Proposal of a PhD thesis in Orange Labs (France)

"Mitigation of fiber nonlinear impairments in high symbol-rate high-order QAM"

In order to respond to the ever-increasing capacity requirements of metro/core optical transport networks, boosted by popular web-based applications, ultra-high definition (4k/8k) video streaming, intensive cloud storage, virtual/augmented reality, as well as by booming machine-to-machine (M2M) connections, WDM systems continue to evolve towards higher data-rates, such as 200 Gbps, 400 Gbps, 600 Gbps and beyond.

In order to be cost-efficient and reduce as much as possible the number of transceivers, transmission techniques try to entail only one carrier but operating at a very high symbol-rate: it is the reason why vendors currently work on single-carrier high symbol rate QAM like 64 Gbaud 64-QAM (carrying overall 600 Gbps). However, at such high speeds, amplified spontaneous emission (ASE) noise and fiber nonlinear effects are particularly detrimental. To cope with the first mentioned impairment (ASE noise), equipment suppliers propose for example to use distributed Raman amplification, while the mitigation of the second impairment (fiber non-linearities) is rather addressed by digital signal processing implemented either at the transmitter or receiver side or at both. Among these compensation techniques, digital back-propagation (DBP) **[1]** or Volterra-series non-linear equalization (VSNLE) **[2]** have been proposed but not implemented industrially because not really efficient at low symbol-rate (32 Gbaups) to mitigate inter-channel non-linear crosstalk, and too complex to implement in an ASIC.

Recently, a new approach has been proposed based on the perturbative resolution of the Manakov equation **[3]** and an implementation of the equalization process both at the transmitter and receiver side through digital pre- and post-equalization **[4]**. This technique allows a significant reduction of the hardware implementation complexity **[4]** and seems to constitute one of the most credible industrial approaches to be achieved in a transceiver operating at high baud-rate with high-order QAM. Indeed with the ever-increasing data rate carried by wavelengths, inter-channel non-linearities are largely reduced at the expense of intra-channel non-linear crosstalk (mainly self-phase modulation) which is emphasized and for which the above mentioned digital equalizers recover a good efficiency.

It is also useful to recall that other short/medium or long-term approaches are proposed. In the first category, sub-carrier multiplexing (SCM) **[5]** performs an optimization of the symbol-rate to find the baud-rate which trades-off as much as possible inter- and intra-channel non-linear crosstalk, while still using only one transceiver. SCM could improve transmission performance of ~20 % with respect to high symbol-rate QAM without non-linear equalization. In the second category, more advanced techniques based on what was made 20 years ago with solitons are proposed. These approaches, named non-linear Fourier transform (NFT) **[6]** or non-linear inverse synthesis (NIS) **[7]**, use a variant of OFDM implementing a specific non-linear processing to make this NFT waveform robust to fiber non-linear effects.

In this PhD thesis, we will implement theoretically, numerically and experimentally over high symbol-rate (43 Gbaud, 64 Gbaud) high-order QAM (16QAM, 64QAM) nonlinear crosstalk mitigation techniques which have from an industrial point of view the most important potential/interest. Their efficiency will be compared to the one of DBP used here as a reference. In a second step, SCM will be implemented to provide some comparison elements and to status over the best approach (single-carrier high baud-rate QAM with intra-channel digital non-linear equalization or SCM with low baud-rate and no equalization). In the last part of the thesis, longer-term approach will be investigated based on NFT/NIS techniques by taking into account realistic constraints such as the fiber type (G652 standard single-mode fiber) over which the propagation has to be performed or advanced modulation formats which allow to reach high spectral efficiency.

The laboratory is equipped with the most advanced test and measurement equipments, namely a 4-channels 92 GSaps sampling speed, 30 GHz analog bandwidth arbitrary waveform generator (AWG) as well as a 4-channels, 80 GSaps sampling speed, 35 GHz bandwidth digital sampling oscilloscope (DSO) , present in only 5 or 6 labs in Europe. The other tools present in the lab are:

- 20x100 km G.652 standard single mode fiber line with 20 EDFAS
- 10x100 km LEAF fiber
- 4x100 km G.652, G.654, G.655 fiber-based recirculating loop with both pure EDFA or hybrid Raman-EDFA amplification
- 4-channels, 64 GSaps sampling speed, 20 GHz analog bandwidth AWG
- 4-channels, 50 GSaps sampling speed, 20 GHz analog bandwidth DSO
- Multiple OSAs with one having 20-MHz resolution
- Multiple low phase noise laser with two having less than 10-kHz linewidth
- …

PhD supervisor in Orange Labs / Contact : Erwan PINCEMIN (email: erwan.pincemin@orange.com / Tel: +33 2 96 07 06 59)

[1] E. Ip and J. M. Kahn, “Compensation of dispersion and nonlinear impairments using digital backpropagation,” J.Lightwave Technol. 26(20), 3416–3425 (2008).
[2] F. P. Guiomar, J. D. Reis, A. L. Teixeira, and A. N. Pinto, “Digital postcompensation using Volterra series transfer function,” IEEE Photon. Technol. Lett. 23(19), 1412–1414 (2011).
[3] P. Johannisson, M. Karlsson, "Perturbation Analysis of Nonlinear Propagation in a Strongly Dispersive Optical Communication System," J. Lightwave Technol. 31(8), 1273-1282 (2015).
[4] Y. Gao, J. C. Cartledge, A. S. Karar, S.-H. Yam, M. O’Sullivan, C. Laperle, A. Borowiec, K. Roberts, "Reducing the complexity of perturbation based nonlinearity pre-compensation using symmetric EDC and pulse shaping," Optics Express 22(2), 1209-1219 (2014).
[5] P. Poggiolini, “Analytical results on system maximum reach increase through symbol rate optimization”, OFC, paper Th3D.6 (2015)
[6] M.I. Yousefi, F.K. Kschischang, “Information Transmission Using the Nonlinear Fourier Transform, Part I: Mathematical Tools,” IEEE Transactions on Information Theory, Vol. 60, No. 7, July 2014.
M.I. Yousefi, F.K. Kschischang, “Information Transmission Using the Nonlinear Fourier Transform, Part II: Numerical Methods,” IEEE Transactions on Information Theory, Vol. 60, No. 7, July 2014.
M.I. Yousefi, F.K. Kschischang, “Information Transmission Using the Nonlinear Fourier Transform, Part III: Spectrum Modulation,” IEEE Trans. on Information Theory, Vol. 60, No. 7, July 2014.
[7] Son Thai Le, Jaroslaw E. Prilepsky, and Sergei K. Turitsyn,”Nonlinear inverse synthesis for high spectral efficiency transmission in optical fibers,” Optics Express 22(22), 26721-26741 (2014).