Inter-Band Nonlinear Interference Canceler for Long-Haul coherent optical OFDM Transmission

Abdelkerim Amari, Philippe Ciblat and Yves Jaouën
Institut Mines-Telecom/Telecom ParisTech, Paris, France
Email: abdelkerim.amari@telecom-paristech.fr

***Abstract*—In the context of long-haul multi-band coherent OFDM transmission (at 400 Gbps), we propose an inter-band nonlinear interference canceler based on Volterra series. This new type of receiver significantly improves the BER performance compared to the standard third-order inverse Volterra series nonlinear equalizer.**

I. Introduction

Super-channel approaches, such as Nyquist-WDM and multi-band orthogonal-frequency-division-multiplexing (MB-OFDM) signals, allow both high spectral efficiency, small guard-band which makes them promising candidates for 400 Gbps and 1 Tbps long-haul WDM transmission [1], [2]. By using the MB-OFDM technique, bit-rate elasticity would be obtained by playing both over the number of bands and the modulation format transported by the sub-carriers constituting the OFDM bands. In addition, high spectral efficiency modulation formats, such as 16-QAM, are of primary importance for increase the spectral efficiency. However, their higher OSNR requirement and increased sensitivity to fiber nonlinear effects lead to a dramatic reduction of the transmission reach. Therefore, mitigating nonlinear impairments is essential for long-haul high data rate optical communications.

Several approaches have been considered to mitigate nonlinear effects such as digital back propagation (DBP) [3] and third-order inverse Volterra series transfer function (IVSTF) based nonlinear equalizer (NLE) [4], [5]. These techniques are typically used only to compensate for intra-channel nonlinear effects and the main interest of IVSTF compared to DBP is its computational load since parallel processing can be done. On the other hand, multi-band/channel transmission approach leads to inter-band/channel nonlinear interference, reducing significantly the nonlinear equalization performance [6].

Therefore, in the context of multi-band coherent OFDM, we propose an Inter-band Nonlinear Interference Canceler (INIC). The nonlinear interference cancellation has been already considered in wireless communication system [7], [8]. The INIC is proposed hereafter to compensate for the inter-band/channel interference. Actually, the contribution of the detected symbols of adjacent bands is rebuilt based on VSTF fiber model and removed from the band of interest. Therefore our receiver is related to the large class of Decision Feedback Equalizer (DFE). Through simulations, we show a significant gain in terms of BER.

II. Proposed INIC receiver

We consider a single mode fiber (SMF) with N spans, each of length L, attenuation coefficient α, second-order dispersion parameter β_2, and nonlinear coefficient γ. As shown in [9], the VSTF model is a powerful tool for solving the so-called nonlinear Schrödinger equation that governs the wave propagation within a SMF. Let X be the transmitted signal and Y the fiber output of the N-th span. In the frequency domain, the transmitted signal X is written as:

$$X(\omega) = [X_x(\omega), X_y(\omega)]$$

where X_x and X_y are the transmitted signal in polarization x and y respectively. In the following equations, we focus on polarization x. Similar processing has to be done for polarization y. In multi-band transmission context, the transmitted signal X of polarization x can be written as:

$$X_x(\omega) = \sum_{m=1}^{M} X_{x,m}(\omega)$$

where $X_{x,m}$ is the transmitted signal on band m and M is the number of transmitted bands. In addition, the transmitted signal $X_{x,m}$ carries a sequence $S_{x,m}$ of information symbols (typically QAM symbols). Based on VSTF, the received signal Y_x of polarization x can be written, with respect to the transmitted signal X as follows :

$$\begin{aligned} Y_x(\omega) &= H_1(\omega)X_x(\omega) \\ &+ \iint H_3(\omega_1, \omega_2, \omega-\omega_1+\omega_2)X_x(\omega-\omega_1+\omega_2) \\ &\times [X_x(\omega_1)X_x^*(\omega_2) + X_y(\omega_1)X_y^*(\omega_2)]d\omega_1 d\omega_2 \end{aligned}$$

where H_1 and H_3 denote the first-order and third-order VSTF kernels respectively and given by [5]:

$$H_1(\omega) = e^{-j\omega^2\beta_2 NL/2}$$

$$H_3(\omega_1, \omega_2, \omega-\omega_1+\omega_2) = \frac{-jC}{(2\pi)^2}H_1(\omega)\sum_{k=0}^{N-1} e^{-jk\beta_2\Delta\Omega L}$$

with $\Delta\Omega = (\omega_1 - \omega)(\omega_1 - \omega_2)$ and $C = 8\gamma(1 - e^{-\alpha L})/9\alpha$.

As the receiver proceeds band by band, a band selection is done before signal processing. The received signal $Y_{x,m}$ on the band m is disturbed by intra-band nonlinear effect and Inter-band Nonlinear Interference (INI). The intra-band nonlinear effect is compensated using IVSTF-NLE. As the INI caused by the two closest adjacent bands is more important than other INI

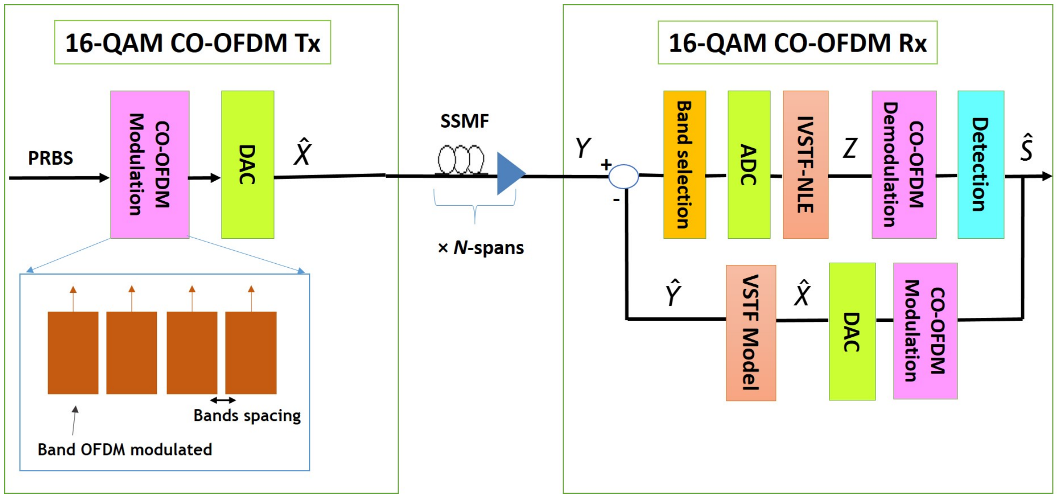

Fig. 1: Transmission diagram

terms caused by further bands, the INI is well approximated by the contribution of the two closest adjacent bands when central bands are considered. The cancellation of this INI is done hereafter based on decision feedback equalizer principle.

During the first step, the fiber output signal is equalized at the receiver side using the third-order IVSTF-NLE for N-span fiber. The IVSTF-NLE output signal $Z_{x,m}$ for polarization x and selected band m can be written as:

$$
\begin{aligned}
&Z_{x,m}(\omega) = K_1(\omega)Y_{x,m}(\omega) \\
&+ \iint K_3(\omega_1,\omega_2,\omega-\omega_1+\omega_2)Y_{x,m}(\omega-\omega_1+\omega_2) \\
&\times [Y_{x,m}(\omega_1)Y^*_{x,m}(\omega_2)+Y_{y,m}(\omega_1)Y^*_{y,m}(\omega_2)]d\omega_1 d\omega_2
\end{aligned}
$$

where K_1 and K_3 are the first-order and third-order IVSTF kernels respectively and given by [5]:

$$
\begin{aligned}
&K_1(\omega) = e^{j\omega^2\beta_2 NL/2} \\
&K_3(\omega_1,\omega_2,\omega-\omega_1+\omega_2) = \frac{jC}{(2\pi)^2}K_1(\omega)\sum_{k=1}^{N} e^{jk\beta_2\Delta\Omega L}.
\end{aligned}
$$

Then, a threshold detector is applied on $Z_{x,m}$ for each band m in order to find out the detected symbols $\widehat{S}_{x,m}$ corresponding to the transmitted symbols $S_{x,m}$.

During the second step, the objective is to re-build the received signal associated with each interference band given the detected symbols on these bands in order to removing it on the band of interest m. We thus build $\widehat{Y}_{x,m}$ the output of the VSTF model of the considered fiber (here, the SMF) for polarization x and the detected symbols $\widehat{S}_{x,m}$. Consequently, we have:

$$
\begin{aligned}
&\widehat{Y}_{x,m}(\omega) = H_1(\omega)\widehat{X}_{x,m}(\omega) \\
&+ \iint H_3(\omega_1,\omega_2,\omega-\omega_1+\omega_2)\widehat{X}_{x,m}(\omega-\omega_1+\omega_2) \\
&\times [\widehat{X}_{x,m}(\omega_1)\widehat{X}^*_{x,m}(\omega_2)+\widehat{X}_{y,m}(\omega_1)\widehat{X}^*_{y,m}(\omega_2)]d\omega_1 d\omega_2
\end{aligned}
$$

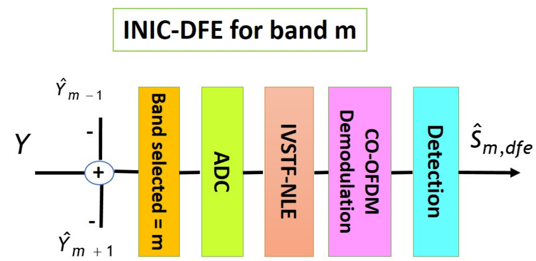

Fig. 2: INIC

where $\widehat{X} = [\widehat{X}_{x,m}, \widehat{X}_{y,m}]$ is the re-modulated signal corresponding to the detected symbols $\widehat{S} = [\widehat{S}_{x,m}, \widehat{S}_{y,m}]$. Due to nonlinear effect, one can notice that $\widehat{Y}_{x,m}$ is not only on band m but is also spread over adjacent bands $m-1$ and $m+1$. Finally, if the band of interest is denoted m, we subtract its closest adjacent band signals $\widehat{Y}_{m-1}(\omega)$ and $\widehat{Y}_{m+1}(\omega)$ from the original received signal Y. The final decision $\widehat{S}_{m,dfe}$ is taken on the signal $Y_{m,dfe}$ after it has been passed once again through a band selection and through the IVSTF receiver to compensate for the intra-band nonlinear effect, where we have

$$
Y_{m,dfe}(\omega) = Y(\omega) - \widehat{Y}_{m-1}(\omega) - \widehat{Y}_{m+1}(\omega).
$$

Fig. 1 shows the transmission diagram where the transmitted signal spectrum consists of four bands OFDM, and a single mode fiber with N spans is used as transmission medium. The receiver structure is based on decision feedback equalizer which explains the loop. Fig. 2 precises the INIC implementation for the band m.

The proposed INIC roughly triples the complexity compared to the IVSTF-NLE. Indeed, assuming that the complexity comes from the (I)VSTF operator, the IVSTF-NLE requires M IVSTF, whereas in our case, each band reconstruction needs one additional VSTF (so M VSTF) and each $Y_{m,dfe}$ is passed through an extra IVSTF (so M IVSTF). Therefore we need $3M$ (I)VSTF instead of M.

III. Simulation results

The simulation setup is inspired from the SASER European project whose the goal is to design a 400 Gbps system for long-haul communications. We transmit four OFDM modulated bands of bandwidth 20 GHz and spaced by 2 GHz interval guard. We consider a Dual-Pol-16QAM OFDM with 512 subcarriers and a 11% loss in efficiency due to the cyclic prefix on each band. The transmission line consists of 8 spans of 100 km. Each span is a standard SMF with $\alpha = 0.2\text{dB.km}^{-1}$, $\beta_2 = 17\text{ps.nm}^{-1}.\text{km}^{-1}$, and $\gamma = 1.4\text{W}^{-1}km^{-1}$. An Erbium-Doped Fiber Amplifier (EDFA) with a 5.5 dB noise figure and a 20 dB gain is also used at each span. All results in this work concern the central bands because they are the most degraded by nonlinear effects.

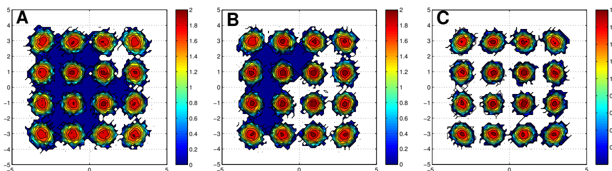

Fig. 3: Constellations: (A) linear equalization; (B) IVSTF-NLE; (C) Proposed INIC

In Fig. 3, we show the constellations after linear equalization, IVSTF-NLE and INIC respectively. The constellation after INIC is clearer and the points are more visible which should lead to better BER.

In Fig. 4, we plot BER vs. input power when only one single-polarization is active. The performance of the IVSTF-NLE is closed to those of the linear equalization because of the inter-band interference. In contrast, the proposed INIC strongly outperforms the IVSTF-NLE.

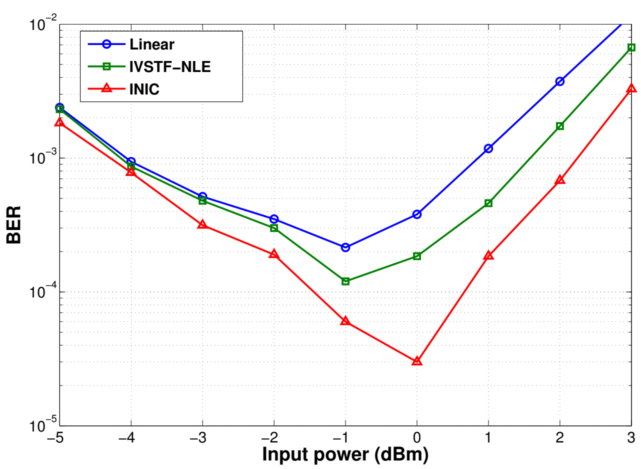

Fig. 4: BER vs. input power for 4-band Single-Pol-16QAM OFDM

In Fig. 5, we plot BER vs. input power when both polarizations are active. The gain of the proposed INIC compared to the IVSTF-NLE still exists but is less stronger than in the single polarization case. This can be explained by the existence of XpolM nonlinear effects [10] whom proposed INIC does not treat and so does not combat. Nevertheless, we have a non-negligible BER improvement in comparison to the IVSTF-NLE.

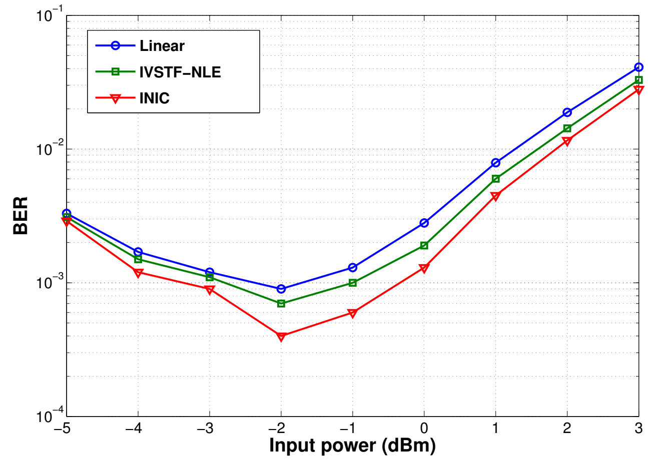

Fig. 5: BER vs. input power for 4-band Dual-Pol-16QAM OFDM

IV. Conclusion

We proposed an inter-band nonlinear interference canceler for multi-band coherent optical transmission system. We showed that the proposed INIC significantly improves system performance in single and dual polarization configuration compared to the standard IVSTF-NLE.

Acknowledgment

The work is funded by SASER European CELTIC program.

References

[1] J. Renaudier, et al, “Spectrally efficient 1Tb/s Transceivers,” OFC, paper M2G.3, 2015.

[2] S. Chandrasekhar, “OFDM based superchannel transmission technology,” J. Lightwave Technol., Vol.**30**, pp.3816-3823 ,2012.

[3] E. Ip et al., “Compensation of dispersion and nonlinear impairments using digital back propagation,” J. Lightwave Technol., Vol.**26**, no.20, pp.3416-3425,2008.

[4] J. D. Reis and et al., “Unveiling nonlinear effects in dense coherent optical WDM systems with Volterra series,” Opt. Expr., vol.**18**, no.8, pp.8660-70, 2010

[5] L. Lui and et al., “Intrachannel Nonlinearity Compensation by Inverse Volterra Series Transfer Function,” J. Lightwave Technol., Vol.**30**, no.3, pp.310-316, 2012.

[6] D. Rafique and et al., “Digital back-propagation for spectrally efficient WDM 112 Gbit/s PM m-ary QAM transmission,” Opt. Expr., vol.**19**, no.6, pp.5219-5224, 2011.

[7] D. D. Falconer, “Adaptive equalization of channel nonlinearities in QAM data transmission systems,” Bell System Technical J., Vol.**57**, no.7, 1978.

[8] E. Biglieri et al., “Adaptive cancellation of nonlinear intersymbol interference for voiceband data transmission,” J. Sel. Areas Commun, Vol.**2**, no.5, pp.765-777,1984.

[9] K. Peddanarappagari et al., “Volterra series transfer function of single-mode fibers,” J. Lightwave Technol., Vol.**15**, no.12, pp.2232-2241, 1997.

[10] A. Bononi et al., “Performances of 400 Gbps coherent 16-QAM multi-band OFDM adopting nonlinear mitigation techniques,” ECOC, paper Th.1.D.5, 2013.