Analytical, Simulative and Experimental Investigation of Transmission Impairments on Optical Fibers in DWDM-Systems

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Abstract: For optical DWDM communication systems, several impairments limit the data rate and the transmission length. Therefore, it is desirable to develop transmission formats that are robust towards these impairments. For the investigation of these effects we present strategies which combine analytical, simulative as well as experimental considerations.

1. Introduction

In order to utilize the enormous bandwidth provided by the optical fiber, today's optical communication systems apply multiplexing techniques both in the time domain (time-division multiplexing, TDM) and in the frequency domain (wavelength-division multiplexing, WDM). The simultaneous transmission of a large number of data streams by means of these techniques gives rise to linear and nonlinear impairments on the transmission quality:

- High data rates per channel (10Gb/s, 40Gb/s up to 160Gb/s) make the data transmission sensitive for group velocity dispersion (GVD) and polarization mode dispersion (PMD). In addition, for a good signal-to-noise ratio the signal power must be relatively high (i.e. in the order of magnitude of some mW), which gives rise to nonlinear effects like self-phase modulation (SPM) [1].
- For efficient utilization of the provided bandwidth [2] in recent times the channel spacing between different wavelength channels has been decreased (dense wavelength-division multiplexing, DWDM) and now takes on values of 50GHz (≈0.4nm) and below. Thus, interchannel effects come along like linear crosstalk, cross-phase modulation (XPM), and four-wave mixing (FWM) [3].

The most popular transmission format is the on-off-keying (OOK) technique. In recent years, a large variety of sophisticated and bandwidth-efficient modulation formats has been applied to optical transmission like duobinary modulation [4,5], single-sideband modulation [6,7], and phase-shift keying techniques [8,9]. These formats must be investigated with respect to their properties towards the transmission impairments listed above.

The paper is organized as follows: first linear and nonlinear effects on optical DWDM communication systems are discussed. In a second step, several methods for investigating these effects are introduced and applied for XPM. With the help of these results, examples for modulation formats being robust towards XPM are developed.

2. Linear and nonlinear impairments on optical fibers

2.1 Single channel considerations

For single channel transmission the light of one laser at a particular wavelength is modulated by one data stream and transmitted through the optical channel. The effects described below give rise to crosstalk between adjacent data pulses which is known as intersymbol interference (ISI).

2.1.1 Linear effects

A very well-known linear effect is group velocity dispersion (GVD). The origin of GVD is the frequency-dependent refraction index of the fiber, which results in a group delay, that is frequency-dependent, too. Since an optical pulse has a bandwidth that is (in dependency of the data rate) significantly different from zero, the different frequency components of the optical signal (which is a superposition of optical pulses) travel at different velocities. Therefore, the pulses are spread in the time domain.

GVD can be represented by a quadratic phase response of a linear system, $\phi(f)\sim f^2 L$, where L represents the length of the fiber. If the data rate is doubled, the maximum transmission length without dispersion compensation techniques is divided by 4. For example, on standard single-mode fiber for the OOK technique the maximum transmission length for a data rate of 10Gb/s is about 80km whereas for a data rate of 40Gb/s it is reduced to 5km.

A second linear effect is polarization mode dispersion (PMD) of first order. Because fibers are not exactly circular, the two orthogonal fiber modes do not have exactly the same group velocity, which results in a differential group delay. Therefore, if the energy of an optical pulse is coupled into both modes, the two parts are transmitted at different velocities, which results in pulse broadening.

2.1.2 Nonlinear effects

For single channel transmission, the most important nonlinear effect is self-phase modulation. The origin is the dependency of the fiber refraction index on the optical power, which results in a phase modulation (PM) of the optical signal. In the presence of GVD, the PM is converted into intensity modulation (IM).

2.2 Considerations for DWDM transmission

For DWDM-systems, data streams of 10Gb/s or 40Gb/s are multiplexed in the frequency (wavelength) domain by using lasers of different wavelengths. The number of channels that can be transmitted simultaneously can take on large values (e.g. 80x40Gb/s=3.2Tb/s) and depends on the data rate per channel and the usable bandwidth given by the fiber and optical amplifiers. The acceptable channel spacing is limited by the effect of linear crosstalk. However, for high input powers nonlinear crosstalk effects occur, too, which can require even larger channel spacings.

2.2.1 Linear effects

For narrow channel spacing, there is a partial overlap of the transmission channels in the frequency domain. The effect depends on a large number of parameters, such as the channel spacing and the filtering characteristics of the multiplexers and demultiplexers. To avoid linear crosstalk, channel spacings for the on-off-keying technique of 25GHz and 100GHz for line rates of 10Gb/s and 40Gb/s are selected, respectively. Both methods have a spectral efficiency of 0.4bit/s/Hz. However, the spectral efficiency can be improved by using sophisticated modulation formats, e.g. duobinary coding with 0.8b/s/Hz [10].

2.2.2 Nonlinear effects

For DWDM transmission, the nonlinear refraction index causes the interchannel effects XPM and FWM. For XPM the fiber refraction index is influenced by the instantaneous optical power of the sum of all channels. Thus, the optical power in one channel induces PM in adjacent channels, and because of GVD this PM is converted into IM. The influence of XPM can be mitigated by a larger channel spacing.

For FWM three optical waves (i.e. transmission channels) generate a fourth one. These newly created frequency components add up to existing transmission channels.

FWM and XPM are often modeled as signal-dependent noise. An approach for XPM is found in the next section.

3. Methods for investigation of transmission impairments

3.1 General

In order to develop transmission systems that are robust towards the effects presented in the previous section, a deep understanding of these effects is essentially necessary. There are three approaches, which are discussed in the following:

- Analytical modeling techniques base on physical equations like the nonlinear Schrödinger equation (NLSE). With the help of certain assumptions and approximations a simple description by means of linear and nonlinear systems theory is intended. The great advantage of this method is, that the impact of the effects in dependency of system parameters can be seen clearly. On the other hand the accuracy of the assumptions and approximations depends strongly on system parameters.
- Numerical simulations base on the same physical equations. Much less approximations are required, which gives more accurate results and can be used to check the validity of the analytical calculations. On the other hand, to obtain dependencies on system parameters without the knowledge of analytical approximations a large number of simulations is required and the evaluation of the results is a very time-consuming approach.

  For the numerical simulation, we have developed our own simulation tool called MOVE-IT [11].
- Finally, to come close to a real system, a validation by experiment is essential. By means of this, the underlying physical equations and the proper selection of the system parameters can be confirmed.

The best understanding of the impact of certain transmission impairments is given by combining the three approaches presented here. This is clarified for the example of XPM in the following subsection.

3.2 Example XPM

The basis for the analytical analysis is the NLSE in the form of coupled differential equations [1]. As a result, the XPM-induced perturbation on an unmodulated test channel (=probe) originating from a disturbing channel (=pump) can be described by a linear system [12] as shown in fig. 1.

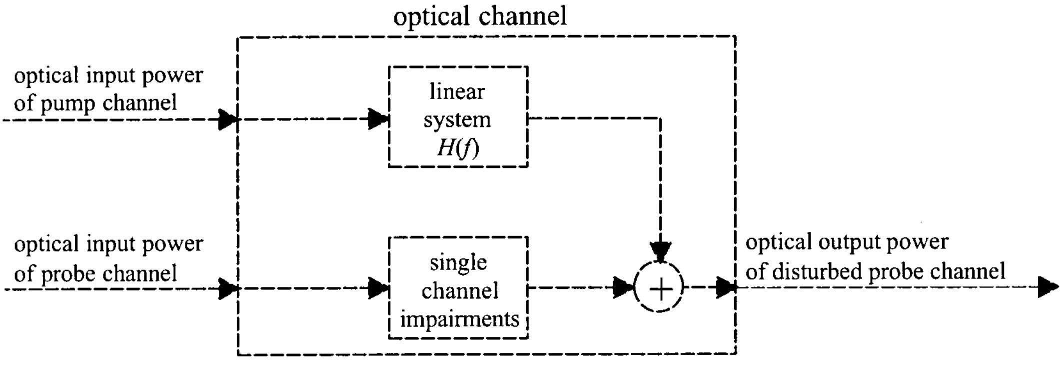

Fig. 1 . Analytical model for XPM with the help of a linear system

The input power of the pump channel is filtered by a linear system and then added to the probe channel as a noise signal. In [12] the transfer function $H(f)$ is shown to equal

$$H(f) = 4\gamma P_p(L)\frac{\sin\left(2\pi^2\beta_2 f^2 L\right)}{\alpha - j2\pi f d_{pp}}, \qquad (1)$$

where α, β_2 and γ account for fiber loss, GVD and nonlinearity, respectively, d_{pp} represents the difference between the group velocities of pump and probe channel, L equals the fiber length and $P_p(L)$ is the mean power of the probe channel at fiber output. The results for the three methods of investigation for $H(f)$ are depicted in fig. 2 for a channel spacing of 50GHz on 50km of standard single mode fiber. The theoretical and simulative results are in very good agreement, the experimental results show minor deviations.

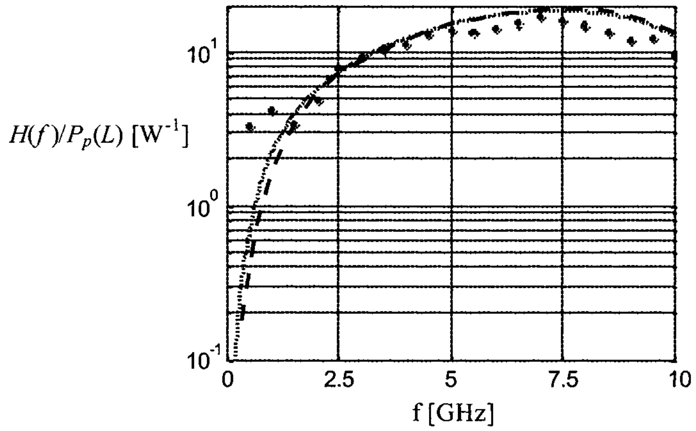

Fig. 2 . Theoretical (solid), measured (dotted) and simulated (dashed) absolute value for $H(f)$ as defined in (1), normalized by mean power of the probe channel

As can be seen, for the underlying model for XPM, the transfer function is of highpass character up to frequencies of ≈7GHz. This clarifies, that the impact of XPM can be significantly reduced, if the power of one WDM-channel is kept at a constant value, i.e. the power has only frequency components at f=0. This is fulfilled best for phase-shift-keying (PSK) modulation formats [8,9]. For PSK-formats, the information is carried by the phase of the optical carrier frequency. A ‘0’ bit corresponds to a carrier phase shift of π, while a ‘1’ bit corresponds to a carrier phase shift of 0.

The superior performance of the PSK-modulation is shown in fig. 3 for a dispersion managed 8-channel long-haul CF-RZ-DPSK DWDM setup [9] over 3000km of single mode fiber. Up to 2000km no penalty for the PSK-format can be seen in contrast to the on-off-keying (=amplitude-shift-keying, ASK) technique that shows a penalty of 1.5 dB. Even for 3000km the penalty for the PSK-format remains under the 1dB threshold.

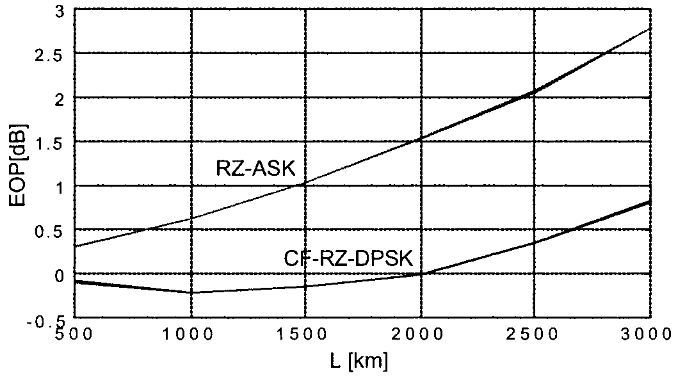

Fig 3: 8x10Gb/s with Δf=100GHz, P_{in} =9dBm/ch: Eye-opening penalty of 4th channel with increasing length

4. Conclusion

The most important linear and nonlinear impairments for single-channel and for WDM-transmission on optical high-speed communication systems are discussed. As a method for investigating these effects the combination of analytical, simulative and experimental techniques is presented. Finally, with the help of results for the effect of XPM the PSK-modulation is shown to be robust towards this particular effect.

5. References

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