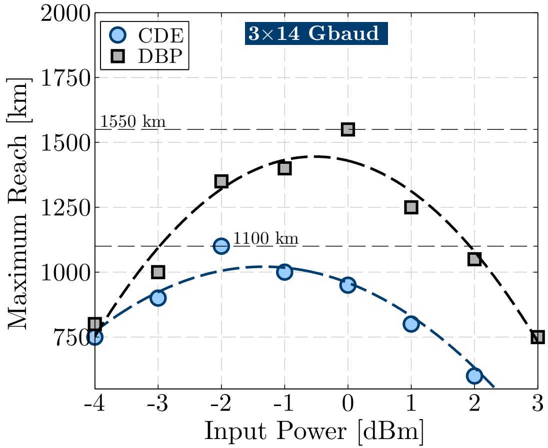
- maximum reach **after CDE** - 1100 km;

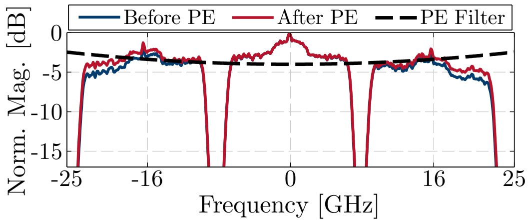
F. P. Guiomar et al, ``**Multi-Carrier Digital Backpropagation for 400G Optical Superchannels**,'' to be submitted to IEEE/OSA JLT, 2015. (**invited paper**)

MC-DBP: Experimental Results for PM-64QAM

- DBP optimization and performance of 400G superchannels based on PM-64QAM:







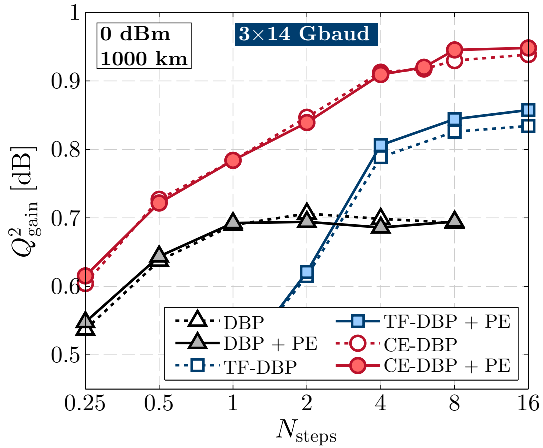
- maximum reach **after CDE** - 1100 km;
- maximum reach **after DBP** - 1550 km;

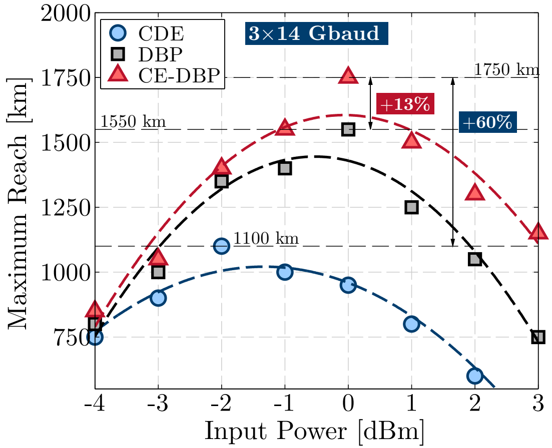
F. P. Guiomar et al, ``**Multi-Carrier Digital Backpropagation for 400G Optical Superchannels**,'' to be submitted to IEEE/OSA JLT, 2015. (**invited paper**)

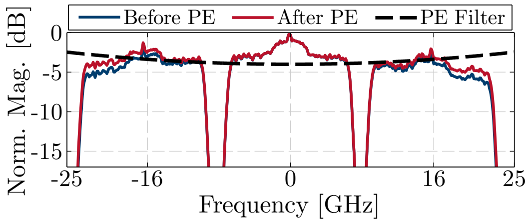
OPTCOM

MC-DBP: Experimental Results for PM-64QAM

- DBP optimization and performance of 400G superchannels based on PM-64QAM:







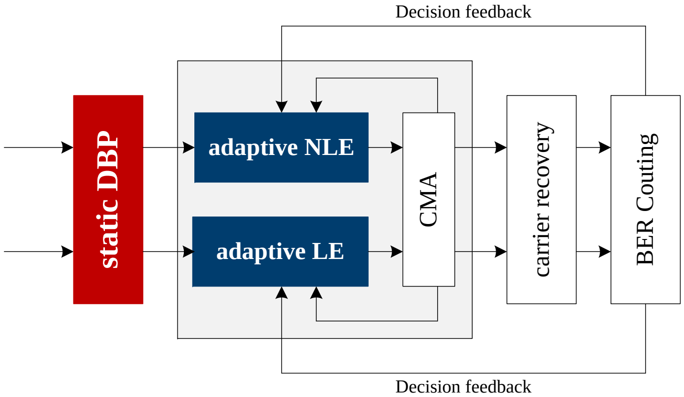
- maximum reach **after CDE** - 1100 km;
- maximum reach **after DBP** - 1550 km;
- maximum reach **after CE-DBP** - 1750 km;
  - 13% over DBP and **60% over CDE**.
- The required DBP spatial resolution is very **similar** to that found for ULH based on PM-16QAM.

F. P. Guiomar et al, ``**Multi-Carrier Digital Backpropagation for 400G Optical Superchannels**,'' to be submitted to IEEE/OSA JLT, 2015. (**invited paper**)

Open Research Topics on Nonlinear Equalization

Static + Adaptive Nonlinear Equalization

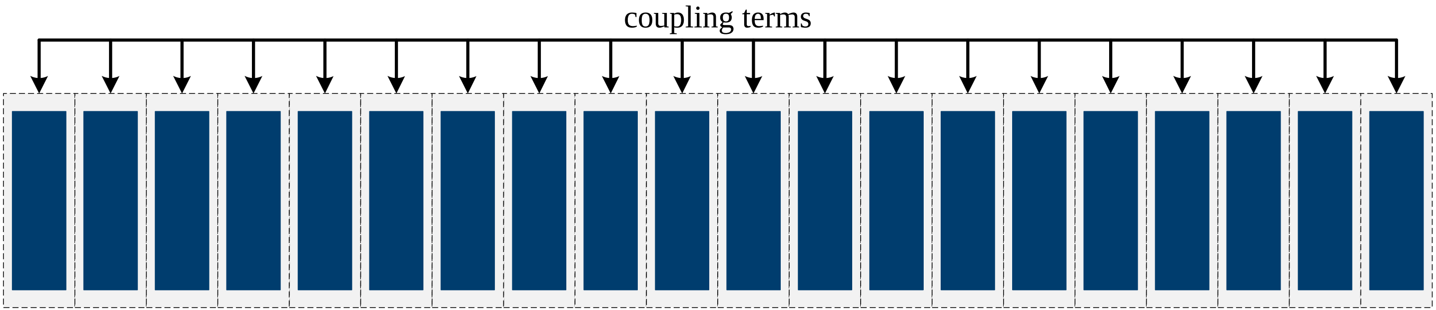
- A practical implementation of DBP requires some **adaptation capabilities**;
  - Uncertainties on the link parameters;
  - Non-homogenous power/gain profile;
  - Other temporal variations due to temperature, bending...
- Fully adaptable DBP would be **too complex** and **very difficult to converge**;
  - The same happens with linear equalization (static + adaptive);



- The bulk estimated nonlinearities can be compensated with a **static equalizer**;
- A low complexity **adaptive equalizer** (Volterra?) optimizes the initial solution.

DBP for Subcarrier Multiplexing

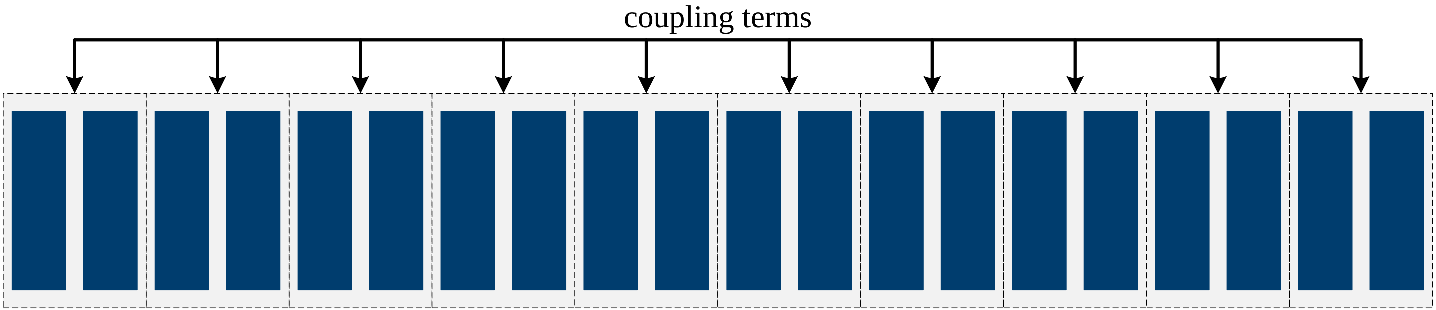
- What is the **best performance vs complexity** trade-off?
  - Low symbol-rate per subcarrier $\Rightarrow$ **reduced DBP complexity** per subcarrier;
  - Many subcarriers $\Rightarrow$ **many DBP processing chains**;
  - How to efficiently deal with FWM?



- **Too many coupled equations** may be suboptimum;
  - Too many DBP chains - lots of FFT/IFFT pairs;
  - A **fully frequency domain** approach can be beneficial (VSNE?).

DBP for Subcarrier Multiplexing

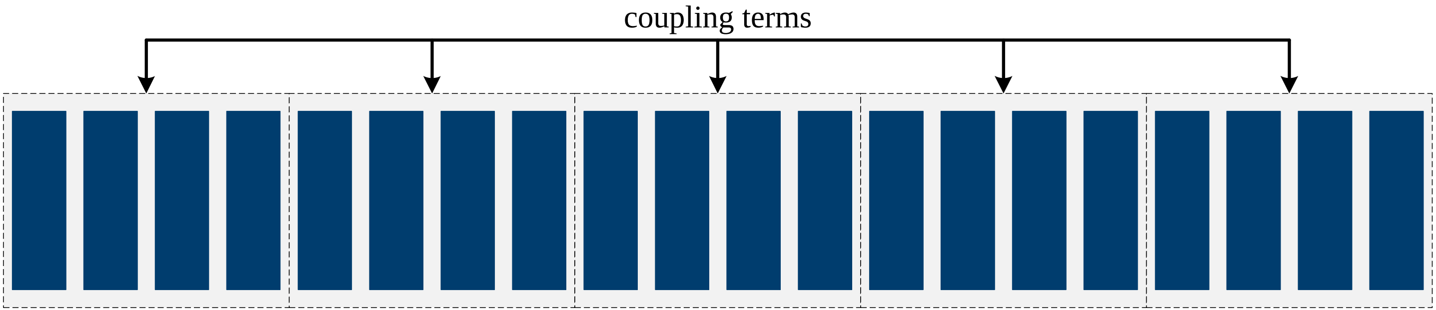
- What is the **best performance vs complexity** trade-off?
  - Low symbol-rate per subcarrier ⇒ **reduced DBP complexity** per subcarrier;
  - Many subcarriers ⇒ **many DBP processing chains**;
  - How to efficiently deal with FWM?



- **Too many coupled equations** may be suboptimum;
  - Too many DBP chains - lots of FFT/IFFT pairs;
  - A **fully frequency domain** approach can be beneficial (VSNE?).
- The most efficient solution is likely to be based on an **hybrid CE/TF-DBP approach**;
  - Tradeoff between complexity per DBP chain and number of DBP chains;

DBP for Subcarrier Multiplexing

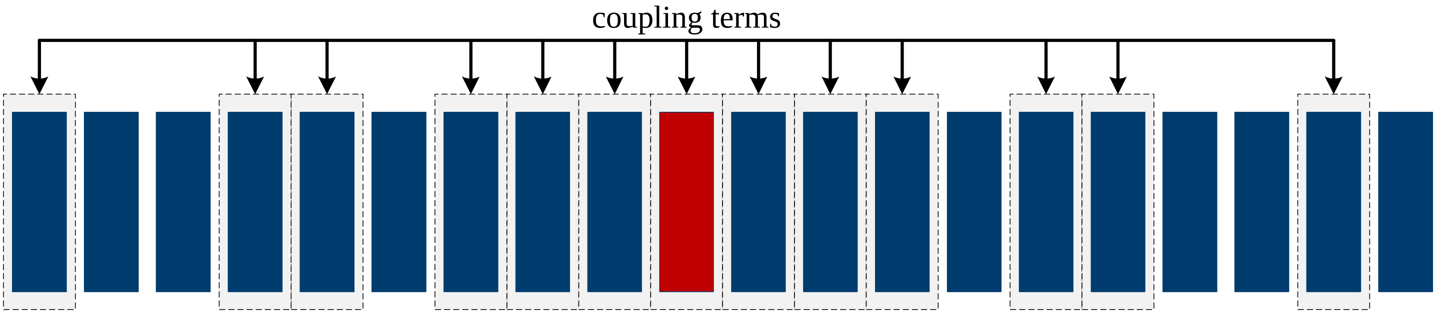
- What is the **best performance vs complexity** trade-off?
  - Low symbol-rate per subcarrier $\Rightarrow$ **reduced DBP complexity** per subcarrier;
  - Many subcarriers $\Rightarrow$ **many DBP processing chains**;
  - How to efficiently deal with FWM?



- **Too many coupled equations** may be suboptimum;
  - Too many DBP chains - lots of FFT/IFFT pairs;
  - A **fully frequency domain** approach can be beneficial (VSNE?).
- The most efficient solution is likely to be based on an **hybrid CE/TF-DBP approach**;
  - Tradeoff between complexity per DBP chain and number of DBP chains;

DBP for Subcarrier Multiplexing

- What is the **best performance vs complexity** trade-off?
  - Low symbol-rate per subcarrier ⇒ **reduced DBP complexity** per subcarrier;
  - Many subcarriers ⇒ **many DBP processing chains**;
  - How to efficiently deal with FWM?



- **Too many coupled equations** may be suboptimum;
  - Too many DBP chains - lots of FFT/IFFT pairs;
  - A **fully frequency domain** approach can be beneficial (VSNE?).
- The most efficient solution is likely to be based on an **hybrid CE/TF-DBP approach**;
  - Tradeoff between complexity per DBP chain and number of DBP chains;
- FWM will be dominant: Not all subcarriers need to be taken into account.

The FLEX-ON Project

What is Flex-ON?

- **Flexible Optical Networks** – Time Domain Hybrid QAM: DSP and Physical Layer Modelling;
- **H2020 project**: Marie Skłodowska-Curie Individual Fellowship;

  ``The Marie Skłodowska-Curie actions, named after the double Nobel Prize winning Polish-French scientist famed for her work on radioactivity, support researchers at all stages of their careers, irrespective of nationality. Researchers working across all disciplines, from life-saving healthcare to 'blue-sky' science, are eligible for funding. The MSCA also support industrial doctorates, combining academic research study with work in companies, and other innovative training that enhances employability and career development''.
- **24 months**: October 2015 - October 2017;
- Includes a secondment (3 months) with CISCO Photonics.
- Divided into 5 WPs:
  - **WP1** – Digital modulation techniques;
  - **WP2** – Simulation tools and DSP subsystems;
  - **WP3** – NL prediction and equalization tools;
  - **WP4** – Laboratorial implementation, test and validation;
  - **WP5** – Management and dissemination;

What are the Main Objectives?

- **Scientific Objectives**:
  - Optimization of **digital modulation techniques** for spectrally efficient transmission with **high bit-rate granularity**, low energy consumption and robust signal propagation;
  - Development of **efficient DSP subsystems** for flexible optical transceivers;
  - Development of **NL prediction and equalization tools**;
  - Implementation of a **laboratorial testbed** for validation purposes;
  - Provide **new skills and career opportunities** for the ER and potentiate **new collaboration opportunities for the host organisation**.

What are the Main Objectives?

- **Scientific Objectives**:
  - Optimization of **digital modulation techniques** for spectrally efficient transmission with **high bit-rate granularity**, low energy consumption and robust signal propagation;
  - Development of **efficient DSP subsystems** for flexible optical transceivers;
  - Development of **NL prediction and equalization tools**;
  - Implementation of a **laboratorial testbed** for validation purposes;
  - Provide **new skills and career opportunities** for the ER and potentiate **new collaboration opportunities for the host organisation**.
- **Dissemination and Public Engagement**:
  - Participate in the **European Researchers' Night**;
  - Organize an **MSCA seminar** to promote the Marie Skłodowska-Curie Actions among undergraduate students and early stage researchers;
  - Design a **website** with both technical and simplified materials;
  - Dissemination of optics and photonics at **high-schools**;
  - Organize an **yearly workshop** on flexible optical transceivers in POLITO;
  - Organize a **workshop at an international conference**.

Thanks for your attention!

fernando.guiomar@polito.it

OPTCOM