Propagation Impairment in Single-Wavelength, Single-Fiber Bidirectional Optical Transmission

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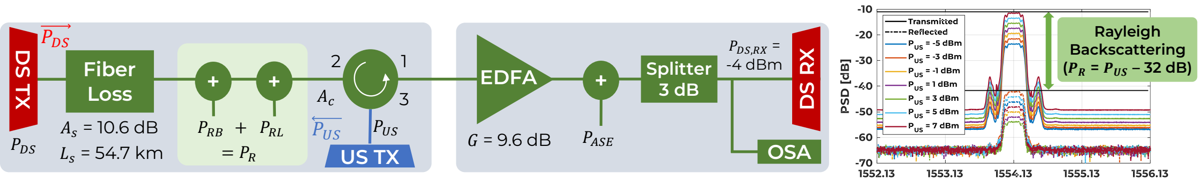
Abstract: We experimentally observe bidirectional transmission of two same wavelength coherent channels on a single fiber. We show that Rayleigh backscattering and, especially, lumped reflections are additional impairments and provide QoT mathematical modeling.

1. Introduction

Bidirectional transmission is a convenient opportunity to double the overall capacity for every fiber strand. This may be particularly useful in the context of metro and access network, where the capacity demand due to the ongoing expansion and new fiber's deployment would require substantial investments. The standard approach to bidirectional transmission is to spectrally separate the flows in opposite directions, using one upstream (US) and one downstream (DS) channel band and employing band splitters/combiners in each node to separate the flows. While this approach is convenient for low cost 10 Gbps transceivers, it becomes less appealing when applied to more costly coherent interfaces, where the transmitter share of the total system cost is significantly higher. The issue with coherent channels is that the local oscillator at the receiver needs a signal at the same wavelength of the incoming signal, hence the spectral separation technique would double the required interfaces. A possible approach to simplify the coherent receiver structure and enable the 100 Gbps and beyond would be to use the same wavelength for both directions, using an optical circulator to discriminate flows in opposite directions in place of the band splitter/combiner [3,6]. However, this may bring some peculiar impairments that do not exist in case of unidirectional transmission, which must be entirely encompassed within a QoT figure used to assess the physical transmission feasibility. For unidirectional coherent transmission the GSNR can be used as a unique QoT figure [2] if all the propagation impairments can be modeled as additive white Gaussian noise (AWGN) sources. The same reasoning can be thus extended to the bidirectional transmission. We have first observed the involved phenomena in a laboratory setup. Although similar observations have been previously reported in other works [4,6], here we focus on a single span system with two counterpropagating coherent channels at 100 Gbps on the same wavelength, generated with modern and commercial hardware. The extension to multi-channel propagation is instead devoted to future investigation. We show that the significant additional impairments on the received channel are the Rayleigh backscattering reflection and, especially, lumped reflections, originated by the counterpropagating channel. We also provide a simple mathematical model to estimate the QoT degradation due to such impairments, targeted to the control plane of optical system exploting bidirectional transmission.

2. Experimental Results and QoT Modeling

The experimental setup to investigate the aforementioned problem (Fig.1(a)) is based on a single spool of Standard Single Mode Fiber (SMF) of $L_s = 54.76$ km and overall loss of $A_s = 10.61$ dB ($\alpha_{dB} = 0.194$ dB/km) which has been characterized with an Optical Time Domain Reflectometer (OTDR). On this fiber, two independent, same-wavelength, channels, are simultaneously counter-propagated and separately received thanks to an optical circulator at one fiber end. We refer to the channel under test (CuT), colored red in Fig.1(a), as the downstream (DS) channel, whereas the interfering, counterpropagating channel (colored blue) is the upstream (US). Transmission and detection of both channels are managed by a commercial AS7716-24SC Cassini transponder, along with two independent Lumentum CFP2-DCO modules, generating and detecting a R_s = 32 GBaud, dual polarization (DP)-QPSK modulated signal delivering 100 Gbps per channel. At the receiver, an EDFA forces the DS CuT received power to the optimum value of $P_{DS,RX} = -4$ dBm. The DS signal is progressively loaded with a variable



(a) (b)

Fig. 1. (a) Experimental setup abstraction for the DS channel. Reflected US power $P_R = P_{RB} + P_L$ modelled as AWGN noise at the DS fiber end. (b) OSA PSD of the US signal backscattered fraction vs launch power P_{US}.

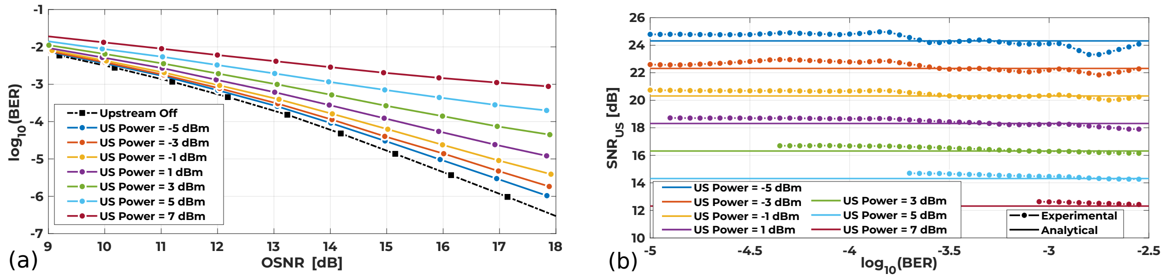


Fig. 2. (a) Experimental BER vs. OSNR vs. US launch power P_{US}. (b) DS CuT SNR degradation due to US signal ($\mathrm{SNR_{US}}$) vs. BER: experimental (circles), analytical model (continuous straight lines).

ASE noise source, thus setting the Optical Signal to Noise Ratio (OSNR), measured with an Optical Spectrum Analyzer (OSA) and the corresponding Bit Error Rate (BER) is read from the transponder DSP interface, thus obtaining the BER vs OSNR characteristic curves. The main target of the experiment is to evaluate the CuT performance degradation as a function of the US channel launched power P_{US} between -5 and 7 dBm, keeping a fixed CuT power $P_{DS} = -3$ dBm. First, we have observed the overall amount of US reflected power with an OSA at the circulator port 1 (Fig.1(a)) and turning off the DS channel. We observed a reflection 32 dB below each US launched power level. (Fig.1(b)). In Fig.2(a) we instead report the BER vs OSNR curves of the DS channel for each US power level. The black curve shows the baseline performance of the (unidirectional) DS CuT with the US channel turned off, encompassing ASE noise e self-channel non-linear interference (NLI) only. The colored continuous curves instead show a QoT degradation as P_{US} increases due to the presence of the counter-propagating US. We model such effect as an additional QoT penalty $\mathrm{SNR_{US}}$ due to the US channel on the overall DS CuT $\mathrm{GSNR_{DS}}$, so that $\mathrm{GSNR_{DS}}^{-1} = \mathrm{OSNR}^{-1} + \mathrm{SNR_{NL}}^{-1} + \mathrm{SNR_{US}}^{-1}$. The DS only black curves includes only the first two terms of due to ASE (OSNR) and NLI ($\mathrm{SNR_{NL}}$). The $\mathrm{SNR_{US}}$ is extrapolated subtracting the $\mathrm{GSNR_{DS}}$ curve for each US power level from the $\mathrm{GSNR_{DS}}$ curve of the unidirectional case, after interpolation at the same BER and is reported in Fig.2 (circles). The $\mathrm{SNR_{US}}$ values are flat US power-wise, representing a constant additive noise and scale linearly with unitary dB-slope as P_{US} increase, so that there is no cross-channel interaction between the US and DS. Hence, the $\mathrm{SNR_{US}}$ contribution is likely solely due to US power back-reflected in the same DS direction (Fig.1(a)). Such reflections may be of two types: the Rayleigh backscattering (RB) [5,7] - a *distributed effect* along the fiber - and the lumped reflections due to fiber splices, connectors, etc. We assume that both the contributions are white (within the DS channel bandwidth) since they share the same PSD of the spectrally flat (as in Fig.1(b)), depolarized coherent US channel. We also assume them Gaussian distributed and independent onthe DS channel (as generated by the US). Hence, we abstract the setup with AWGN sources as in Fig.1(c), so that $\mathrm{SNR_{US}} = {}^{P_{DS}}/_{A_s P_R}$, being P_R the sum of the Rayleigh P_{RB} and lumped P_L terms, which can be modeled as:

$$P_R = P_{RB} + P_L = A_{c,32} P_{US} \left(R_{RB} + R_L \right) = A_{c,32} P_{US} \left(2S\alpha_R \frac{1-e^{-4\alpha L_s}}{4\alpha} + \sum_i R_i e^{-4\alpha L_i} \right) \tag{1}$$

R_{RB} is the equivalent reflectance of the distributed Rayleigh backscattering obtained by solving the power evolution differential equation [7]. Here, α_R is the Rayleigh backscattering field loss (≈ 0.15 dB/km) [1,7], $S = 1.5 \cdot 10^{-3}$ is the Rayleigh capture factor [5,7] - the back-scattered light portion. R_L sums for all the lumped losses, being L_i the fiber position in the US direction where the i-th reflection happens and R_i its reflectance. $A_{c,32}$ is the circulator loss between port 3 and 2 ($\approx$ 0.8 dB). In both the contributions, the exponential terms account for the round-trip loss of the US power and the its reflected portion. However, the OTDR did not show any reflection on the fiber and the used FC/APC connectors ensure reflectivities < -50 dB. In our setup we can thus neglect the R_L contribution. This is further confirmed by the fact that the R_{RB} estimation by Eq.1 delivers -32.3 dB, in perfect accordance with the reflectance measured as in Fig.1(b). Fig.2(b) reports also the $\mathrm{SNR_{US}}$ model estimations using Eq.1 as straight continuous lines, which is outstandingly accurate as RB intensity prediction.

3. Conclusions

We have experimentally observed the bidirectional transmission of two same-wavelength coherent channels and given a QoT estimation tool. Besides RB, lumped losses may severely impair the channel performance. Indeed, while in our controlled laboratory setup such features are absent, in typical metro and access network segments they are very common. Reflections at the US (DS) channel's input connector or in the first fiber kilometers may impair severely the DS (US) channel since there the US still carries a large power. Hence, the problem of bidirectional transmission is not inherently propagative but requires careful handling of all the interconnections.

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