Cross-Phase Modulation Induced Nonlinear Phase Noise in Spectral Efficient WDM DPSK-OOK systems

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***Abstract* – This paper provides a simple and efficient model for involving both SPM and XPM - induced nonlinear phase noise in WDM systems with mixed DPSK-OOK channels. An analytically based new model is derived from the two-channel pump-probe model and later extended to multi-spanWDM systems. The proposed model is developed to determine the effects of XPM induced nonlinear phase noise on DPSK channels from neighbouring OOK channels.**

***Keywords* – Cross-phase modulation (XPM), differential phase-shift keying (DPSK), nonlinear phase noise, WDM systems.**

I. INTRODUCTION

Recently, 40Gb/s advanced modulation formats such as DPSK and DQPSK, have been investigated to upgrade transmission capacity [2-9]. The tolerances to linear and nonlinear transmission impairments are studied in single channel transmission, where an implementation of novel NRZ-advanced modulation format, provides a better dispersion tolerance, but suffers from strong nonlinear impairments. The impairments caused by the cross phase modulation in high bit rate DWDM systems will affect the performance of these systems to a greater extent. To evaluate the optical system performance under the influence of cross phase modulation XPM, an analytical model for mixed DPSK and OOK multi channel system is developed in this paper, which is faster, simple and as accurate as possible. Previous analytical studies involved analyzing the intensity modulation generated phase noise in single channel or pure DPSK systems. This paper provides a simple and efficient model for involving both self phase modulation (SPM, single channel effect) and XPM (multi-channel effect) induced nonlinear phase noise [1] in mixed WDM optical systems. The roots of this model lie in the derivation of the analytical formula for sensitivity of 40Gb/s DPSK or 40Gb/s DQPSK channels from 10Gb/s OOK channels. These modulation formats can be an effective way to increase spectral efficiency and overcome transmission impairments. DQPSK is a very attractive format because it is just a little more complex than binary DPSK and suitable for upgrade of the existing DWDM systems, specially applied for high capacity transmission. It seem to have the potential for reducing cost by increasing dispersion tolerance and allowing transmissions to 40 Gb/s per channel or higher, using cheaper, established 10Gb/s components.

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II. THE ERROR PROBABILITY OF DPSK SIGNALS AS A FUNCTION OF SNR

The error probability is derived analytically for differential phase-shift keying (DPSK) signals contaminated by both self- and cross-phase modulation (SPM and XPM) induced nonlinear phase noise. XPM-induced nonlinear phase noise is modeled as Gaussian distributed phase noise. When fiber dispersion is compensated perfectly in each fiber span, XPM-induced nonlinear phase is summed coherently span after span and is the dominant nonlinear phase noise for typical wavelength-division-multiplexed (WDM) DPSK systems. For systems without or with XPM-suppressed dispersion compensation, SPM-induced nonlinear phase noise is usually the dominant nonlinear phase noise. For calculating the error rate of DPSK transmission we employ the model given in [2]. It uses a matched optical filter in front of the receiver for optimization of the receiver performance and assumes single polarization. Combined with the Gaussian approximation for the distribution of the XPM-induced nonlinear phase noise (Nicholson Model [3]), form [2] and [4] we get analytical expression for the error rate of DPSK:

$$p_e \approx \frac{1}{2} - e^{-\frac{\rho_s}{2}} \sqrt{\frac{\rho_s}{\pi}} \sum_{n=0}^{\infty} \frac{(-1)^n}{2n+1} \left(I_n\left(\frac{\rho_s}{2}\right) + I_{n+1}\left(\frac{\rho_s}{2}\right) \right) \times \\ \times \left| \Psi_{\Phi NL}\left(\frac{(2n+1) < \Phi_{NL} >}{\rho_s + 1/2}\right) \right|^2 e^{(-\frac{2n+1}{2}\sigma^2_{XPM})} \qquad (1)$$

where the influence of neighboring channels is determined by phase variance σ^2_{XPM}, n is a summation index, $I_n(.)$ denotes modified Bessel function of first kind and n^{th} order, $<\Phi_{NL}>$ is the mean nonlinear phase shift, ρ_s is the SNR and the characteristic function of the nonlinear phase noise [4] is

$$\left|\Psi_{\Phi}(j\nu)\right| = \sec\sqrt{j\nu}\, \exp(\rho_s \sqrt{j\nu} \tan\sqrt{j\nu}) . \qquad (2)$$

The trigonometric function with complex argument can be calculated by the following relationship

$$(\sec\sqrt{j\nu})^{-1} = \cos\sqrt{\frac{\nu}{2}} \cosh\sqrt{\frac{\nu}{2}} - j\sin\sqrt{\frac{\nu}{2}} \sinh\sqrt{\frac{\nu}{2}} \qquad (3)$$

The nonlinear phase shift is approximated by [4]

III. NONLINEAR PHASE NOISE VARINACE DUE TO CROSS-PHASE MODULATION

The Calculation of the nonlinear phase noise variance as a function of frequency is based on the two-channel pump-probe model of [5] and later extended to multi-span WDM systems.

A. Calculation of phase noise variance

For simplicity the model have two WDM channel, and co-propagating OOK channels are assumed to be co-polarized to cover the worst case scenario. The phase variance as a function of frequency separation between the channels [6] is:

$$\sigma^2_{xpm}(\Delta\lambda) = 4\int_{-1/T}^{1/T} \Phi_{P_2(f)} \left|H_{12}(f)\right|^2 \sin^2(\pi f T)df\ , \qquad (4)$$

where

$$\Phi_{P_2} = 2P_0 S_{sp1} + 2S_{sp1}\nu_{opt} \qquad (5)$$

is the noise power spectral density of the pump channel, $\sin^2(\pi fT)$ is phase transfer function of receiver delay line interferometer, S_{sp1} is the spectral density of the amplifier noise, V_{opt} is the optical filter bandwidth and P_0 is the lunched power of the pump channel. The integration is reduced from $\pm\infty$ to $\pm 1/T$ by taking into account only the phase noise over a bandwidth confined within the bit-rate. The dependence of the variance of Eq. (4) on $\Delta\lambda$ is originated from the dependence of the amplitude-phase conversion function of the fiber $H_{12}(f)$ on $\Delta\lambda$ and can be expressed from [7] and [8]as

$$H_{12}(f) = 2\gamma \frac{1-e^{-\alpha L + j2\pi f d_{12} L}}{\alpha - j2\pi f d_{12}}, \qquad (6)$$

where γ is the nonlinear coupling coefficient, α is fiber attenuation coefficient, L is the fiber length, $d_{12} \approx D\Delta\lambda$ is the relative walk-off between two channels with wavelength separation of $\Delta\lambda$ and dispersion coefficient D.

B. Multi span WDM system

In WDM system with (2M + 1)-channels, for the worse case of the center channel, the XPM contribution has to be summed over all neighboring channels [8], the nonlinear phase noise variance in the first span is equal to:

$$\sigma^2_{XPM,1} = \sum_{k=1}^{M} \sigma^2_{XPM,0}(k\Delta\lambda) \qquad (7)$$

In case of full inline dispersion compensation - the worst case, the noise contribution sums up coherently and for a system with N fiber spans, the variance of the overall XPM-induced nonlinear phase noise depends on the method of dispersion compensation.

$$\sigma^2_{XPM,tot} = N^2\sigma^2_{XPM,1} + (n-1)^2\sigma^2_{XPM,2} + ... + \sigma^2_{XPM,N} \quad (8)$$

When the whole spans have the same configuration and same noise variance, the total phase noise is

$$\sigma^2_{XPM,tot} = \frac{1}{6}N(N+1)(2N+1)\sigma^2_{XPM}\ . \qquad (9)$$

C. *The model*

The need of a simulation testbed is of strong interests for convenience of design, investigation and verification on benefits and shortcomings of advanced modulation formats on the transmission system. Simulation semi-analytical model is constructed to investigate the DPSK-OOK system and obtain the results. The block diagram of the simulation model utilized for this purpose is shown in Figure 1 and the eye diagram at the receiver on figure 2.

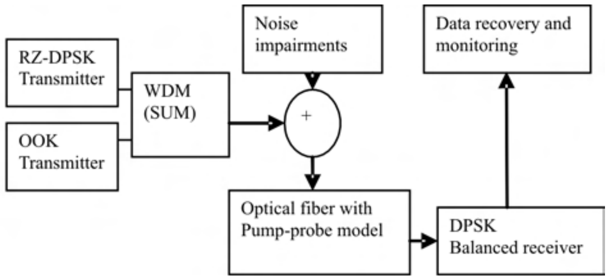

Fig. 1. Block diagram of simulated model

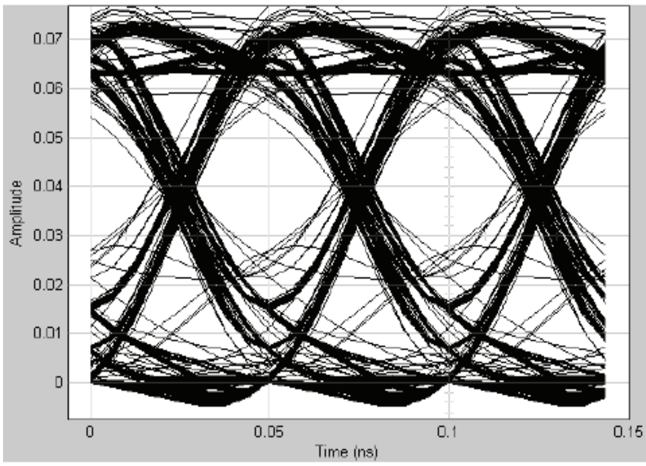

Fig. 2. Simulated eye diagram of RZ-optical pulses

IV. DISCUSSION AND RESULTS

One challenge in numerical simulations is to provide a reliable estimate of the BER. Due to limited computation time, a typical simulation programs uses only hundreds of bits and therefore, the BER is usually not counted directly but estimated by evaluating the statistics fluctuations in the received signal. It is a standard practice in numerical simulations of OOK systems such fluctuations to be often characterized by a Q-factor and BER to be obtained through the complementary error function (erfc). Figure 3 shows error probabilities as a function of SNR for WDM DPSK systems obtained through formula of equation (1).

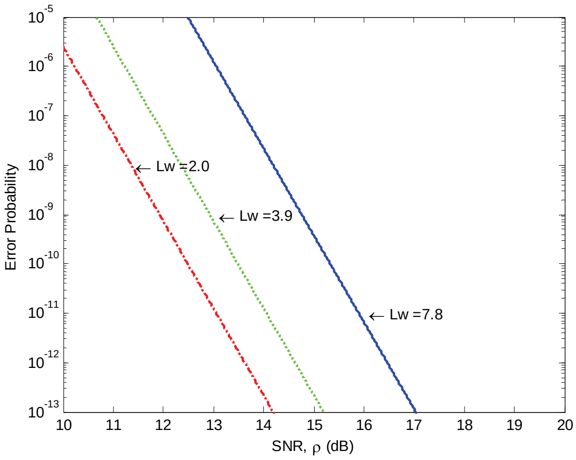

Fig. 3. Error probability as a function of SNR

Normally 10-Gb/s systems using non-zero dispersion-shifted fiber, 50-GHz spacing (NZDSF) and D = 4 ps/km/nm has a walk-off length Lw=T/d12 of 62.5 km. 40-Gb/s systems have a walk-off length of 7.8 km (100 GHz spacing, ($\Delta\lambda$ = 0.8 nm) and D = 4ps/km/nm). The walk-off length of figure 3 forms a geometric series corresponds to typical 10 and 40-Gb/s systems in NZDSF and standard single-mode fiber (SSMF) with dispersion coefficients of D = 4 and 16 ps/km/nm, respectively. The characteristic function of Eq. (2) assumes a dispersionless fiber. With fiber dispersion, due to walk-off effect, the nonlinear phase noise caused by cross-phase modulation should approximately have Gaussian distribution. The SNR penalty as a function of nonlinear phase shift is shown on figure. 4. For a perfect dispersion compensation such that XPM-induced nonlinear phase noise adds coherently, XPM-induced nonlinear phase noise gives the same SNR penalty as SPM- induced nonlinear phase noise when the walk-off length is about L_w = 7,8 km for $<\Phi_{NL}>$ less than 1 rad. With the same mean nonlinear phase shift, the nonlinear phase noise induced SNR penalty of 10-Gb/s systems is smaller than that for the corresponding 40-Gb/s systems.

We emphasize here that (1) is based on the assumption of Gaussian approximation for the distribution of the XPM-induced nonlinear phase. Because XPM-induced nonlinear phase noise is generated by the interaction of many bits or WDM channels, the Gaussian approximation is valid and XPM-induced degradation on DWDM system performance is not a strong function of number of channels. Therefore, 5-channel modeling system can be sufficient for system investigation on the effects of XPM The XPM effect can be integrated into the propagation model with ease. The mean nonlinear phase is approximated by $<\Phi_{NL}>\approx N\gamma L_{eff}P_0$ and the walk-off length is the main constraint for nonlinear interaction between two or multiple pulses when the XPM effects occur. More specifically, XPM can be considered to have no effects when the faster moving pulse completely walks through the slower moving pulses.

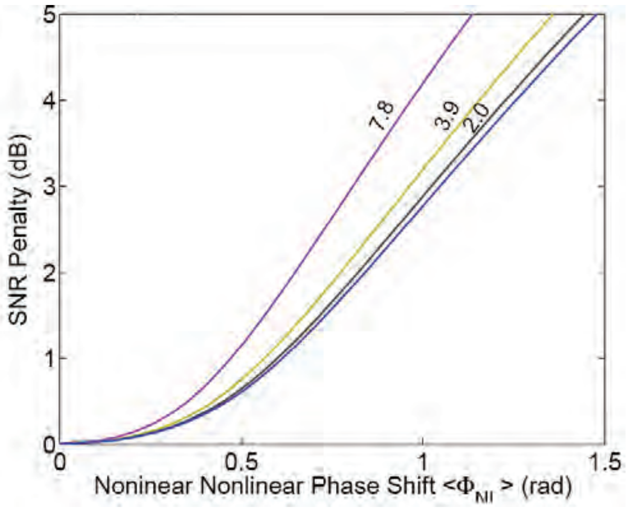

Fig. 4. SNR penalty as a function of nonlinear phase shift<ΦNL>

Figure 5 shows the signal to noise (SNR) penalty for DPSK (DQPSK) probe channel. The SNR penalty versus lunched power per channel for 5 channel system(100GHz channel separation) with 4 neighboring OOK channels When the co-propagating DPSK channels yield very low additional penalties on the probe channel, the penalty caused by co-propagating OOK channels increase fast with increasing lunch power P_0. It is important and this fact can be explained with signal dependent part of the noise variance has the most significant XPM contribution for OOK channel and not so important for the DPSK and DQPS channels. We have to confess with the increasing of the lunch power also increases absolute SNR and a settlement by compromise must be taken. The optimum operation point of every optical system is where linear and nonlinear impairments balance each other.

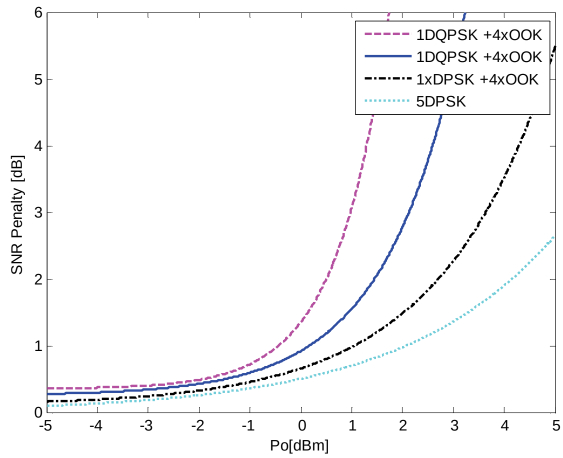

Fig. 5. SNR penalty versus lunched power

V. CONCLUSION

We have investigate the performance degradation of DPSK systems through the represented theoretical model for the influence of XPM induced nonlinear phase noise from co-propagating intensity modulated channels in the multi-span

WDM systems. The performance of the system was measured with different nonlinear phase shift. The BER curves dependence of XPM penalty is based on the amplitude phase conversion function of fiber, delay interferometer function and ASE noise.

The represented theoretical model for the influence of XPM induced nonlinear phase noise from co-propagating intensity modulated optical channels has demonstrated that for low penalties, it is beneficial DPSK channels to use higher rate than OOK. However, 40-Gb/s systems have four times the bandwidth and require four times the power of the corresponding 10-Gb/s systems having the same SNR.

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