Analysis of Impact of Polarization Dependent Loss in Point to Multi-Point Subsea Communication Systems

Kaoutar Benyahya[1], Christian Simonneau[2], Amirhossein Ghazisaeidi[1], Philippe Plantady[2], Alexis Carbo Meseguer[2], Alain Calsat[2], Haik Mardoyan, Vincent Letellier[2] and Jérémie Renaudier[1]

(1) *Nokia Bell Labs, Route de Villejust, 91620 Nozay, France* (2) *Alcatel Submarine Networks, 91620Nozay,, France*

kaoutar.benyahya@nokia-bell-labs.com

Abstract: We report on numerical investigation of the impact of polarization dependent loss generated by the wavelength selective switches as well as the amplifiers in a point to multi-point subsea- systems. We show that penalties due to R-OADM do not exceed 0.5dB when WSS PDL's is below 0.33dB for 15 in-line WSS.

1. Introduction

Subsea communication systems are the backbone of global data transmission. Today, up to 99% of transcontinental data traffic is carried by subsea cables connecting more than 80% of the countries in the world. This later keep increasing and will reach up to 95% in the coming years. Thanks to the advent of coherent optical transmission, capacity has significantly increased and reached multi-terabit throughput per fiber pairs [1]. To continue improving the data rates per cable with optimal available power and reduced cost per bit, spatial division multiplexing (SDM) systems have been deployed by increasing the number of fibers per cable [2]. On top of transcontinental communications, and thanks to the SDM approach, undersea systems projects are evolving towards an enhanced connectivity with an increasing number of landing points. Consequently, the number of Subsea R-OADM and associated wavelength selective switches (WSS) deployed for some submarine cable could be large. Polarisation dependant loss (PDL) of submarine EDFA is very low and current design rules of submarine cable takes into account the small impact of the cumulated PDL due to these EDFAs. On the other hand, the PDL of the WSS components could not be kept as low as PDL of EDFAs and therefore PDL of a large number of subsea WSSs might have an impact on the transmission performance requiring additional margin. To mitigate the PDL, solutions have been proposed such as Space-time coding [3] however, this solution comes with increased equalization complexity. Therefore, performance margin should be guaranteed considering the worst-case scenario of performance degradation due to the PDL. In this paper, we investigate the SNR margin at outage probability down to 10^{-7}, considering the PDL coming from WSSs and EDFAs. First, we present an analytical model based on the Minimum-Mean-square-Error (MMSE) criterion for SNR prediction, Second, an example of experimental validation of the model is detailed using a 9447km straight-line testbed and commercial transponders. Finally, the PDL of the WSS components, as well as the impact of their location in submarine link will be discussed. We show that for a12300km long submarine link with 15 in-line WSS base R-OADM the additional penalties due to the PDL of R-OADM for an outage probability of 10^{-7}could be below 0.5dB when the WSS PDL is below 0.33dB.

2. Numerical model

In coherent digital communication, blind equalization based on adaptive constant modulus (CMA) as well as multimodulus (MMA) algorithms are the most widely implemented [4]. These algorithms are based on the MMSE criterion on signal amplitude, where the channel taps are blindly estimated with no need of pilot symbols. These algorithms have a close convergence to the true MMSE equalizer, for which theory is well established [5-6]. Hence, we will use MMSE theory to assess the impact PDL in point to multi-point subsea link. Fig.1 (a) depicts a simplified example of a submarine link with multiple landing points. The link is assumed to be a succession of N_S spans and N_W WSS components as illustrated in Fig.1 (b), respectively represented by their 2x2 channel transfer function H_n where

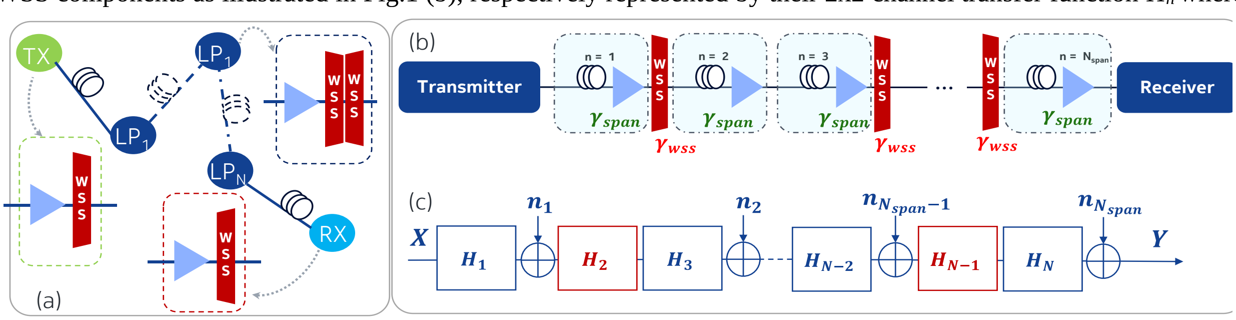

Fig.1(a): Simplified multi-point submarine link with different landing point (LP). (b): System model assumed for analytical study (c) its equivalent mathematical model

n is their corresponding index in Fig.1(c). The received signal Y is given by Eq. (1) in table.1 where H_{sig} is the total channel transfer function seen by the signal from the transmitter to the receiver as given in Eq. (3). It depends on the PDL value Λ_n, in Eq. (6). The theoretical SNR for "x" and "y" polarizations is then computed according to Eqs. (9) and (10), where N_0 is the total additive white gaussian noise (AWGN) variance including transmitter, receiver and ASE noise, and H_{eq} is the equivalent channel transfer function. H_{eq} is computed according to Eq. (7) based on H_{sig} and the noise whitening filter $W^{-1/2}$.

(1)	$Y = H_{sig}X + Z$	(6)	$\Lambda_n = 10 * log10\left(\frac{1+\gamma_n}{1-\gamma_n}\right)$
(2)	$n = \nu(i)$	(7)	$H_{eq} = W^{-\frac{1}{2}}.H_{sig}$
(3)	$H_{sig} = \prod_{i=\mathrm{N_S}+N_W}^{1} H_{\nu(i)}$	(8)	$W = \sum_{j=N_S}^{1}\left(\prod_{i=\Gamma(j)}^{1} H_{\nu(i)}\right)$
(4)	$H_n = R_{\Theta_n}\begin{bmatrix}\sqrt{1+\gamma_n} & 0 \\ 0 & \sqrt{1-\gamma_n}\end{bmatrix}R_{-\Theta_n}$	(9)	$MMSE_i = \left[\left(N_0 I + H_{eq}^H H_{eq}\right)^{-1}\right]_{i,i},\ i \in \{x,y\}$
(5)	$R_{\Theta_n} = \begin{bmatrix}\cos(\theta_n) & \sin(\theta_n) \\ -\sin(\theta_n) & cos\ (\theta_n)\end{bmatrix}$	(10)	$SNR_i = \frac{1}{MMSE_i} - 1$
Z: colored noise		θ_n: random rotation angle, $\theta_n \sim U[0,2\Pi]$	
H_ν : EDFA and WSS channel transfer function		N_0 : additive white gaussian noise	
ν : vector of EDFAs and WSSs indexes		Γ: vector of EDFAs indexes	
I: 2x2 identity matrix		{x,y}: index of polarization {x} and {y}	

Table 1: theoretical equations

3. Experimental validation

We set an experimental testbed representative of a submarine line described in Fig. 2. The line comprises of 171 spans of 55km of submarine fiber (110µm^2 surface area) and 191 single stage EDFAs (34nm bandwidth, output power 16.8dBm). To flatten the channel power excursion of the line (within 1dB) 5 Waveshaper (WS) and 3 fixed equalizing filter (SEQ) are evenly distributed along the line. Moreover 9 polarization controllers followed by adjustable PDL element are also evenly distributed along the line. For the measurement we use a commercial transponder with one channel (1550.32nm) modulated with 69GB QPSK modulation followed by a polarization controller. we use ASE source to load the amplifier line. All the 10 polarization controllers are synchronously activated with a random sequence to statistically scan the polarization state of the line. After each polarization change, we measure the Q factor at the receiver. We measure Q factor for 6700 different states of polarization during approximately 7 days; each Q factor is averaged over 10s. We measure the probability distribution function (PDF) of the Q factor with all adjustable elements first set to 0dB and second set to 0.5dB. Results are displayed in Fig. 3.a. For numerical investigation, we consider the same number of spans and WSS and PDL elements as experiment, we set the SNR to 9.5dB in the absence of any PDL impact. We consider a PDL of 0.05dB for the EDFAs. First, we assessed the impact of amplifiers PDL Λ_s=0.05dB and the value of the PDL elements to Λ_W=0dB (black lines and symbols) and Λ_w=0.5dB (blue line and symbols). Fig.2(b) shows the experimental as well as numerical logarithmic SNR distribution. We notice a ±0.07dB around 9.5dB for experimental case which is due to the finite sequence length. We observe that simulation match well the case with Λ_s=0.05dB for both value of PDL element 0dB and 0.5dB. Simulation has also been made considering

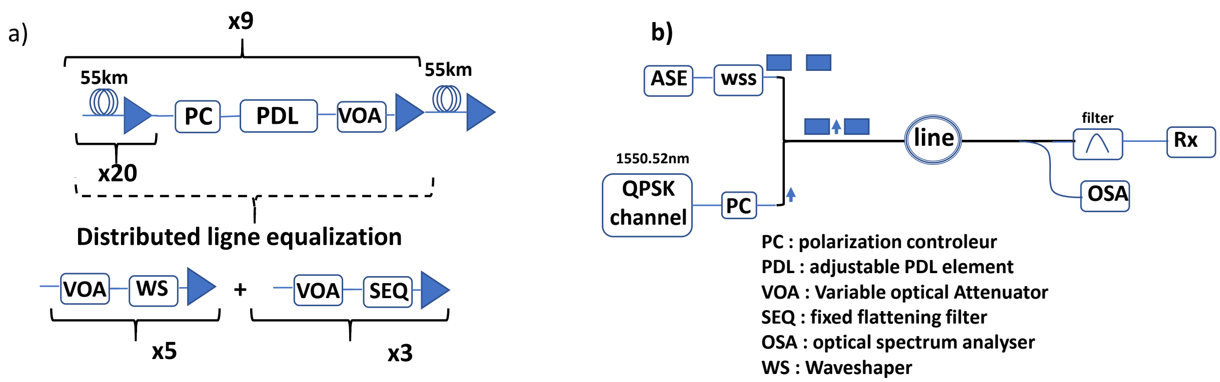

Fig.2(a): line description, (b) emitter and receiver a PDL for EDFA Λ_s=0.15dB (dotted lines) for comparison leading to 1dB additional penalty at outage probability of 10^{-5} showing the importance of keeping EDFAs PDL at a very low value. After model experimental validation, we numerically investigate the impact of PDL WSS in a more complex but realistic configuration by simulation. Indeed, in experiment it is extremely time consuming to measure the outage probability as low as 10^{-5} or 10^{-7}. We set the distance to 12300km and increase the span count to 201 and WSS count to 15. We distribute the WSS placement from the beginning of the link point A to the end point B as depicted in Fig.3(a), We assumed three cases, the first case with all WSS components having the minimum PDL of 0.15dB, the second case with 0.33dB and the third case with a maximum PDL of 0.5dB. We assume the SNR in the absence of PDL is equal to 6.4dB and set the PDL of EDFAs Λ_s to 0.05dB. The PDL impact is assessed for propagation from A to B as well as for the reverse direction B to A. Fig.3(c) shows the logarithmic SNR distribution in the absence of WSS and for the three different values of Λ_W, filled and empty markers represent respectively the propagation from A to B and from B to A. We notice that impact of amplifiers does no exceeds 0.2dB while the additional WSS impact may reach 1.2dB at an outage probability of 10^{-7}. However, penalties due to R-OADM do not exceed 0.5dB when the PDLof WSS components is below 0.33dB. Furthermore, we observe that SNR penalty strongly depends on the propagation direction when the PDL WSS increases. Fig.3(d) plots the SNR penalty versus WSS PDL for the two directions at probability of 10^{-5} and 10^{-7}, for both probabilities we observe that the most impacted direction is from B to A, in fact, a large number of WSS components at the beginning of the link impact more the link performance. Also, SNR penalty increases steeply when increasing the Λ_W and the gap between the two direction becomes wider.

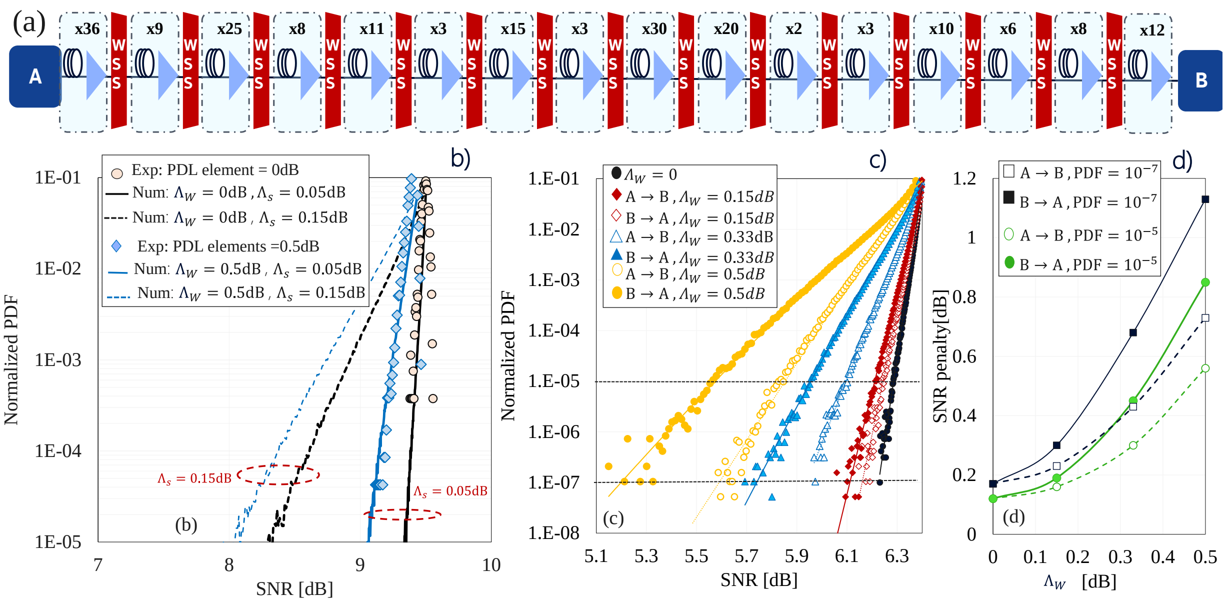

Fig.3(a): submarine line used for simulation of figure 3c) and 3d) (b) experimental and numerical SNR distribution for line used in experiment of Fig2, (c), (d) numerical SNR distribution for propagation in both directions for different values of Λ_W (d) SNR penalty versus Λ_W at outage probability of 10^{-5} and 10^{-7}

4. Conclusion

The impact of the PDL of submerged equipment's of multi-point submarine cable communication systems has been numerically investigated with a simplified model. The numerical model has been experimentally validated with a straight-line testbed and commercial transponders. We show that the introduction of a large number of R-OADM in submarine link could lead to additional penalties that should be carefully assessed. We show that penalties due to R-OADM do not exceed 0.5dB when WSS PDL's is below 0.33dB for 15 in-line WSS.

5. Acknowledgement

This work has been partially funded by the ANR-17-CE25 MUSICO project

References

[1] "376 Pb/s × km Transmission Record over 13,419km Using TPCS-64QAM and C-Band EDFA-Only", Omar Ait Sab et. Al. proc. OFC 2017
[2] "Evolution of High Capacity Submarine Open Cables", J.-C. Antona, A. Carbo-Meseguer, V. Letellier, proc. ACP 2019
[3] "Mitigation of PDL in coherent optical communications: How close to the fundamental limit?" P. Delesques et al. proc. ECOC 2012
[4]" Blind Equalization using the Constant Modulus Algorithm ", Hanks H. Zeng and Lang Tong, Proc. ICSP, Beijing 1996.
[5] "An accurate model for system performance analysis of optical fibre networks with in-line filtering", I. F. de Jauregui Ruiz, et Al. proc. ECOC 2019
[6] J. G. Proakis, "Digital Communication theory", McGrawHill (2002).