Impact of SRS-induced crosstalk for different modulation formats in WDM systems

Stefan Schöllmann, Jochen Leibrich, Christoph Wree and Werner Rosenkranz
Chair for Communications, University of Kiel, Kaiserstr. 2, D-24143 Kiel, Germany
e-mail address:sts@tf.uni-kiel.de

Abstract: In this paper we investigate the combined effect of SRS crosstalk and GVD on amplitude and phase shift keyed modulation formats considering RZ and NRZ pulse shaping.

OCIS codes: (060.5060) Phase modulation; (290.5910) Stimulated Raman Scattering

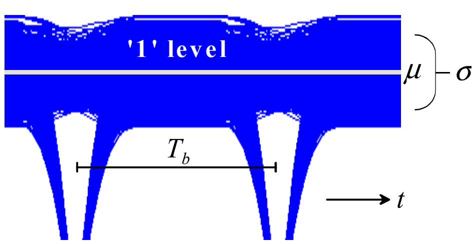
1. Introduction

The constant demand for more capacity on optical fibers can be met by increasing the number of transmission channels, which for constant bandwidth efficiency requires to increase the total width of the WDM spectrum. Based on this development the nonlinear effect of Stimulated Raman Scattering (SRS) gains in importance, which depends on the bandwidth of the WDM spectrum, channel number and signal power. Due to SRS, high frequency channels act as energy pumps for low frequency channels [1]. This energy transfer has two consequences for an optical WDM system: Firstly, a spectral tilt downward from lower to higher frequencies is generated [2], which can be compensated for by an appropriate wavelength-dependent gain. Secondly, the '1' level of each channel is broadened, which evokes a significant degradation of the eye opening and is considered as one important limiting effect for broadband WDM transmission. The broadening of the '1' level is influenced by group velocity dispersion (GVD) [3].

In this paper, we compare amplitude shift keyed (ASK) and phase shift keyed (PSK) modulation formats regarding robustness towards SRS crosstalk. The structure is as follows: In sect. 2 we describe the method for comparing different modulation formats quantitatively. Sect. 3 depicts the simulation setup. In sect. 4 the results are given and discussed: The impact of SRS crosstalk for varying power levels and different values of the dispersion parameter is investigated. Based on these results in the second part we compare NRZ-ASK with RZ-DPSK for Standard Single Mode Fiber (SSFM) and Nonzero Dispersion Shifted Fiber (NZDSF) in a multi-span setup.

2. Method for Quantitative Investigation of SRS crosstalk

As illustrated in fig.1 the spreading of the '1' level due to SRS crosstalk is quantified by the variance σ^2 of the samples taken at the center of the eye. The values of σ^2 can be calculated for zero dispersion and ASK modulation according to [2] and [3] as



$$\sigma_{P1}^2 = \frac{N(N-1)(2N-1)\Delta f^2 g_R^2 L_{eff}^2}{216 \cdot 10^{26}} P^4 \qquad (2.1)$$

Fig.1: Magnification of the upper part of the eye diagram showing standard deviation and mean value for '1' level broadened due to SRS crosstalk.

where P is the peak power of each channel, Δf is the channel spacing, g_R is the Raman gain coefficient, N is the number of channels and L_{eff} = [1-exp(-αL)] is the effective length of the fiber with α as loss coefficient and L as fiber length. Making use of σ, a measure for the eye closure is obtained by calculating the ratio of σ and the mean value of the '1' level quantified by μ. For bipolar data (e.g. PSK), both the '1' level and the '-1' level suffer SRS crosstalk. As for this case the eye opening is twice the mean value, the ratio of σ and μ can still be used as a measure for eye closure.

3. Simulation setup

For all simulations, a WDM setup according to fig. 2 was implemented. To emulate broadband multi-channel transmission, 11 channels were distributed over a bandwidth of 5 THz resulting in 500 GHz channel spacing.

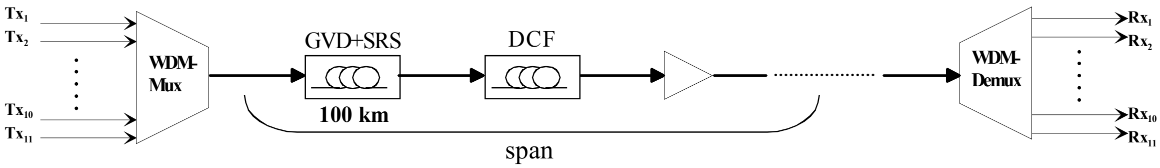


Fig.2: Simulation setup for evaluating the robustness of different modulation formats towards SRS crosstalk

The modulation formats generated in the transmitters (TX, 10 Gb/s) were ASK and DPSK with NRZ and RZ pulse shaping, respectively. Both ASK and DPSK were generated by driving a Mach-Zehnder modulator (MZM) in push-pull configuration, were the swing of the driving voltage was doubled for DPSK and the bias was set to zero. For RZ pulse shaping, a second MZM driven by a 10 GHz clock created an RZ pulse train from the continuous wave laser output. Differential demodulation in the receiver (RX) for DPSK formats was performed using a delay-and-add interferometer and balanced detection [4].

The length of the transmission fiber was 100 km per span, the dispersion of which is compensated for by 100%. For the simulation, all nonlinear effects except for SRS were neglected.

4. Results and Discussion

Fig. 3 shows SRS crosstalk represented by σ of the '1' level depending on optical power per channel (see (2.1)) and dispersion coefficient for NRZ-ASK, NRZ-DPSK and RZ-DPSK, respectively.

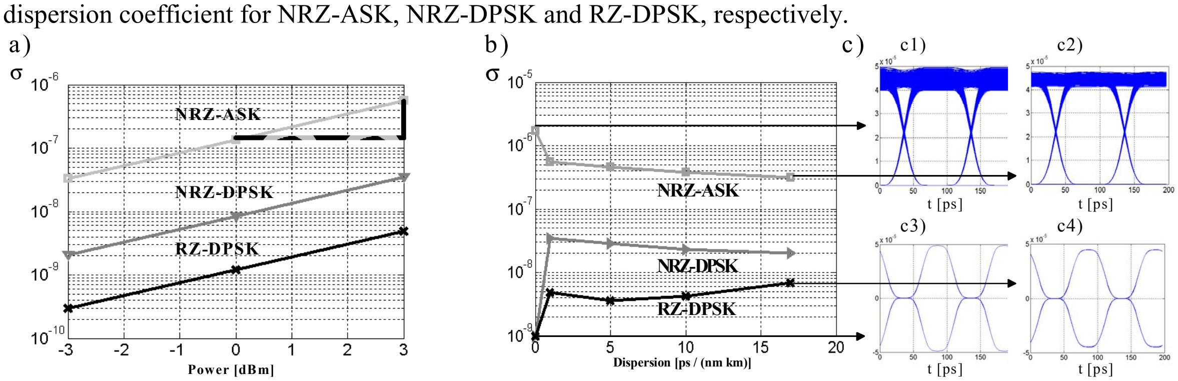


Fig. 3: Dependence of standard deviation σ of '1' level for different modulation formats on a) varying optical power levels b) varying dispersion constants with constant optical power level of 3 dBm after transmission over 100 km; c) eye diagrams for parameter set given in b)

Fig. 3a points out in double logarithmic scale a constant gradient being equal for all curves for varying power levels. It is verified by the triangle in fig. 3a that doubling the power yields quadruplication of σ. Thus, the specific modulation format has no impact on the power dependence. This means that the variance is proportional to P^4 for all formats considered (see (2.1)). However, the proportionality factor differs depending on the particular format.

According to fig. 3b, PSK modulation in general shows significant lower standard deviation compared to ASK modulation for all values of the dispersion coefficient. Moreover, RZ pulse shaping for DPSK results in additional reduction of the spreading of the '1'-level. For increasing dispersion constants all NRZ-curves are characterized by approximately the same negative gradient, while the standard deviation for RZ-DPSK first decreases and than increases for large values for D. The results are explained as follows:

Firstly, lower standard deviations for PSK modulated signals in general are due to the SRS-induced crosstalk being equal for each bit. This is a direct consequence of the optical power for PSK being independent of the current bit, which is due to the fact, that for PSK the symbols '+1' and '-1' are transmitted (in contrast to ASK with the symbols '1' and '0'). On the contrary, for ASK modulated signals the power and consequently the crosstalk depend on the bit pattern resulting in a spreading of the '1' level.

Secondly, for zero dispersion the '1' level of an ASK modulated signal is split up into $2^{(N-1)}$ discrete levels which yields maximum standard deviation (fig. 3c1, the discrete nature is not visible due to the large number of levels). Making the step towards dispersive fiber results in group velocity differences between the channels, i.e. a continuous change of the relative position of the bits between the signals in neighboring channels, resulting in an averaging process on the SRS crosstalk. In addition, due to the large channel spacing the initial synchronization of the data signal is destroyed already after some hundreds of meters. As a result of the averaging process, for ASK modulation the discrete '1' levels go over into a continuum, which at the same time reduces the width of the '1' level (fig. 3c2). The reduction of the standard deviation increases for high dispersion constants.

On the other hand, using PSK modulation for zero dispersion (fig. 3c3) as well as for dispersive fiber (fig. 3c4) only slight spreading occurs which is lower than for ASK modulation by more than one order of magnitude.

Thirdly, further reduction of the standard deviation σ using RZ-DPSK is explainable with the periodic time characteristic of the optical power [5]. This implies discrete spectral lines for the optical power, compared to the continuous frequency spectrum for NRZ-pulse shape. Hence, NRZ-pulse shapes exhibit arbitrarily low frequencies in comparison to RZ-DPSK. Modeling the averaging process in the frequency domain, low frequencies contribute to the spreading of the '1' level to a larger extent compared to high frequencies as it can be shown in a similar derivation as for XPM [6], where the process of crosstalk from one channel to another was derived to follow a lowpass characteristic. Therefore, RZ-DPSK with discrete spectral lines shows very low spreading of the '1'-level.

Fourthly, for higher dispersion constants the exact periodic time characteristics are destroyed for RZ-DPSK. Founded on this circumstance lower frequencies are generated and the signal is influenced negatively. Nevertheless, the increase of the standard deviation is below a level of significance (fig. 3c4).

Fig. 4a illustrates the comparison of NRZ-ASK and RZ-DPSK for two different fibers [SSMF with D=17 ps/ (nm km), D_s = 0.06 ps/ (nm^2 km); NZDSF with D=4.2 ps/ (nm km), D_s = 0.09 ps/ (nm^2 km)] and varying number of spans. Fig. 4b shows the ratio of standard deviation σ and mean value μ depending on the number of spans for NRZ-ASK and RZ-DPSK modulation format. The simulations are based on a high power level of 10 dBm for each of the eleven channels, which was taken in order to emphasize the robustness of PSK-modulation formats.

In the simulation the gain tilt due to SRS was compensated for after each span by appropriate wavelength-dependent amplification.

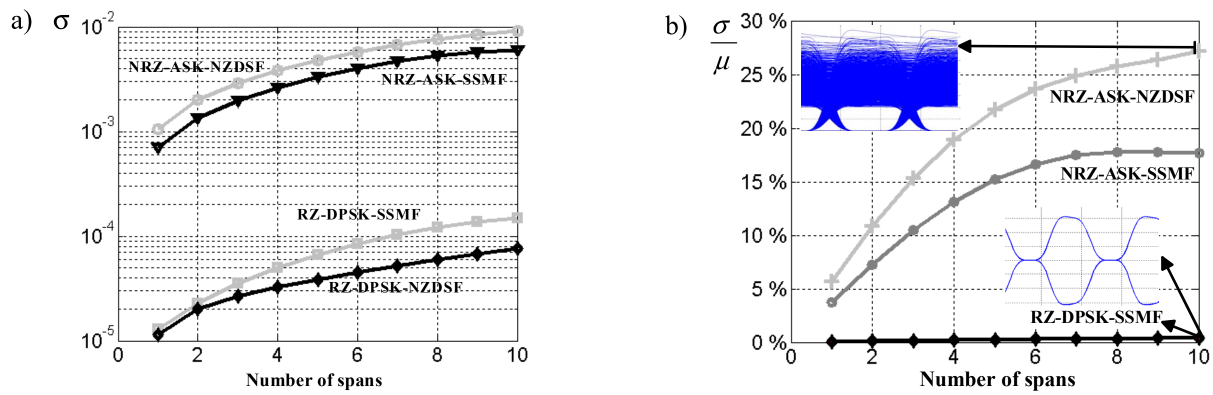


Fig. 4: a) Dependence of standard deviation σ of '1' level towards different number of spans b) Dependence of the ratio (σ/μ) for different number of spans

In fig. 4a it is clearly visible that a larger number of spans increases the standard deviation for all modulation formats investigated. Furthermore RZ-DPSK shows an eminent robustness towards SRS crosstalk over long distances. In comparison to RZ-DPSK which exhibits after 10 spans a ratio $\sigma/\mu < 0.5$ %, fig. 4b illustrates clearly the significant increase for NRZ-ASK (up to 27 % for NZDSF). These results confirm the comments that were given in preceding paragraphs. Founded on results shown in fig. 4b under the assumption of a very high power level we postulate that it is valid to neglect the SRS crosstalk completely when using RZ-DPSK modulation format.

5. Conclusion

We have established that in general PSK modulation formats are more robust for all circumstances towards SRS-induced crosstalk. Furthermore we could show that the spreading of the '1' level is additionally reduced by using RZ-pulse shaping for PSK formats. With a simulation for long haul transmission it was possible to show that the crosstalk can be neglected completely for an RZ-DPSK modulated signal.

6. References

[1] Govind P.Agrawal, *Nonlinear Fiber Optics,* (Academic Press, 2001), Chap. 8
[2] F. Forghieri et al., IEEE Photon. Technol. Lett., **7,** 101 (1995)
[3] M. Muktoyuk et al., OFC 2003, paper MF3
[4] M. Rohde et al., Electr. Lett., **36,** pp. 1483-1484 (2000)
[5] J. Leibrich et al., IEEE Photon. Technol. Lett., **14,** No. 2, pp. 155-157 (2002)
[6] J. Leibrich et al., APOC 2002, paper 4906-01