System Performance and Pre-emphasis Strategies for Submarine Links with Imperfect Gain Equalization

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Abstract: We studied C-band system performance penalties due to gain tilt. Several transmission pre-emphasis strategies for penalty compensation were considered. The overall penalties were small and minor differences between strategies were observed for investigated tilt range.

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1. Introduction

Modern submarine communication systems operate over wide optical bandwidths. It is desirable to maintain a uniform channel power evolution over the entire bandwidth [1] as gain shape distortions can accumulate thereby, degrading the system performance. One of the common source of gain shape distortion is a mismatch between EDFA gain and span loss caused by manufacturing variations, cable ageing, repairs, etc. [2, 3]. This gain distortion in submarine links is characterized usually by the end-to-end gain tilt computed as a linear RMS fit to gain spectral profile. In long EDFA chains end-to-end gain tilt is sensitive to the mismatch between EDFA gain and span loss. In example of 10,000 km full C-band system, each 0.1dB average mismatch per 80km span gives approximately 2dB end to end tilt and additional 1dB deviation of actual gain shape from the linear fit.

Historically, submarine fiber systems have used optical signal-to-noise ratio (OSNR) equalization for performance optimization [4]. This equalization was performed by changing transmitter power across wavelengths, also known as transmitter pre-emphasis. This equalization strategy made sense for narrow-band linear systems where OSNR is directly related to channel performance. In these systems, the spectral hole burning effect is relatively uniform across the amplification band. The performance impact of gain shape distortions in such systems has been studied experimentally and analytically [4]. However, modern submarine systems have evolved to support full C or C+L, with higher nonlinearity, larger OSNR difference across the band and flexible rate transponders. In such systems OSNR equalization by transmitter pre-emphasis may not be the best approach and better alternatives are suggested [5] when maximizing the total fiber capacity is the main goal, as opposed to worst channel performance as it was in the past.

In this paper, we present simulations and experimental measurements of the performance penalty for different amounts of system gain tilt. We investigate various pre-emphasis strategies to compensate the tilt penalty and maximize capacity suitable for wide-band nonlinear systems. We also compare the impact of locally accumulated and compensated tilt with end-to-end accumulated tilt and discuss unimportance of worst-case channel performance for capacity estimation with variable rate transponders.

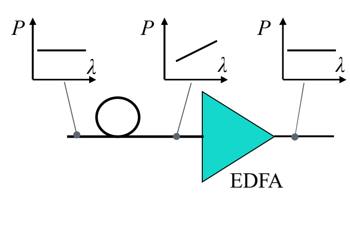

Fig. 1: System Building Block in Simulations

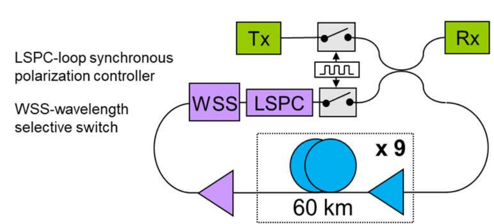

Fig. 2: Experimental setup of the circulating loop testbed.

2. Simulation Setup

To define performance penalty, we need a reference system against which the penalty is compared. The reference system is constructed by concatenating identical building blocks shown in Fig. 1. Each block starts with transmission fiber and ends with an EDFA. The small graphs in Fig.1 schematically show the power spectral densities at various points within this block. By definition, we call this system the reference with zero gain tilt. We design systems to operate near the maximum performance point with respect to transmission fiber nonlinearity (so called operation at nonlinear peak) using EGN model [6]. The transmission fiber has 0.16 dB/km loss and 130 μm^2 effective core area. Each fiber span is 60 km in length. The C-band total output power at nonlinear peak is 18 dBm.

There are multiple ways to create system gain tilt in simulation. For example, one can change fiber span loss or change EDF length in amplifiers or periodically introduce wavelength depended loss along the system length. Introduction of extra losses into the system can have penalty associated with the loss itself. Our goal is to characterize the impact of the tilt only, therefore, we have selected the EDF length adjustment as the mechanism to change the gain tilt. In all our simulations EDF length was adjusted by the same amount in all amplifiers along transmission link.

We consider two ways of tilt accumulation. In first, the tilt is gradually accumulated, in second the gain shape is compensated completely by shape correction filter. This is done each 25 amplifiers or for each "block" of the system to estimate the importance of local tilt accumulation vs. "global" accumulation along the whole system length.

3. Experimental Setup

We experimentally studied a couple of tilted conditions in a circulating loop system. The circulating loop was comprised of transmission fiber with 0.166 dB/km loss and 150 μm^2 effective core area (Fig. 2). Each fiber span was 60 km in length and was separated by EDFAs with a C-band total output power of 19.5 dBm, which corresponds to nonlinear peak power for this setup. Residual gain equalization was performed using a wavelength selective switch (WSS). The same WSS was also used to introduce gain tilt in transmission system. The link was loaded with broadband noise in 37 nm bandwidth. To perform transmission measurements, a part of the noise loading equivalent to eight consecutive channels was blocked using a WSS at the transmitter and substituted with eight measurement channels tuned to the appropriate wavelengths and launch powers. Performance was measured using 35 Gbaud 16QAM channels on a 37.5 GHz grid. The system performance was measured across the band in all cases.

4. Pre-emphasis Strategies and Capacity Calculation

Four different Tx strategies are evaluated in this paper, and they are defined as follows: **1) Flat Tx launch**, where the Tx power of each channel is the same; **2) OSNR Equalization**, where the received OSNR for each channel is matched via the control of Tx channel powers; **3) P_{in} + P_{out} Equalization**, where the average of the Tx and Rx powers of each channel given by $P_{\mathrm{ave}} = (P_{\mathrm{in}} + P_{\mathrm{out}})/2$ is constant across wavelength [4]; and **4) Maximum Capacity Tx Pre-emphasis,** where Tx channel powers are varied using generic optimization algorithm to maximize capacity of the system (simulation only). This is maximum possible capacity available for the system.

Channel signal-to-noise ratio (SNR) refers to any performance related metric or noise contributor, such as linear SNR (SNR_{ASE}), nonlinear SNR (SNR_{NL}), modem implementation SNR (SNRm), and Guided Acoustic-Wave Brillouin Scattering (GAWBS) SNR_{GAWBS} [7] etc. The inverse of channel SNR was calculated by the sum of reciprocals for each noise SNR for this channel. Shannon capacity was then calculated for each channel and total system capacity was calculated as sum of capacities for each channel. For convenience, we converted total capacity back to SNR using inverse of Shannon capacity formula, treating it as if it is a single channel with bandwidth equal to the system bandwidth. We call this value as system SNR and by construction it correctly accounts for wavelength dependent penalties. The system SNRs were calculated for reference and tilted systems and difference in system SNRs in dB was used as SNR penalty. In experiment, total system capacities were estimated by measuring Q-factors for multiple channels at different wavelengths for reference and tilted systems. The SNR penalty was then calculated in similar fashion.

5. Results and Discussion

Fig. 3 (a) and (b) shows the system SNR penalty for different equalization strategies for a 7,000km system at 1dB above the nonlinear peak (a) and 1 dB below nonlinear peak (b). Figure 3 (c) shows penalty for 12,000km system at the peak of nonlinear performance. There are no significant differences between all those cases. Simulation results show that all equalization methods provide almost the same capacity. The Maximum Capacity equalization yields the lowest system SNR penalty, as expected, but the P_{in} + P_{out} equalization differs less than 50 mdB even at the largest tilt values considered. The experimental data measured at approximately ± 5dB tilt confirms the trends at 7,000km. OSNR equalization at + 5dB tilt was performed with only 3dB accuracy due to experimental limitations. OSNR for -5dB tilt was performed with 0.5dB accuracy in experiment. All equalization cases had 0.1dB accuracy in all simulations. One can see that for either Pin + Pout equalization or Maximum Capacity pre-emphasis strategies, the window where penalty is below 0.1dB is rather large, more than 6dB.

Fig. 3 (b) and (c) also contain the results of block equalization for the same mismatch of EDFA gain and span loss as for other curves but re-equalized each 25 amplifiers. One can see that nearly in all cases the impact of the mismatch is close to the maximum capacity curve. Therefore, if the local tilt is within +/- 3dB from the target, its penalty is below 0.1dB on system performance. We expect the impact to be smaller if the gain tilt is equalized more often.

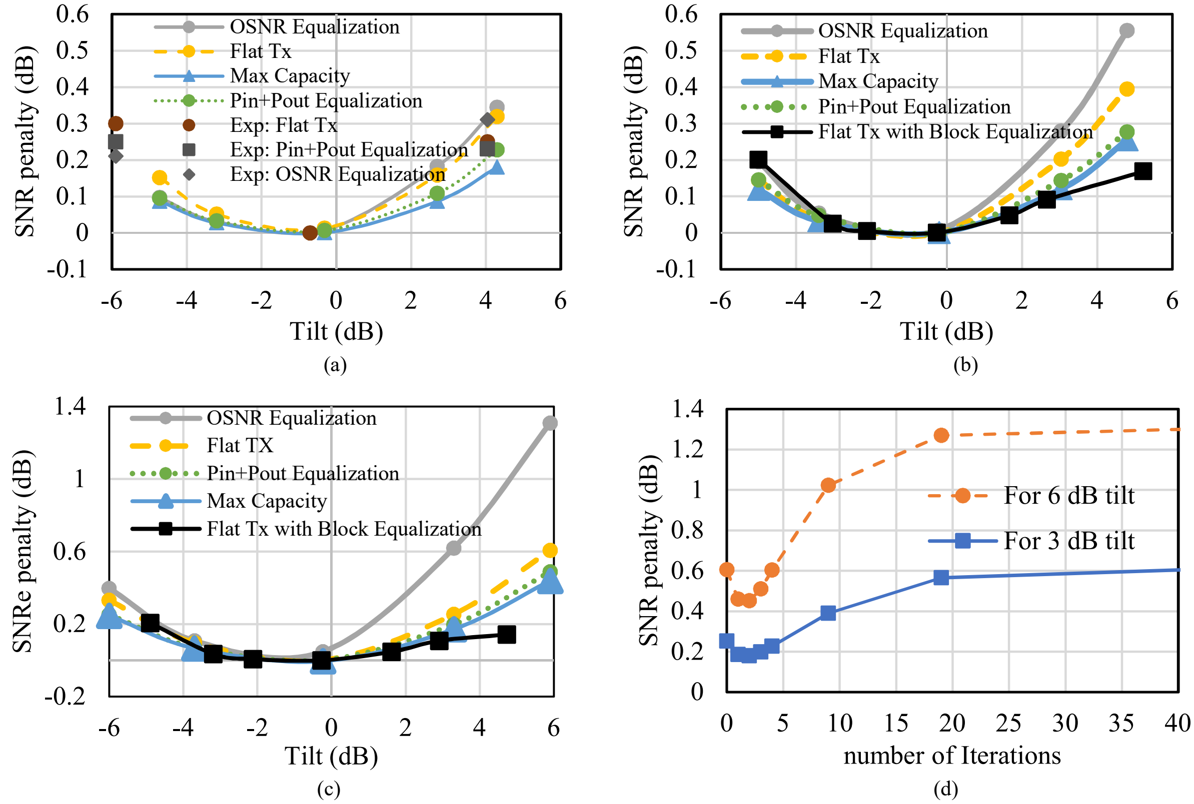

Fig. 3: SNR penalty for systems at 1dB above nonlinear peak for 7,000km system (a); 1dB below nonlinear peak for 7,000km system (b); and nonlinear peak for 12,000km system (c). SNR penalty as a function of number of OSNR equalization iterations for the system at 12,000 km (d).

We noticed that we could achieve better results for OSNR equalization with relaxed requirement for OSNR accuracy or with smaller number of iterations of the equalization algorithm. Figure 3(d) shows SNR penalty for various number of OSNR equalization iterations in simulation of 12,000 km transmission distance. After 2 steps of OSNR equalization iterations, the SNR penalty grows with the number of iterations.

We observed that the total SNR penalties were significantly smaller than the worst channel penalty. For example, for positive 6dB tilt and Pin + Pout equalization at 12,000km, the total SNR penalty was 0.5dB, while the worst channel penalty was 3dB. For negative 6dB tilt the numbers were 0.2dB and 0.7dB respectively.

7. Conclusion

In agreement with the published study [5], we find that total SNR penalty due to system gain tilt is rather small over wide range of gain tilt values. The penalty was smaller than 0.1dB for 6dB tilt window for flat launch and for P_{in} + P_{out} equalization . We confirm this result experimentally and via simulations performed for different system design operating points and transmission distances. While the differences between Tx pre-emphasis strategies are small, P_{in} + P_{out} equalization is the closest to obtain maximum fiber capacity. We show that attempt to flatten RX OSNR lead to a large penalty, hence it is advisable to limit the number of OSNR equalization iterations. With exception of accurate OSNR equalization, the maximum possible aggregated system capacity can be estimated with good accuracy using any other considered pre-emphasis techniques. We show that penalty due to local tilt is below 0.2dB for +/-5dB tilt if it is periodically removed by equalization. We also demonstrate that large values for worst channel SNR penalty do not translate to large system performance penalty when capacity is calculated assuming variable rate transponders.

8. References

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