Joint DGD, PDL and Chromatic Dispersion Estimation in Ultra-Long-Haul WDM Transmission Experiments with Coherent Receivers

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Motivations of the work

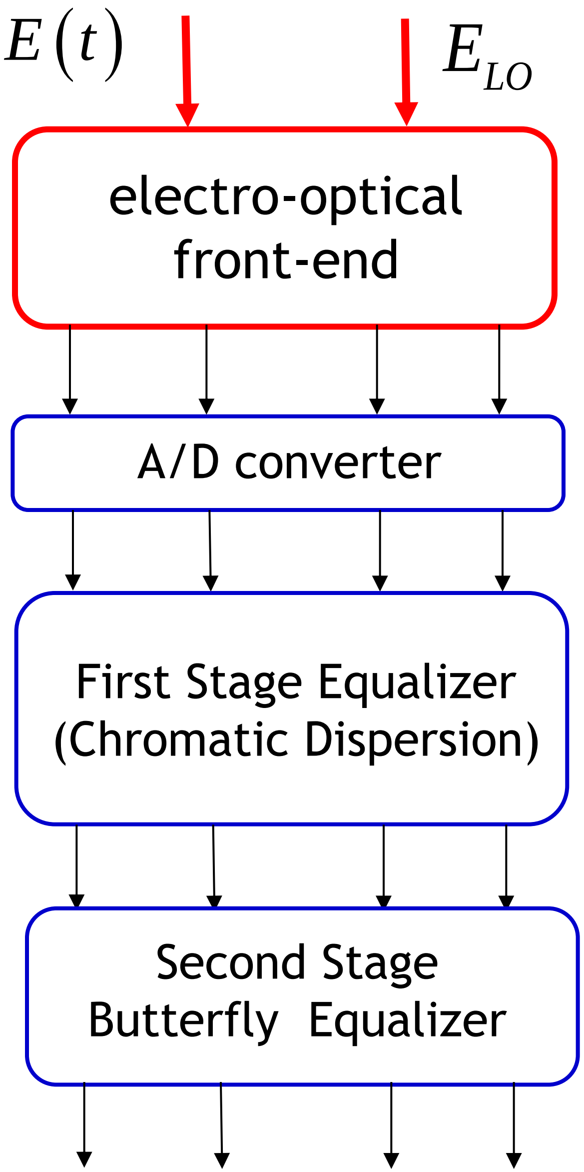
- It has recently been demonstrated by simulations and short reach experiments that the receiver equalizer filter taps can be used to estimate chromatic dispersion (CD), differential group delay (DGD) and polarization dependent losses (PDL).
  - F.N. Hauske et al., J. Lightwave Technol. **27**, 3623 (2009).
  - J.C. Geyer et al., Photon. Technol. Lett. **20**, 776 (2008).
  - S.L. Wodward et al., Photon. Technol. Lett. **27**, 2048 (2008).

- In this work we demonstrate the use of the monitoring algorithms on an **ultra-long-haul system experiment** in which thirty 120 Gbit/s PM-QPSK channels with high spectral efficiency are propagated over 82 recirculations of a loop composed of 98 km of pure silica core fiber (PSCF) with EDFA and Raman amplification.

Outline

- Theory
  - Estimation of channel parameters from the taps of the coherent receiver equalizer
- Simulations
  - Validation of the algorithms
- Experiment
  - Demonstration of the application of the technique in a challenging experimental scenario
- Conclusions

Receiver structure



2 samples per symbol

$\mathbf{W}(n)$

- The second-stage butterfly equalizer can be represented as a 2x2 matrix of complex FIR filters:

$$\mathbf{W}(n) = \begin{bmatrix} w_{xx}(n) & w_{xy}(n) \\ w_{yx}(n) & w_{yy}(n) \end{bmatrix}$$

  - The index "n" runs over the filter taps, n=1,2,… N

Frequency domain

- Digital filters have a Fourier transform which is defined as:

$$\mathbf{W}(f) = F\{\mathbf{W}(n)\} = \sum_{n=1}^{N} \begin{bmatrix} w_{xx}(n) & w_{xy}(n) \\ w_{yx}(n) & w_{yy}(n) \end{bmatrix} \cdot e^{j2\pi n f T_c}$$

where N is the number of taps and T_c is the sampling time

- When the equalizer is fully converged, the matrix **W is the inverse of the channel Jones matrix J**

$$\mathbf{W}(f) = \mathbf{J}^{-1}(f)$$

General features of W(f)

- Theory says that <u>any</u> **W**(f) can <u>always</u> be decomposed as follows:

$$\mathbf{W}(f) = H(f) \cdot e^{+j2\pi^2\beta_2 f^2}\,\mathbf{U}(f)\,\mathbf{P}(f)$$

where:

- **P** is a Hermitian matrix accounting for the inverse channel PDL
- **U** is a unitary matrix accounting for the inverse channel DGD
- the exponential scalar factor is the inverse CD
- H(f) is approximately the inverse of the electro-optical system scalar transfer function

Channel parameters extraction

- A few matrix calculations exploiting the properties of unitary and Hermitian matrices, allow to extract the channel parameters from the matrix **W** [*]

- PDL

$$\mathrm{PDL}(f) = \left|10\log_{10}\left(\lambda_1(f)/\lambda_2(f)\right)\right|$$

$\lambda_1(f)$ and $\lambda_2(f)$ eigenvalues of the matrix $\mathbf{W}^{\mathrm{T}*}(f)\cdot\mathbf{W}(f)$

- Modulus of channel transfer function

$$|H(f)| = \sqrt{\det\{\mathbf{W}(f)\}}$$

[*] J.N. Damask, *Polarization Optics in telecommunications*, Springer (2005)

Channel parameters extraction

- CD and phase of H(f) can be obtained from the even and odd parts of:

$$\text{angle}\left\{\det\left\{\mathbf{W}(f)\cdot\mathbf{P}^{-1}(f)\right\}\right\} = 2\cdot\text{angle}\left\{H(f)\right\} + 4\pi^2\beta_2 f^2$$

- To estimate DGD, one need to first find the matrix **U**(f). This is done as follows:

$$\mathbf{U}(f) = \mathbf{W}(f)\cdot\mathbf{P}^{-1}(f)\cdot H^{-1}(f)\cdot e^{-j2\pi^2\beta_2 f^2}$$

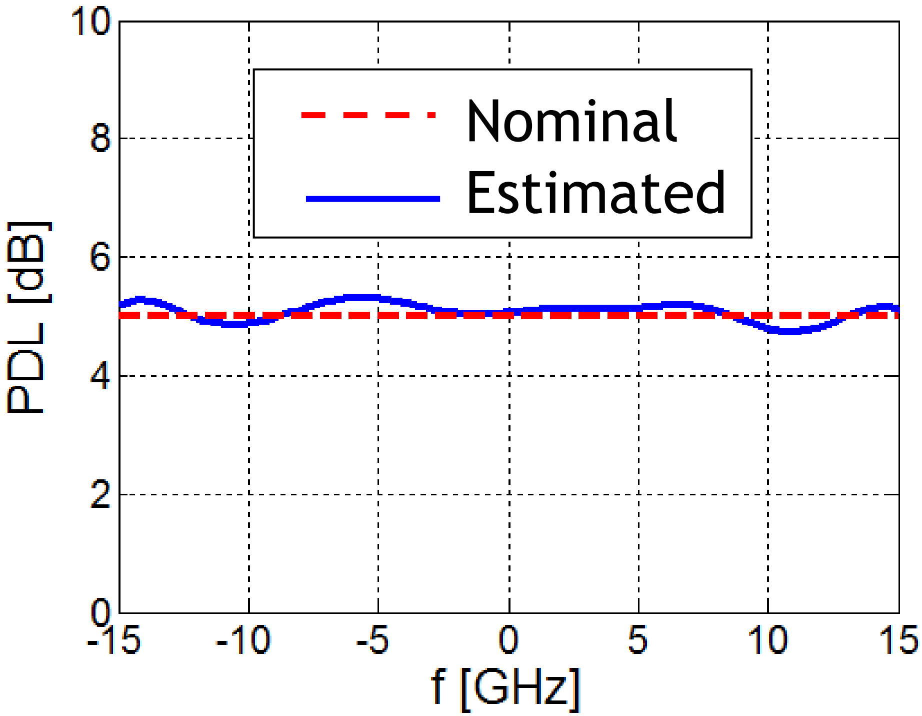
- Once **U**(f) is known, the DGD is found as:

$$\tau_{DGD} = 2\sqrt{\det\left(\frac{1}{2\pi}\frac{\mathrm{d}\mathbf{U}(f)}{\mathrm{d}f}\right)}$$

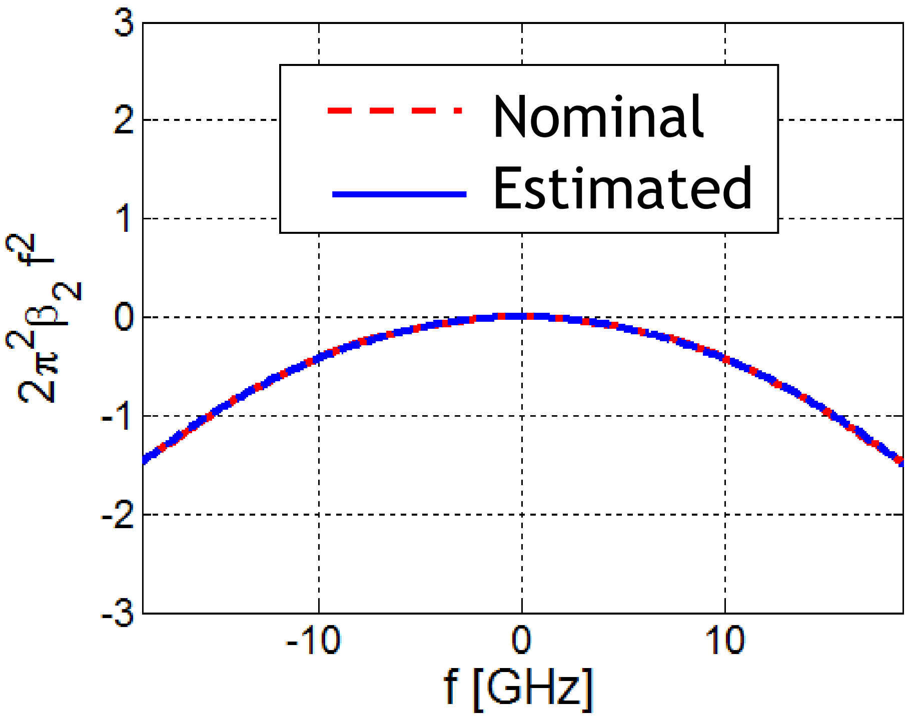
Validation through simulations

- The accuracy of the algorithms based on previous equations in the joint monitoring of channel parameters has been verified through extensive numerical simulations.

Polarization-Dependent Losses



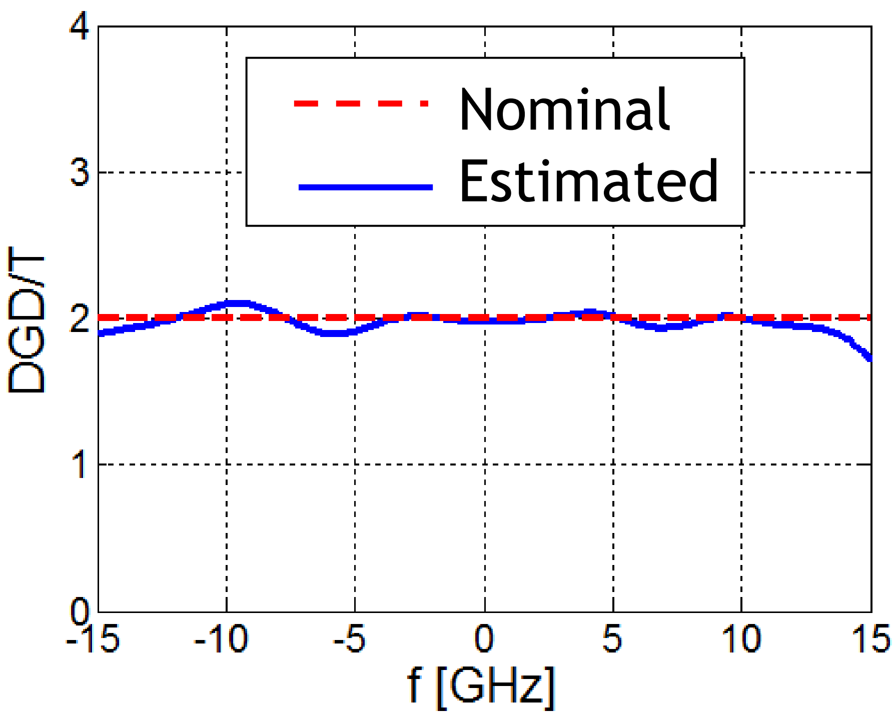
Residual CD



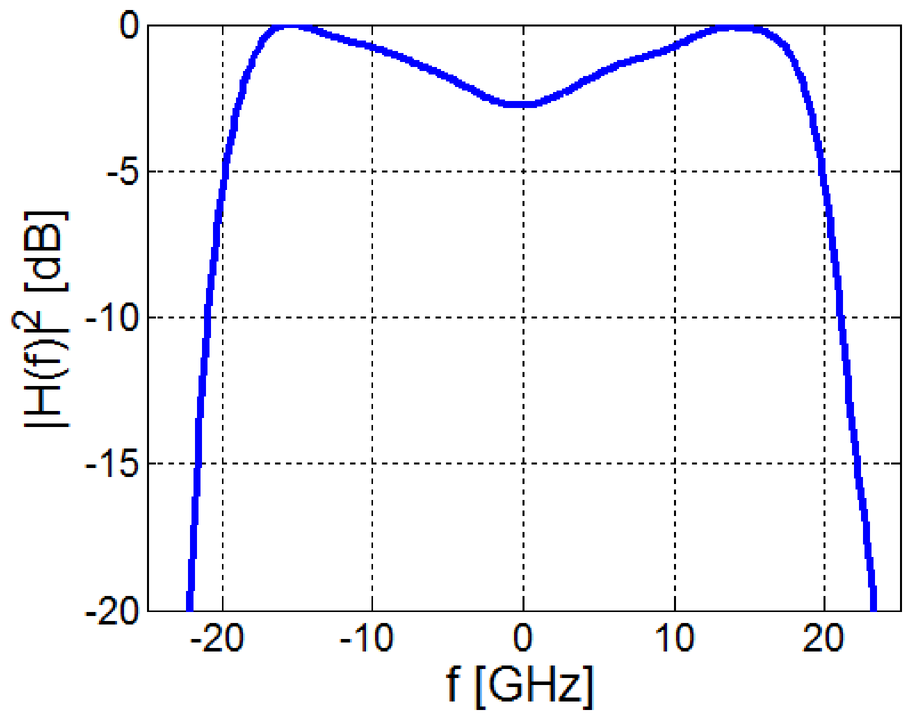
Validation through simulations

OPTCOM

Differential Group Delay



Transfer function



- Note that the plots relative to the estimation of PDL, DGD and CD are shown only in the range [-15,15] GHz, since the values that fall outside the cut-off bandwidth of the receiver are not significant.

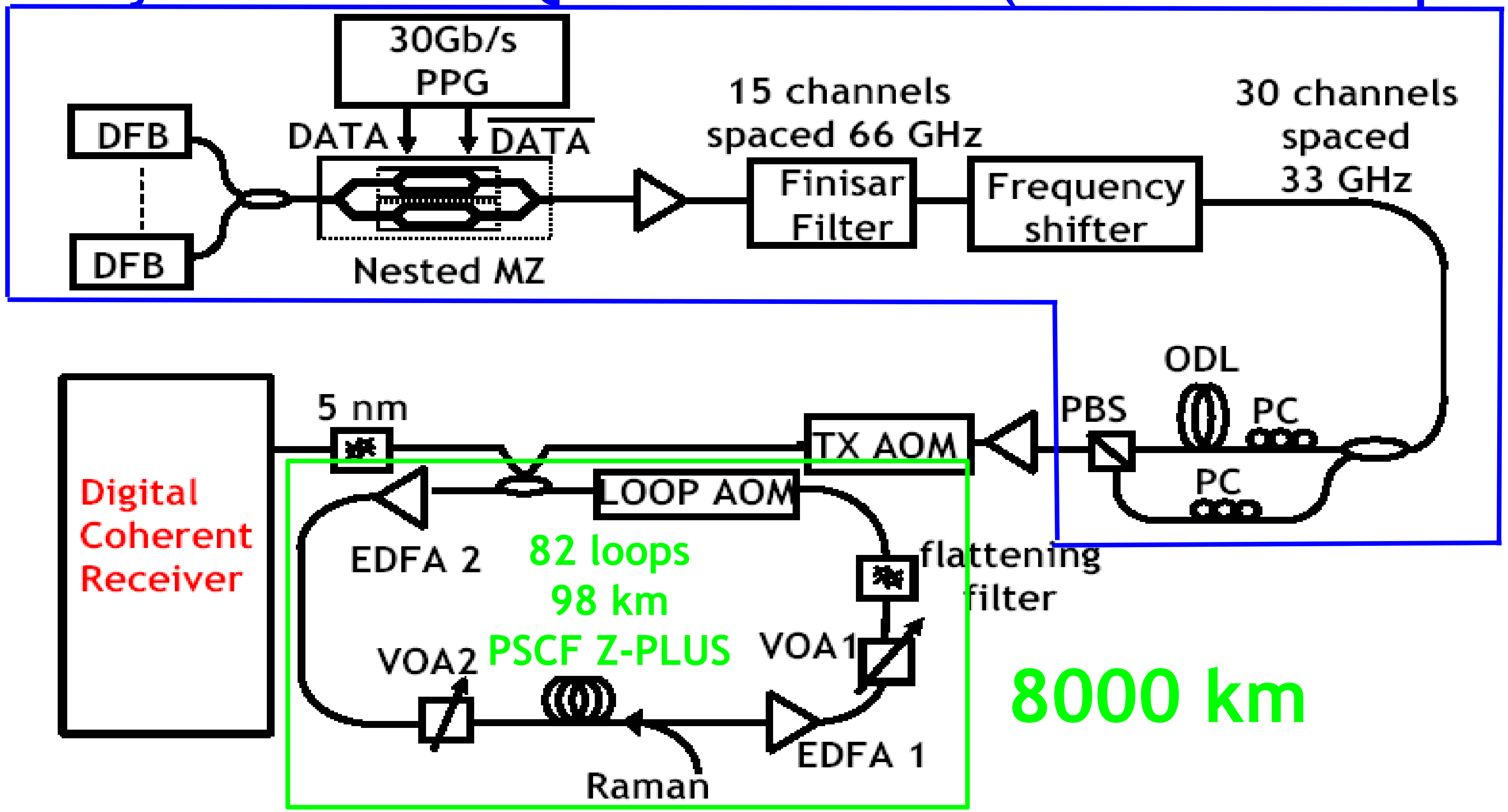
From simulation to experiment…

- When applying the monitoring algorithms to an experimental scenario, we have to take into account that receivers typically introduce amplitude imbalance and time delay among the four electrical signals.

- To prevent this problems from distorting channel parameter estimation, they should be estimated and calibrated out before applying channel estimation equations.

Experimental setup [*]

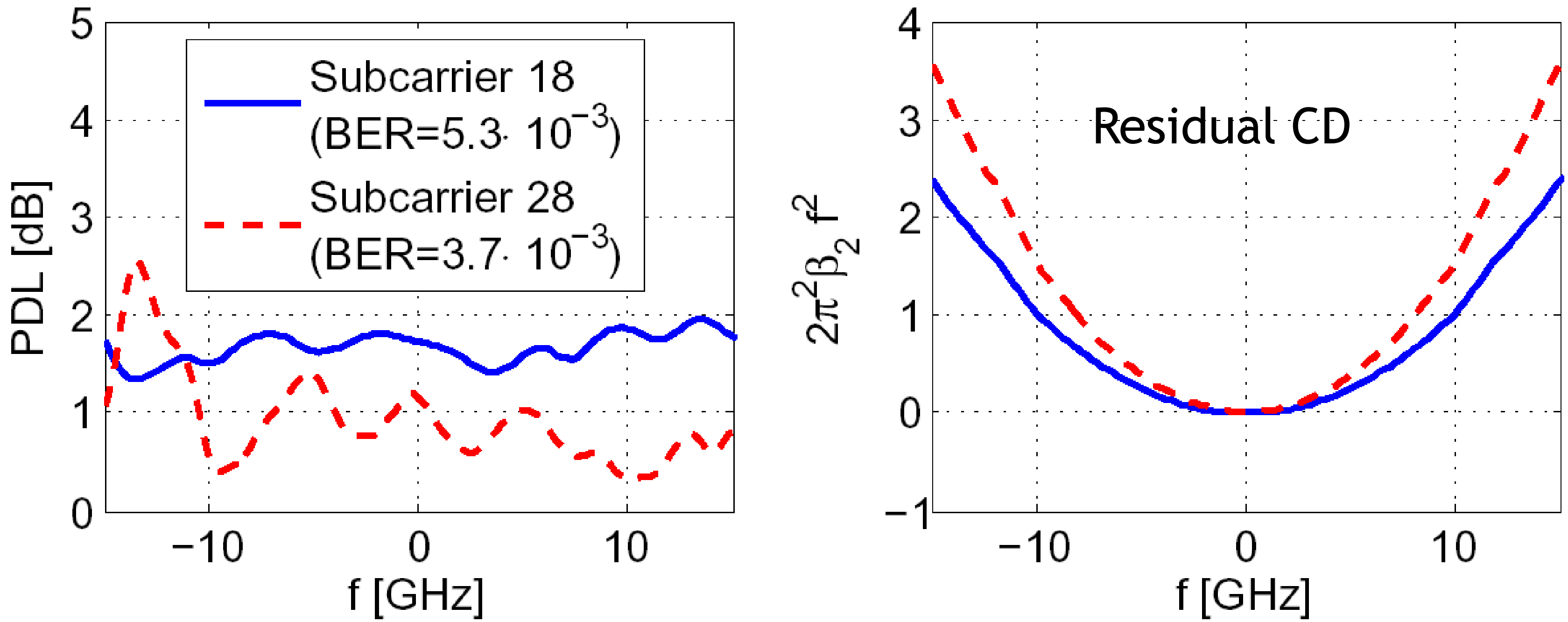
Thirty 120-Gb/s PM-QPSK sub-carriers (1.1 baud-rate spacing)



[*] E. Torrengo et al., "Transoceanic PM-QPSK Terabit Superchannel Transmission Experiments at Baud-Rate Subcarrier Spacing", ECOC 2010, Torino, paper We.7.C.2

PDL and residual CD monitoring

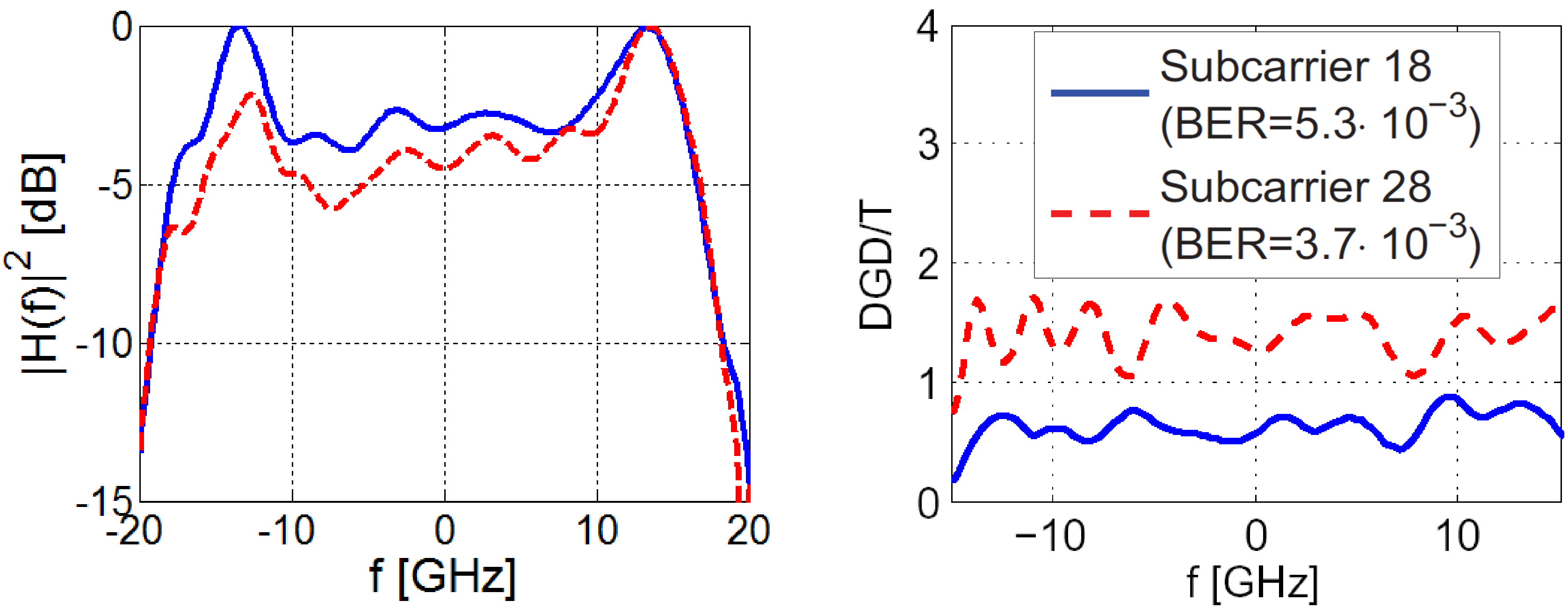
25 taps FIR filter



- The channel estimation plots can be used to “tune” the experimental set-up.
- As an example, the CD curve indicates the residual CD and can give feed-back to the first-stage equalizer.

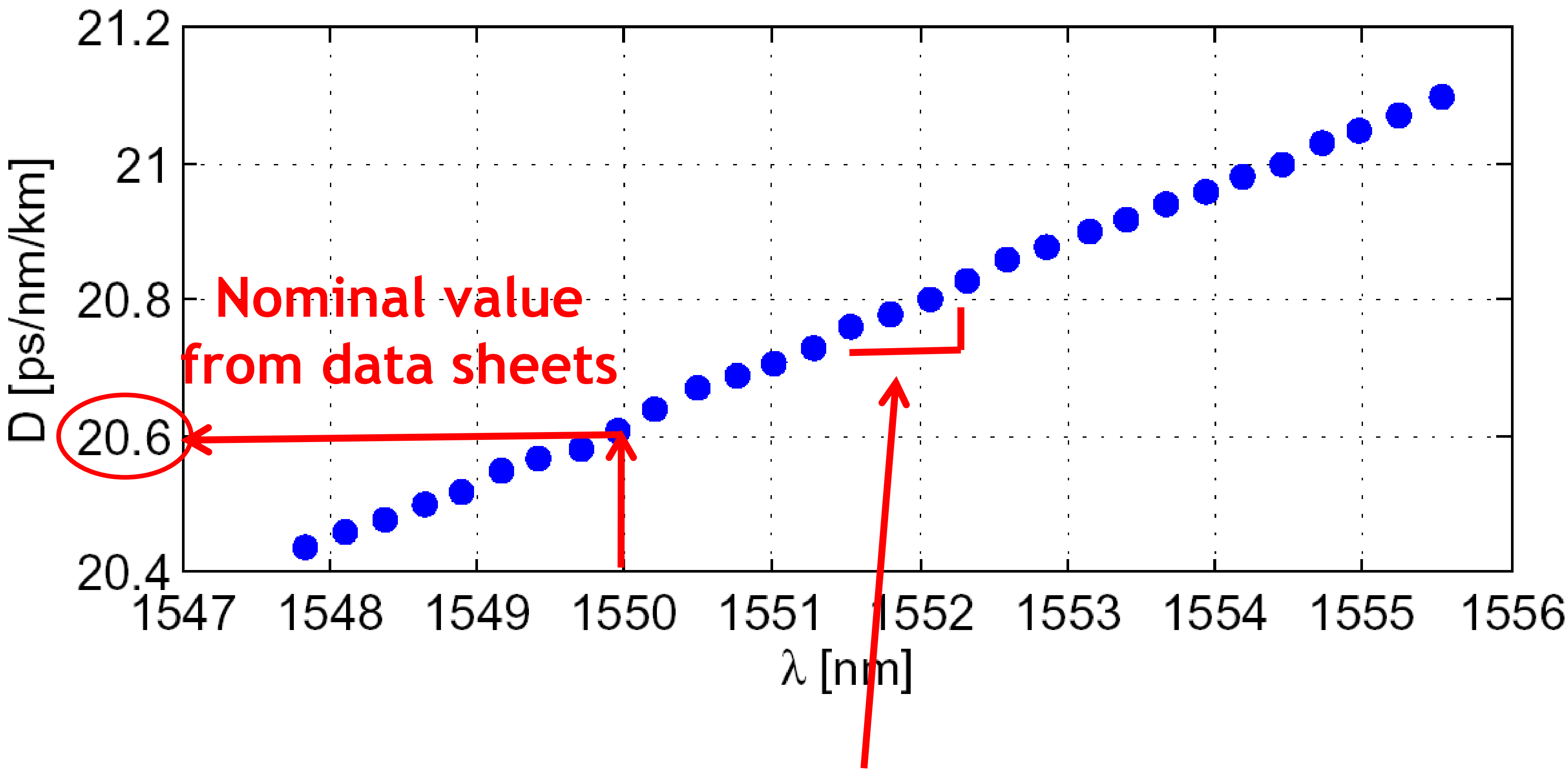
H(f) and DGD monitoring

25 taps FIR filter



- The transfer function plot can be used as an indicator of the correct tuning of the transmitter laser and the optical shaping filter.
- If the passband of the filter is not centered at the laser emitting frequency, the plot of $|H(f)|^2$ is asymmetrical.

Estimated D vs. wavelength

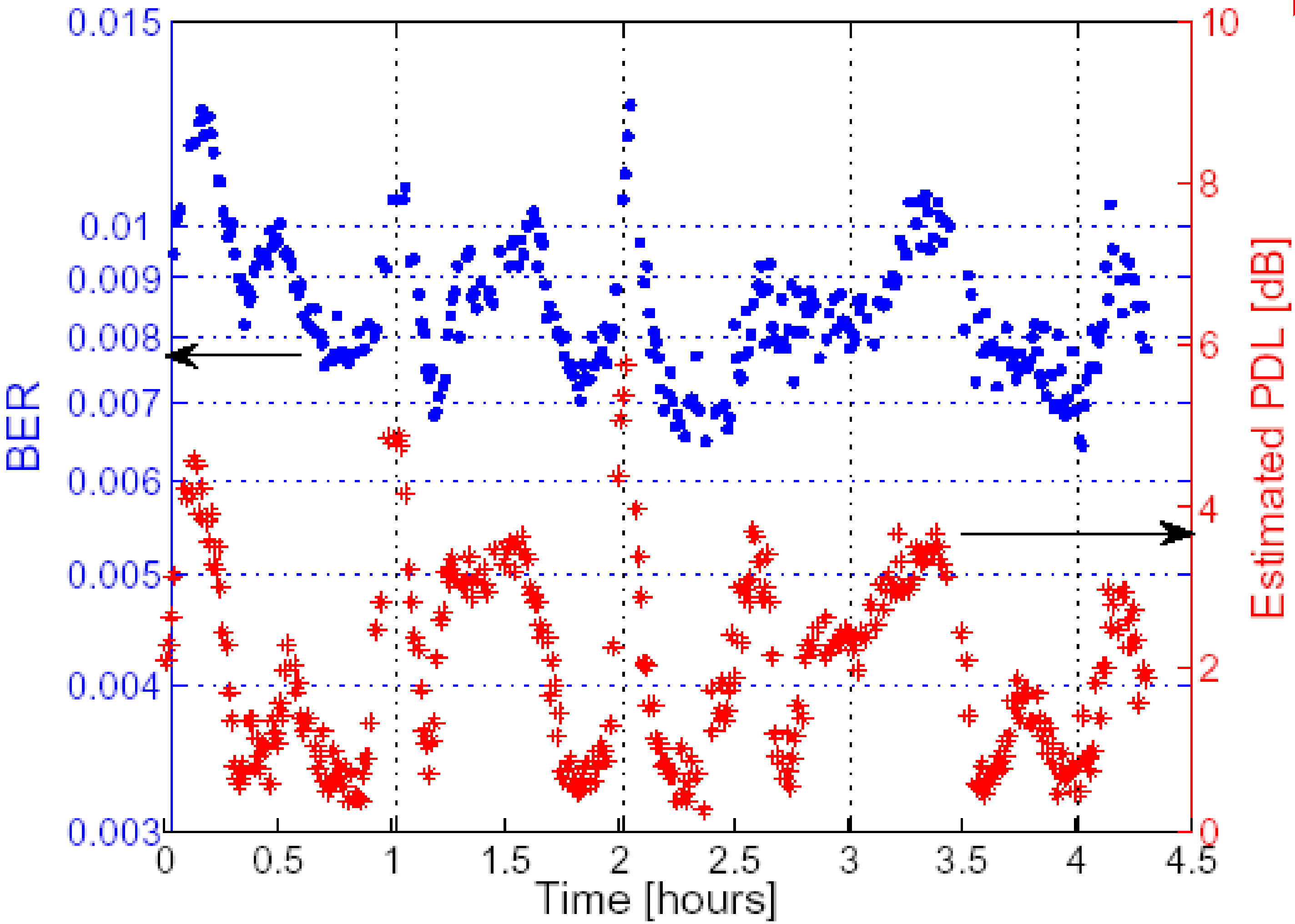


Dispersion slope: 0.057 ps/nm^2/km
(nominal value from data sheets: 0.06 ps/nm^2/km)

Long-term measurements (PDL and BER)

OPTCOM

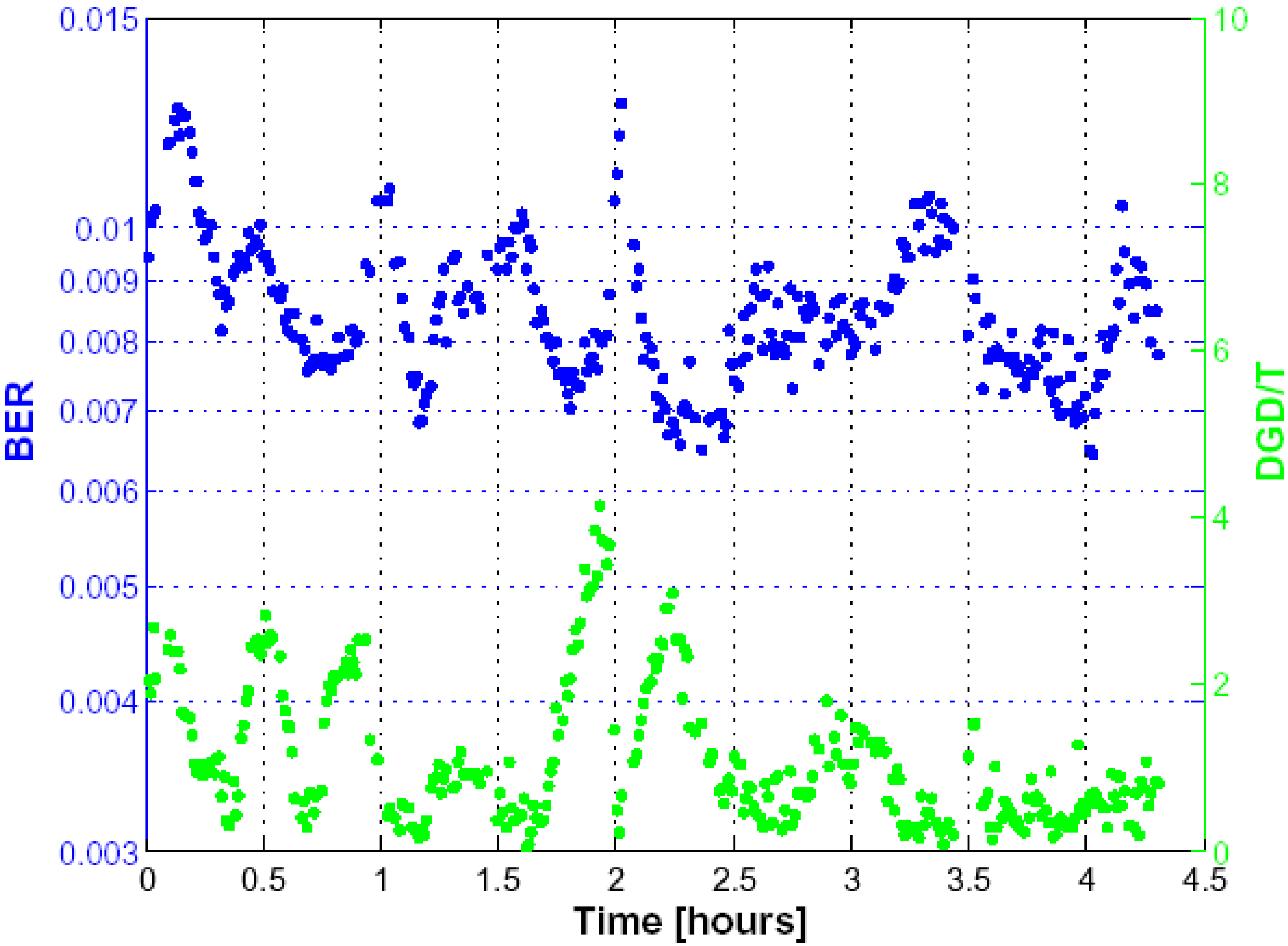
Measurement performed on center channel



- The estimated values of PDL in long-term measurements correspond to the actual PDL present in the system at time of measurement and are strictly related to the values of BER

Long-term measurements (DGD and BER)

Measurement performed on center channel



- The variations of DGD in long-term measurements are not related to the value of BER, since DGD can be completely compensated for by the equalizer.
- The variations of DGD are due to the dependence on the direction of the signal SOP with respect to DGD vector .

Conclusions

- We have shown an experimental demonstration of joint channel parameters estimation based on the use of coherent receiver equalizer taps in a ultra-long-haul high-capacity WDM transmission scenario, characterized by high values of PDL and DGD.

Acknowledgments

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