Investigations of the Dispersion Tolerance of the Nonlinear Optical Transmission Channel for Different Modulation Formats in a WDM-System

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ABSTRACT

We investigate the dispersion tolerance for nonlinear WDM transmission of the modulation formats ASK, DPSK, DQPSK and Duobinary with NRZ as well as RZ pulse shape. We study different dispersion maps and determine for each modulation format an optimized dispersion map to examine the robustness against variations of the dispersion map and against nonlinear effects.

Keywords: Dispersion Tolerance, Nonlinear Channel, Dispersion map

1. INTRODUCTION

Currently most optical fiber communication networks are using NRZ-ASK, which is very susceptible to nonlinear effects. One possibility to make these existing networks more efficient is to upgrade them with a modulation format that is more robust than NRZ-ASK. This upgrade has to be as cost-efficient as possible. The so-called “Cut & Paste” approach satisfies this requirement. With this approach only the transmitter and the receiver has to be substituted and the existing dispersion map is left unchanged. According to this the modulation format with which the network should be upgraded has to fulfill two requirements. The first one is the robustness against nonlinear effects and the second one the robustness against variations of the dispersion map.

Therefore we determine in this paper in a first part an optimized dispersion map for ASK, DPSK, DQPSK and Duobinary with NRZ as well as RZ pulse shape. Afterwards we examine for each modulation format the dispersion tolerance of this dispersion map to investigate the robustness against nonlinear effects. In a second part we investigate for each modulation format the dispersion tolerance of different dispersion maps for studying the robustness against variations of the dispersion map.

2. SIMULATION SETUP

All simulation results are based on a 5-channel WDM system with equal channel spacing of 50 GHz at a data rate of 10 Gb/s as shown in Fig. 1. The mean power of each channel is varied in steps of 3 dBm from -3 dBm up to 3 dBm.

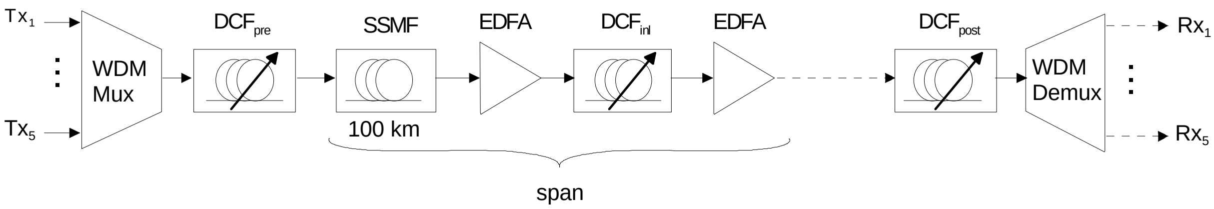

Fig.1: Simulation setup for the investigation of the dispersion tolerance of the nonlinear channel

In the transmitter (Tx) the investigated modulation formats are generated. Duobinary (Duo) is realized by a delay-and-add filter followed by a band limiting low-pass filter [1]. For NRZ-DQPSK a parallel setup as shown in [2] is used. RZ-DQPSK is generated by a serial setup as published in [3]. Both arms of the DQPSK System are driven with 5 Gb/s.

The system is characterized by a variable dispersion pre- and post-compensation scheme with DCF_{pre} and DCF_{post} respectively. Each span consists of a 100 km standard single-mode fiber (SSMF) followed by a DCF_{inl} of variable length. On the SSMF the nonlinear effects cross-phase-modulation (XPM), self-phase-modulation (SPM) and four-wave-mixing (FWM) are considered. The two EDFAs are adjusted in a way that the attenuation on the SMF and the DCF is fully compensated. The number of spans is varied.

At the receiver side (Rx) DPSK and DQPSK are demodulated through Mach-Zehnder interferometers followed by balanced detection [3]. The standard direct detection receiver is used for the other formats.

3. DETERMINATION OF THE DISPERSION TOLERANCE

We use the dispersion tolerance for the nonlinear channel to exhibit the robustness of each modulation format against the nonlinear effects XPM, FWM and SPM and against variations of the dispersion map. In order to analyze the worst case, we only focus on the center channel.

The determination of the dispersion tolerance is based on the width of the eye-opening-penalty (EOP)-vs.-residual dispersion curves at 1 dB EOP degradation. These curves are evaluated with constant pre- and inline-compensation and variable length of the post-compensating fiber DCF_{post}.

In a first step we determine for each modulation format the dispersion tolerance for all simulated combinations of pre- and inline-compensation. In a second step we calculate for each modulation format an optimized dispersion map. Therefore we determine the combination of pre-, inline- and post-compensation, which results in the maximum dispersion tolerance of the nonlinear channel. The values for the pre-, inline- and post-compensation of this combination are the values for the optimized dispersion map. For this optimized dispersion map we determine the dispersion tolerance of the nonlinear channel.

For the results that are presented in the following section 4 we calculate a relative dispersion tolerance of the nonlinear channel based on the dispersion tolerance at a mean input power of -3 dBm per channel.

4. RESULTS AND DISCUSSION

Fig. 3a and 3b shows the absolute value of the dispersion tolerance of the nonlinear channel for the optimized dispersion map at a transmission length of 3000 km for all investigated modulation formats. From this figure it can be seen, that for NRZ-Duo the dispersion tolerance in the low power regime is higher than for all other modulation formats due to the reduced bandwidth. But it can be seen as well that with increasing input power and hence increasing nonlinearities the dispersion tolerance decreases very rapidly [4]. The dispersion tolerance of RZ-Duo is smaller than the dispersion tolerance of its NRZ counterpart due to its wider spectrum and thus bigger susceptibility against dispersion. Thit holds for RZ-DSPK and RZ-ASK, too.

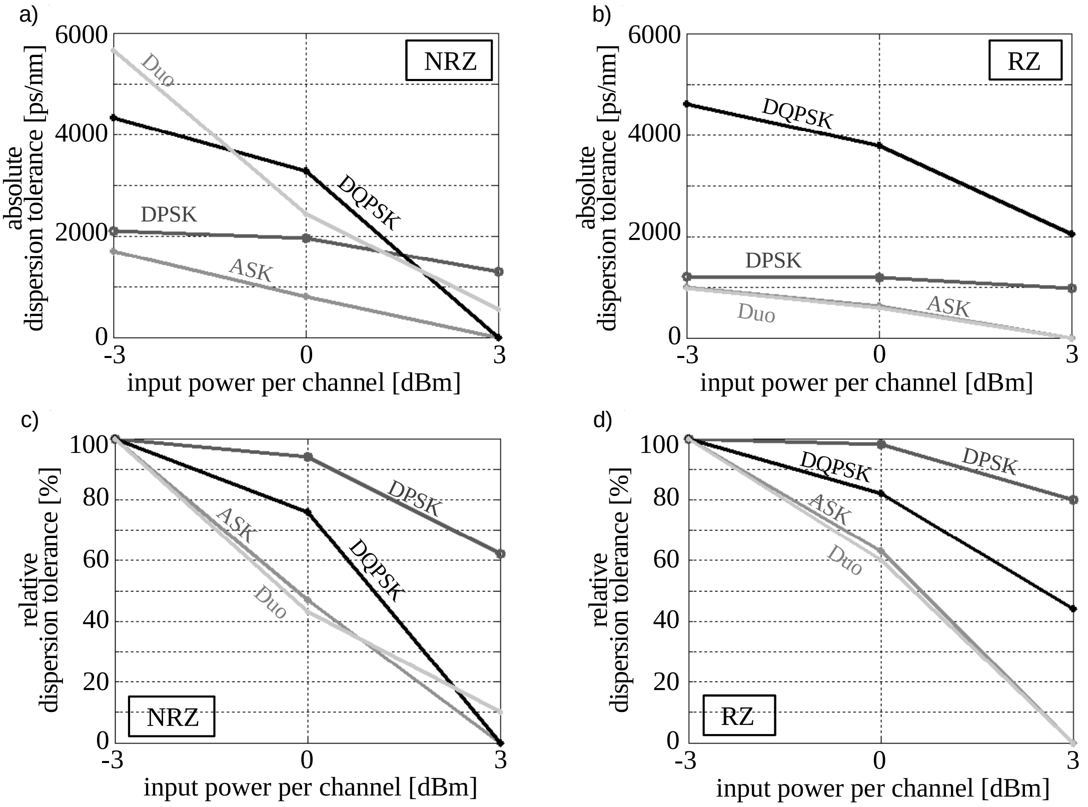

Fig 3: Absolute dispersion tolerance of the nonlinear channel for ASK, DPSK, DQPSK and Duobinary with a) NRZ and b) RZ pulse shape and relative dispersion tolerance of the nonlinear channel for ASK, DPSK, DQPSK and Duobinary with c) NRZ and d) RZ pulse shape for the optimized dispersion map at a transmission length of 3000 km.

The dispersion tolerance of the DQPSK formats is approximately twice the dispersion tolerance of NRZ-DPSK at an input power of -3 dBm per channel due to the smaller symbol rate. However similarly as with NRZ-Duo the dispersion tolerance of the DQPSK formats decreases rapidly with increasing input power. The approximately equal dispersion tolerance of NRZ-DQPSK and RZ-DQPSK at a mean input power of -3 dBm per channel is explainable by the different way symbol transitions take place. Some phase shifts of NRZ-DQPSK occur at a high power level, which causes a chirp and thus a higher susceptibility against dispersion. The degradation of the dispersion tolerance for all investigated modulation formats is shown in fig. 3c and 3d. It indicates that the decrease of the dispersion tolerance of all PSK formats is less than for the ASK and Duobinary formats due to the approximately constant power level on the channel. The gain of the dispersion tolerance compared to NRZ-ASK is between 45 % for RZ-DQPSK and 80 % for RZ-DPSK at a mean input power of 3 dBm. The better performance of the DPSK formats compared to the DQPSK is explainable by the fact, that DQPSK is more sensitive to phase variations than DPSK. The decrease of the dispersion tolerance of RZ-DPSK is less than for NRZ-DPSK due to the greater influence of XPM on lower frequencies. The power spectrum of RZ-DPSK is nearly a line spectrum due to the periodical power signal and thus more robust against XPM [5].

From the previous discussion we have seen that RZ-DPSK is most robust against nonlinear effects for an optimized dispersion map, which is the first requirement of the “Cut & Paste” approach. In the following we investigate all simulated dispersion maps for each modulation format. In fig. 4 the dispersion tolerance of the nonlinear channel is mapped as a function of the pre-compensation and dispersion per span for RZ-DPSK at a mean input power of 0 dBm for different transmission lengths (fig. 4a-c) and for a transmission length of 3000 km at a mean input power of 3 dBm (fig. 4d). The dispersion per span is made up of the dispersion of the SSMF and the DCF of the inline-compensation, so that a fully compensated span has a dispersion per span of 0 ps/nm.

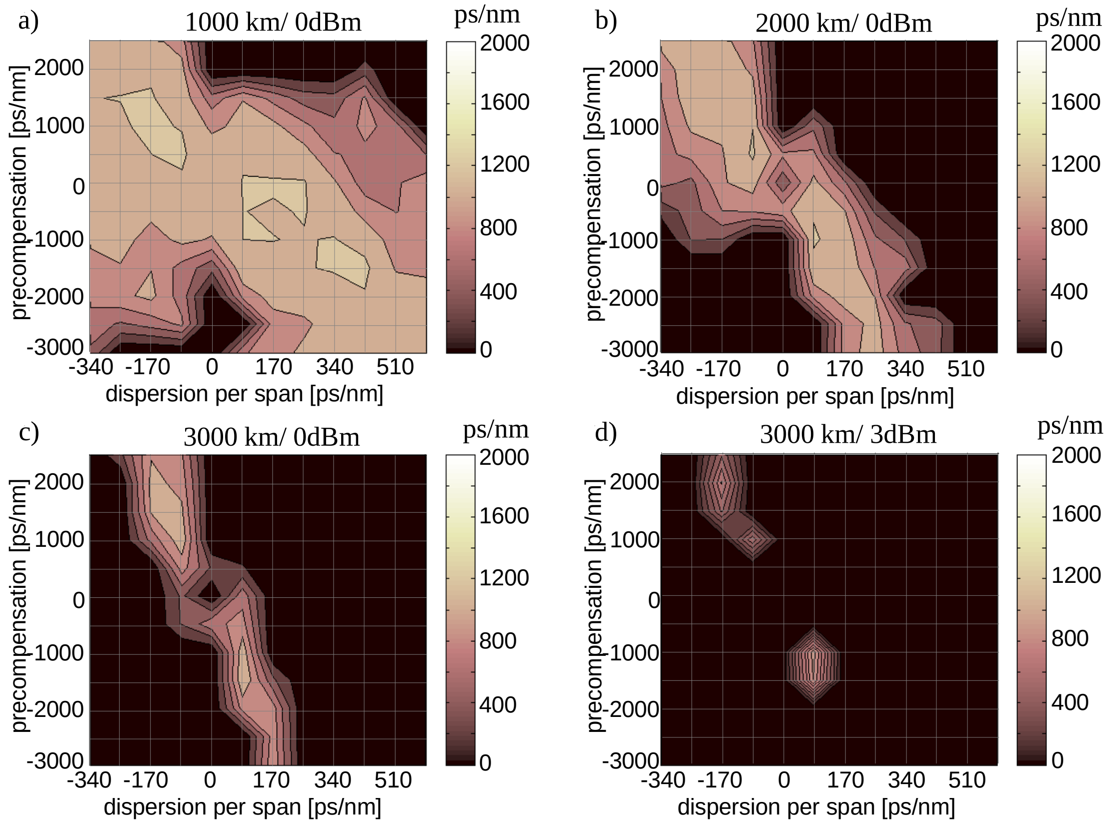

Fig 4: Dispersion tolerance of the nonlinear channel in ps/nm mapped as a function of pre-compensation and dispersion per span for RZ-DPSK at transmission lengths of a) 1000 km, b) 2000 km and c) 3000 km with a mean input power per channel of 0 dBm and for a transmission length of d) 3000 km with a mean input power per channel of 3 dBm.

First of all it can be seen that there are regions with approximately the same dispersion tolerance. So that it is possible for a given pre-compensation (dispersion per span) to choose the dispersion per span (pre-compensation), which is the simplest to realize. The region with a dispersion tolerance above 0 ps/nm can be approximated in principle as a straight line especially for larger transmission lengths and higher input power per channel [6]. Another point is that the regions with a dispersion tolerance with which a transmission is possible decreases with increasing transmission length. It can also be seen that with increasing transmission length the absolute value of the pre-compensation (dispersion per span) has to be larger (smaller) for the same dispersion per span (pre-compensation) to achieve a high dispersion tolerance (fig 4a-c). For a given dispersion per span of -255 ps/nm e.g. the pre-compensation for a transmission length of 1000 km can be between -1000 ps/nm and +2500 ps/nm (fig. 4a) to achieve a high dispersion tolerance. For 2000 km the pre-compensation can only be between +1000 ps/nm and +2500 ps/nm (fig. 4b) and for 3000 km the pre-compensation has to be larger than +2500 ps/nm (fig. 4c). These changes can be described as a clockwise rotation of the dispersion tolerances with which a transmission is possible for increasing transmission lengths. The center of this rotation is the dispersion map with zero pre-compensation and zero dispersion per span.

Similarly as for increasing transmission lengths the regions with a dispersion tolerance with which a transmission is possible decreases with increasing input power. But in contrast to increasing transmission lengths the combinations of pre-compensation and dispersion per span with a high dispersion tolerance keep the same for increasing input power. Figure 4 shows as well that the dispersion tolerance for a full-compensated span especially with no pre-compensation is very small. The explanation of this is the higher influence of the nonlinear effects FWM and XPM. For a full-compensated span the FWM products add coherently, for an under- or over-compensated span they add incoherently [7]. The XPM has a higher influence for a full-compensated span, especially with no pre-compensation because of the smaller walk-off between the channels.

What we have seen in fig. 4 for RZ-DPSK can be transferred in principle to all other investigated modulation formats. Only the regions with a dispersion tolerance with which a transmission is possible and the height of the dispersion tolerance is varying due to the robustness against nonlinear effects for each modulation format.

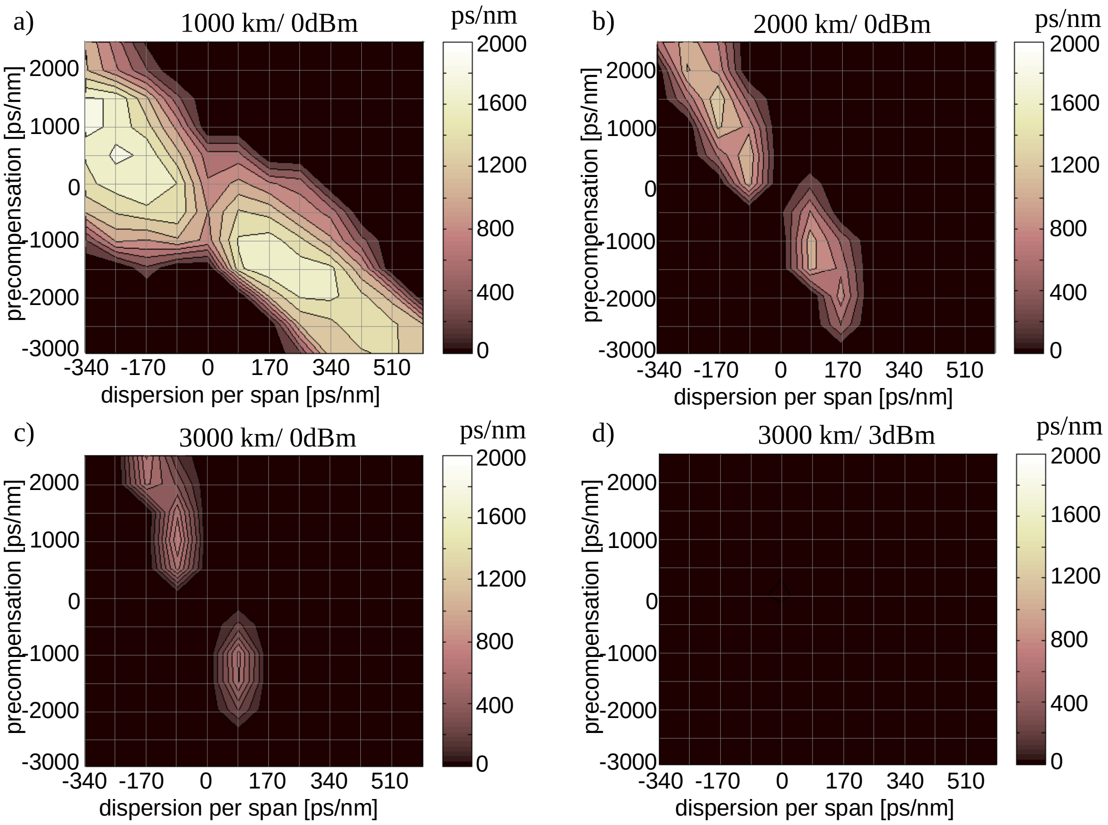

Fig. 5: Dispersion tolerance of the nonlinear channel in ps/nm mapped as a function of pre-compensation and dispersion per span for NRZ-ASK at transmission lengths of a) 1000 km, b) 2000 km and c) 3000 km with a mean input power per channel of 0 dBm and for a transmission length of d) 3000 km with a mean input power per channel of 3 dBm.

Fig. 5 shows the dispersion tolerance of NRZ-ASK for the same transmission lengths and input power as in fig. 4. By comparison of fig. 4 and 5 it can be seen that the regions with a dispersion tolerance with which a transmission is possible (acceptable regions) for NRZ-ASK are narrower than for RZ-DPSK. For NRZ-ASK at an input power of 3 dBm and a transmission length of 3000 km even no transmission is possible. For RZ-ASK and RZ-Duo the width of the acceptable regions are approximately the same as for NRZ-ASK. The width of the acceptable regions for NRZ-Duo is wider than for RZ-DPSK but there are many areas with very low dispersion tolerances. For NRZ-DPSK and NRZ-DQPSK the acceptable regions are narrower than for RZ-DPSK but wider than for NRZ-ASK. The acceptable regions for RZ-DQPSK in the low power regime are the widest of all investigated modulation formats but in the high power regime they are approximately as wide as for RZ-DPSK.

5. CONCLUSION

We investigated the modulation formats ASK, DPSK, DQPSK and Duobinary with NRZ as well as RZ pulse shape regarding the robustness against nonlinear effects and variations of the dispersion map. We have shown that RZ-DPSK is most robust against nonlinear effects for an optimized dispersion map and robust against variations of the dispersion map. Thus RZ-DPSK fulfills both requirements of the “Cut & Past” approach.

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