Revisiting the evaluation of non-linear propagation impairments in highly dispersive systems

Edouard GRELLIER(1), Jean-Christophe ANTONA(1), Sébastien BIGO(1)

(1) Alcatel-Lucent, Bell-Labs, Route de Villejust, 91620 NOZAY-FRANCE. edouard.grellier@alcatel-lucent.com

Abstract *The relevance of the nonlinear phase criterion for predicting performance in highly dispersive systems is investigated. For such systems, we propose and validate a more accurate criterion accounting for dispersion.*

Introduction

The ability to predict transmission penalties due to non linear effects is of great importance in long haul wavelength division multiplexed (WDM) systems. In [1], the authors recommend the non-linear phase shift as a useful and simple parameter to assess the performance of classic 40Gbit/s IMDD (Intensity-modulated direct-detection) terrestrial systems.

However, during the last few years, high bit rates transmissions systems have considerably evolved, with the widespread acceptance of new modulation formats, polarisation division multiplexing (PDM) and coherent detection. Besides, new chromatic dispersion mitigation strategies have caught interest in the past few years, so that highly dispersive systems with sparse or no in-line dispersion compensation are more and more often considered [2-4]. In such systems, dispersion compensation is generally performed digitally in terminals, as demonstrated up to 140,000ps/nm.km at 100Gb/s[4].

In this context, it has become of high interest to find simple criterions to assess the performance of systems operating in the highly dispersive regime.

In this paper, through an extensive numerical study on both direct-detection and coherent systems, we show that the non-linear phase shift is insufficient to predict the performance of a systems operating in the highly dispersive regime and we provide a new, more accurate criterion.

System Setup

In the following, the system under study consists of a transmission link over N_{SPAN} (variable from 5 to 30) 100km-long spans of standard single mode fibre (SSMF) with singly periodic dispersion maps similar to [1]. Dispersion compensation is performed in the receiver and (possibly) in the in-line repeaters, but not in the transmitter. The residual dispersion per span (RDPS) is varied between 0 and 1700 ps/nm and the total amount of cumulated dispersion is always adjusted in the receiver for best performance. Non linear effects in dispersion compensation units are not taken into account, and the possible interactions between the signal and Amplified spontaneous noise (ASE) are overlooked.

We have considered two different scenarios, using direct-detection or coherent detection. The first scenario consists of a single channel modulated at 43b/s with Non-Return to Zero format. In this scenario, a direct receiver is used, modelled by 0.5nm-bandwidth 2nd order Gaussian optical filter, followed by a photodiode, a *28GHz* bandwidth 5th order Bessel electrical filter and an ideal decision gate. We used De Bruijn sequences of 2^{15} bits and the Bit Error Rate (BER) is estimated using a semi-analytical BER method (Karhunen-Loeve based[5]).

The second scenario assumes a single channel or a 7-channel, 50GHz-spaced, WDM multiplex, all modulated at *112Gb/s* with PDM-Quaternary Phase Shift Keying (PDM-QPSK),. Ideal 50GHz bandwidth rectangular electrical filters are used at both transmitter and receiver. In this scenario, an ideal coherent receiver is used. Each channel uses one pseudorandom quaternary sequence of *4096* symbols per polarization in order to mimic a 16-lvl pseudorandom sequence of *2^14* bits. Additionally, random delays are introduced between channels. The BER is estimated by direct error counting with enough noise samples to detect *>400*errors; in the WDM case the BER is estimated on the central channel.

For each configuration, we vary the fibre input power P_{IN}, so as to get the power corresponding to *1.5dB* Optical Signal-to-Noise Ratio (OSNR) penalty at 10^{-3} reference BER. At this power P_{NLT}, we associate a non linear threshold (*NLT*) defined as the product $N_{SPAN}\times P_{NLT}$.

Limits of validity of the non linear phase criterion

In [1], the authors showed that the non linear phase shift Φ_{NL} can be considered as a relevant parameter to assess the performance of terrestrial systems. With the typical setup, Φ_{NL} is found proportional to $N_{SPAN}\times P_{IN}$, this product is thus a useful parameter [6]. As a consequence, the NLT (defined as above) should remain constant when N_{SPAN} varies. However, the study of [1] was limited to dispersion-managed systems far from the highly dispersive regime.

In Fig1, we reported the *NLT* for WDM transmissions with *112Gb/s* PDM-QPSK for various numbers of spans (second scenario), in the cases of full inline dispersion compensation (*RDPS=0ps/nm*) and no in-line dispersion compensation (*RDPS=1700ps/nm*). With full in-line compensation, we observe that the *NLT* remains the same when N_{SPAN} varies, similar results were obtained for single channel and NRZ transmissions, this confirms that in this case Φ_{NL} is reliable to predict the performance of the system and that this can be extended to a coherent QPSK

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system. However, without dispersion compensation and therefore in the highly dispersive regime, we observe an increase of the NLT with the number of spans as shown in Fig1.

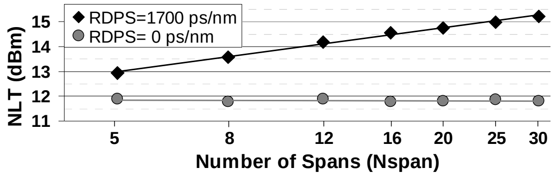

Fig. 1: Evolution of the non linear threshold over the number of 100km SSMF spans, for a coherent WDM 112Gb/s PDM-QPSK transmission with 7 channels. Both cases RDPS=0ps/nm and RDPS=1700ps/nm are reported.

Such discrepancies between dispersion-managed and highly dispersive regimes agree with derivations from analytical models such as [7], emphasizing the synthetic character of the non-linear phase for low values of the product $RDPS \times N_{SPAN}$.

One can explain this by an increase of the inline cumulated dispersion $D_{in} \approx RDPS \times N_{SPAN}$. Indeed if the walk-off (defined as $W = D_{in} \times \Delta\lambda$, i.e. the time shift introduced by ground velocity dispersion between two wavelengths distant of $\Delta\lambda$) is greater than the symbol time, it reduces the impact of non linear effects between those two wavelengths [8].

One remarkable observation is that in logarithmic scales the increase of the NLT in respect with the number of spans appears linear. Suggesting that the NLT could scale like a power of the number of spans.

$$NLT = K \times N_{SPAN}{}^{\alpha}$$

Where K and α are constants. Without dispersion compensation, we find that $\alpha \approx 0.3$ and with full in-line dispersion compensation we observe that $\alpha \approx 0$, thereby matching the non linear phase shift criterion.

As an example, without inline compensation, if the number of spans is doubled, the fibre input power corresponding to *1.5dB* OSNR penalty is reduced by just $3(1-\alpha)=2.1dB$ whereas *3dB* would be predicted by the non linear phase criterion.

Single channel results

The above analysis relying on time-shifts stemming from chromatic time between two channels can be extended to two spectral components within a given channel. Consider a system with the above symbol rate of *25Gbaud/s* and an in-line cumulated dispersion D_{in} of 10^4*ps/nm (i.e. ~600km* length when assuming zero-in-line dispersion). In this system, two spectral components spaced by just *0.04nm* (i.e. closer than the 3dB bandwidth of the signal) are shifted by more than 10 symbol time across the link. Such components should experience the beneficial averaging of the time shift. Hence, in highly dispersion regime, the impact of intra-channel non linear effects is likely reduced by the component-to-component time shifts, just as inter-channel effects are by walkoff.

In Fig2, we compute the NLT of single channel transmissions versus the inline cumulated dispersion, $N_{SPAN} \times RDPS$, using different values of *RDPS* and N_{SPAN}, for both IMDD 43Gb/s and coherent PDM-QPSK 100Gb/s systems.

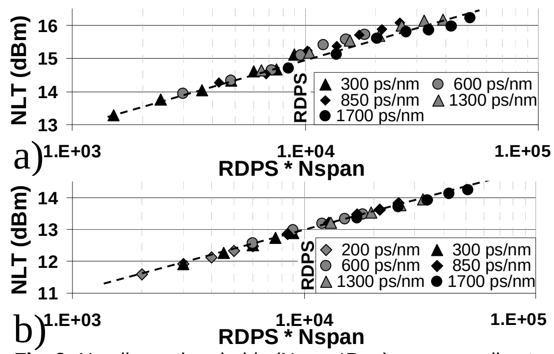

Fig. 2: Non linear thresholds (Nspan*P_{NLT}) corresponding to 1.5 dB OSNR penalty at BER=10^{-3}. a) 43Gb/s IMDD NRZ transmissions over spans of 100km SSMF. b) 112Gb/s coherent PDM-QPSK over spans of 100km SSMF.

As in the WDM case, we observe an increase of the NLT that scales as a power of the number of spans.

Furthermore, if we accept a tolerance of *0.2dB*, we observe that the product $N_{SPAN} \times RDPS$ helps us to predict the NLT of transmissions, as accurately as *RDPS* and N_{SPAN} taken separately.

We obtained similar results for NRZ and coherent PDM-QPSK. This suggests that the behaviour we observe is due to the dispersive regime and not to polarization multiplexing, phase modulation or the coherent detection scheme.

Conclusions

Through numerical studies we showed that in the highly dispersive regime, the non linear phase shift is no longer accurate to assess system performance. We explain this by the averaging of non linear effects due to the walk-off. As a consequence the cumulated dispersion is a valuable parameter. We showed that the mitigation of non linear effects due to walk-off scales as a power of N_{SPAN} and that both inter- and intra-channel non-linear effects are affected.

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