Enabling Transparent Networking over Legacy IMDD Transmission

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XXXIII Cycle

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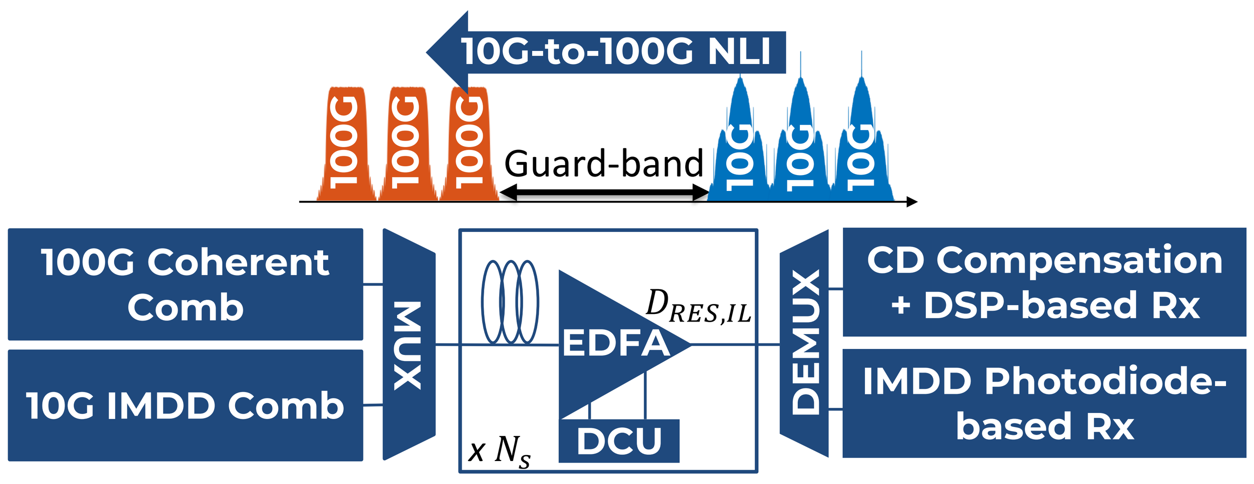
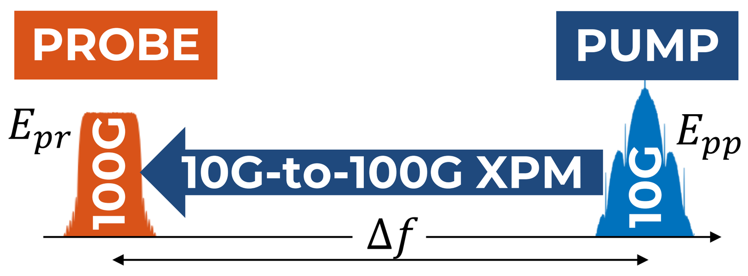
Research context and motivation

- Access and Metro segments of the optical networks still rely on 10G transceivers based on the Intensity Modulation Direct Detection (IMDD) and operated on Dispersion Managed (DM) optical line systems (OLSs), because of large CAPEX savings.
- In the meantime, 100G+ coherent, polarization-multiplexed (PM), DSP-based transmission offering larger capacity, are getting cheaper, so that a medium-term realistic scenario will include DM links operated by mixed 10G/100G transceivers.
- However, it is known that coherent transmission is severely impaired by 10G channels and DM OLSs due to the intense 10G-to-100G non-linear interference (NLI) generation.



Addressed research questions/problems

- The 10G-to-100G NLI problem is traditionally addressed by establishing a large guard-band between 10G and 100 G combs.
- However, guard-band definition is still based on empirical observations depending on the DSP implementation rather than on rigorous considerations on the received optical field.
- Here we focus on the **10G-to100G Cross-Phase Modulation (XPM)**, i.e. the 10G channel modulating the 100G phase proportionally to its power.



XPM is modelled as a multiplicative noise $\rho(t)$ on the 100G field E_{pr}:

$$E_{pr,RX}(t) = \rho(t) \cdot E_{pr,TX}(t)$$
$$\rho(t) \cong (1 + n(t))e^{j\varphi(t)}$$

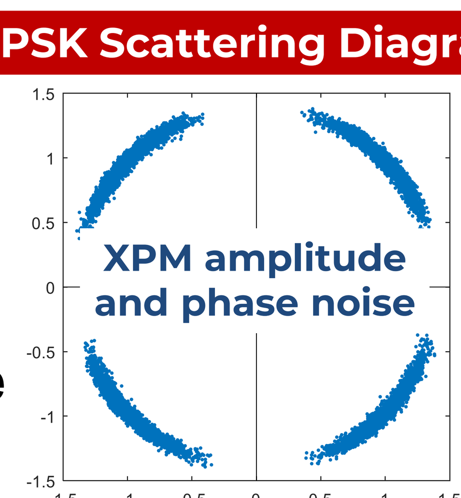
XPM Amplitude Noise

- Part of the generated interference acts as an **additive amplitude disturbances $n(t)$** whose effect can be taken into account in the SNR as a further source of noise as the amplifier ASE noise.

XPM Phase Noise

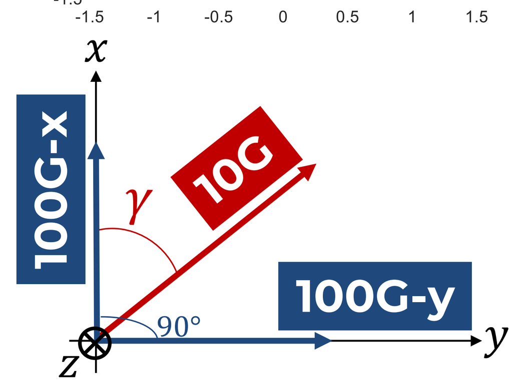
- XPM generates also **phase noise $\varphi_{XPM}(t)$** on the 100G channel whose final effect degrades the transmission performance but **depends on the DSP implementation, especially on the Carrier Phase Estimation (CPE) stage** recovering the original phase of the coherent signal.

QPSK Scattering Diagram



XPM Polarization Effects

- **100G is depolarized** since it carries independent data streams on the two polarizations.
- **10G is polarized**. It has a fixed polarization state.



- The amount of disturbance on the 100G polarization components depends on the the **Relative Polarization Angle γ** between the 10G polarization state and the x-axis of the reference polarization frame at the input of the first fiber span.
- Also, the **effect of PMD and birefringence**, which rotates the 10G polarization state w.r.t. the 100G reference axis along fiber propagation has to be considered.

Adopted methodologies

- As a first step, we have performed an extensive set of **pump and probe simulation vs the 10G-to-100G frequency spacing Δf** in order to evaluate the second order momentum of the XPM amplitude and phase noise from $\rho(t)$. Done in **single polarization to get the worst case pump-probe polarization alignment**:

$$\rho(t) = \frac{E_{pr,RX}}{E_{pr,TX}} \qquad n(t) = |\rho(t)| \qquad \varphi(t) = angle(\rho(t))$$

Evaluate Power of $n(t)$
Evaluate std.dev. of $\varphi(t)$

- Going to dual polarization, we have evaluated the **2x2 transfer function of the XPM phase noise $\bar{\bar{T}}(t)$**, considering the polarization states $\rho_X(t)$, $\rho_Y(t)$ and birefringence-PMD effects, so that $\vec{E}_{pr,RX} = \bar{\bar{T}} \cdot \vec{E}_{pr,TX}$:

$$\bar{\bar{T}}(t) = e^{j\bar{\varphi}(t)} \begin{bmatrix} \cos\theta\, e^{j(\psi+\Delta\varphi(t))} & \sin\theta\, e^{-j(\psi-\Delta\varphi(t))} \\ -\sin\theta\, e^{j(\psi-\Delta\varphi(t))} & \cos\theta\, e^{-j(\psi+\Delta\varphi(t))} \end{bmatrix}$$

θ, ψ Equivalent Polarization rotation and phase shift

$$\bar{\varphi} = (\varphi_X + \varphi_Y)/2 \qquad \Delta\varphi = (\varphi_X - \varphi_Y)/2$$

Common mode phase noise term
Polarization phase noise term

- Assuming independent CPEs on x and y, we have computed the **inverse time average of $\bar{\bar{T}}(t)$**, so that the residual impairment is evaluated as $\langle\bar{\bar{T}}(t)\rangle^{-1} \cdot \bar{\bar{T}}(t)$:

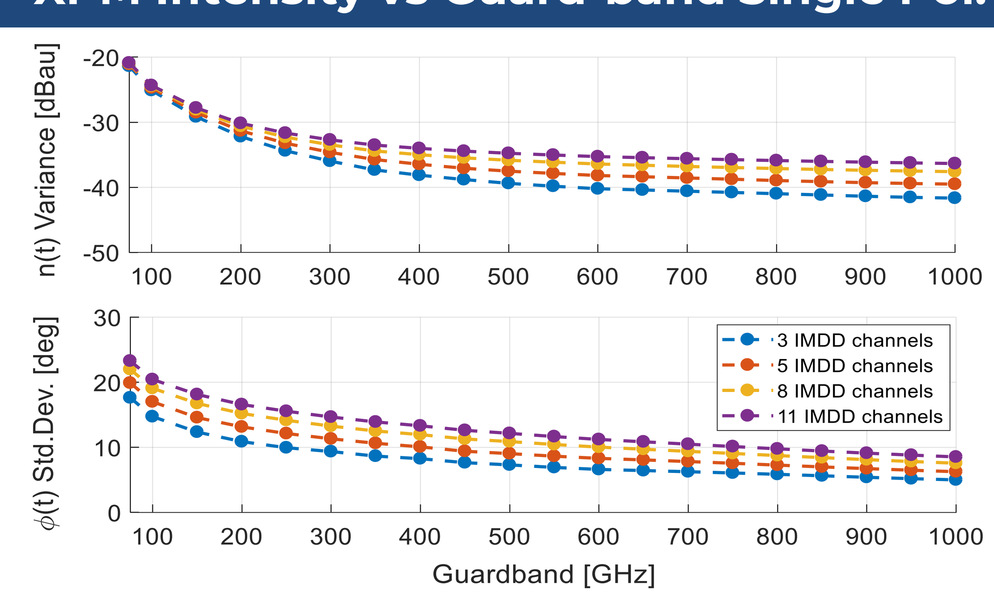
$$e^{j\bar{\varphi}_e(t)} \begin{bmatrix} \cos^2\theta\, e^{j\Delta\varphi_e(t)} + \sin^2\theta\, e^{-j\Delta\varphi_e(t)} & \sin\theta\cos\theta\, e^{-j2\psi}\left[e^{j\Delta\varphi_e(t)} - e^{-j\Delta\varphi_e(t)}\right] \\ \sin\theta\cos\theta\, e^{j2\psi}\left[e^{j\Delta\varphi_e(t)} - e^{-j\Delta\varphi_e(t)}\right] & \cos^2\theta\, e^{-j\Delta\varphi_e(t)} + \sin^2\theta\, e^{j\Delta\varphi_e(t)} \end{bmatrix}$$

$$\bar{\varphi}_e = \bar{\varphi} - \bar{\varphi}_{avg} \qquad \Delta\varphi_e = \Delta\varphi - \Delta\varphi_{avg}$$

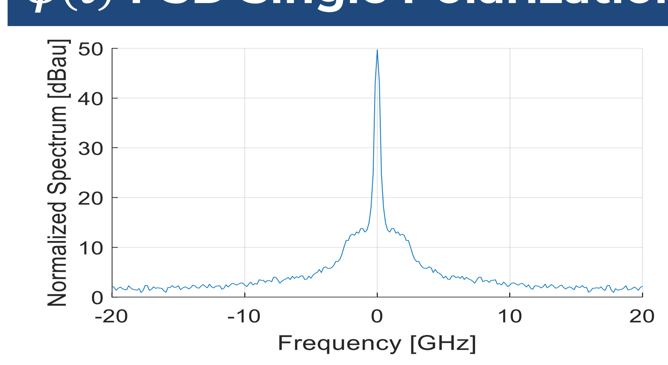
Imbalance between φ_X and φ_Y leads to additional polarization noise!

Novel Contributions

XPM Intensity vs Guard-band Single Pol.



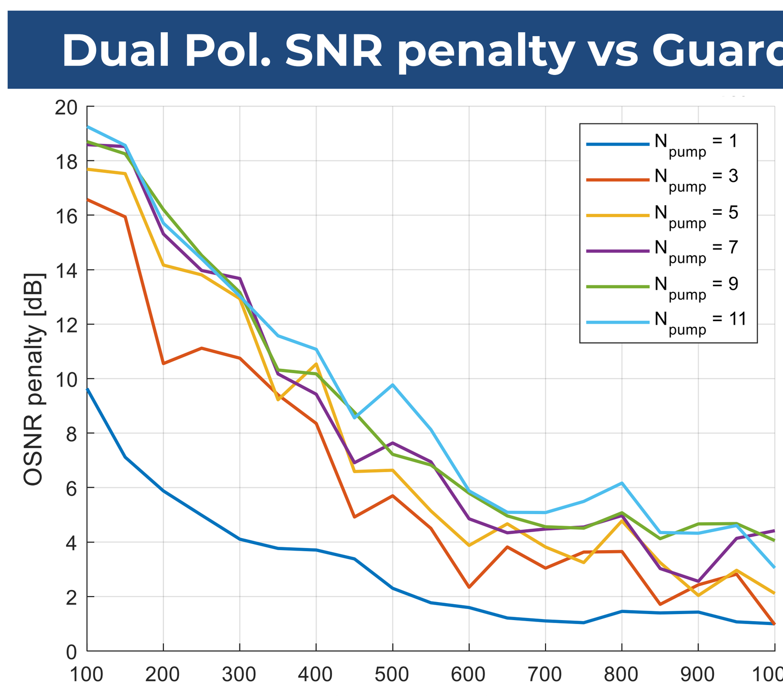
$\varphi(t)$ PSD Single Polarization



$\varphi(t)$ has a narrow band, so it can be recovered by standard CPE

- Since XPM by each 10G pump is additive, its amplitude and phase noise intensity can be evaluated vs the number of pumps N_p and Guard-band.
- Phase noise intensity can be useful to set the Guard-band w.r.t. DSP tolerance.

Dual Pol. SNR penalty vs Guard-band estimation using analytical model



- Test the analytical model by applying φ_X, φ_Y on a 100G signals and receiving it with a DSP.
- φ_X, φ_Y were obtained from single polarization φ by splitting it accordingly with the 10G-to-100G angle γ.
- SNR penalty has been evaluated w.r.t. the linear propagation of with 20 dB OSNR.

10G pumps PMD rotation, stronger at larger guard-bands, spreads the XPM impairment uniformly on the 100G polarizations ($\Delta\varphi_e \to 0$), mitigating the polarization noise term.

Future work

- Future works are focused on the validation of the dual polarization estimation both by extensive simulations and experiment. Also the analytical model will be improved to enable a fast estimation of the guard-band needed to get a certain QoT.

Submitted and published works

- ***Virgillito, E.*** *et al., "Observing and Modeling Wideband Generation of Non-Linear Interference" ICTON 2019*
- ***Virgillito, E.*** *et al., "Propagation Effects in Mixed 10G-100G Dispersion Managed Optical Links" ICTON 2019*
- ***Virgillito E.*** *et al., "Statistical Assessment of Open Optical Networks" MDPI Photonics 2019*
- *Ferrari, A.;* ***Virgillito E.*** *et al., "Band-division vs Space-division multiplexing: a network performance" submitted JLT*
- *Ghillino, E.;* ***Virgillito, E.*** *et al. ",Assessing the Impact of Design Options for an Optical Switch in …" ICTON 2019*
- *Ferrari, A.;* ***Virgillito, E.*** *et al. "Power Control Strategies in C+L Optical Line Systems" OFC 2019*
- ***Virgillito, E.*** *et al., "Quality of Transmission Estimator Enabling the Transparency Paradigm in Legacy…", ICTON 2018*
- *Ghillino, E.;* ***Virgillito, E.*** *et al, "The Synopsis Software Environment to Design and Simulate Photonic…", ICTON 2018*
- *Cantono, M.; Ferrari, A.;Pilori, D.;* ***Virgillito, E.*** *et al., "Physical Layer Performance of Multi-Band Optical Line …", JOCN 2019*

List of attended classes

- 01SHBRP – Examples of Graph Optimization in Management Science (19/1/2018, 20h)
- 01QRRRV – Advanced iterative techniques for digital receivers (25/6/2019, 20h)
- 01REKRV - Coherent detection: a revolution in optical communication (7/2/2019, 30h)
- 01SIKRV – Optical Components for Telecom (17/5/2018, 20h)
- 01MNFIU – Parallel and Distributed Computing (26/6/2018, 25h)
- 01RELKG – Probabilità Applicata e Machine Learning (03/9/2018, 20h)
- 01SHCRV – Unsupervised Neural Networks (09/04/2018, 30)
- 01QORRV – Writing Scientific Papers in English (23/05/2018, 15h)