Multipath Interference Influence on Raman Assisted Transmission Systems Performance Degradation

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Abstract - **A novel multipath interference (MPI) model independent on modulation format, MPI crosstalk level, optical and electrical filter choice is proposed in this paper. MPI and ASE noise impact on receiver performance is considered taking into account the transfer functions of optical and electrical filters, intersymbol interference and receiver noise. ASE noise components are assumed to be colored Gaussian with power spectral density determined by EDFA output filter. The components of multipath interference are considered to be independent and depolarized with power spectral density determined by the signal spectrum. The comparison with widely used Gaussian crosstalk model is made and shown that Gaussian crosstalk model gives satisfying results just for low crosstalk level values. Also Gaussian crosstalk model is valid just for NRZ, rectangular shape of optical filter transfer function and integrate and dump electrical filter.**

I. Introduction

The current trend toward internet protocol (IP) dominated transmission has increased capacity demand outside the erbium doped fiber amplifier (EDFA) bandwidth (typically 35 nm in C-band) and transmission rates to 40 Gb/s or greater. IP based optical transmission also requires much higher distances. All-Raman and hybrid Raman/erbium-doped fiber amplifiers are enabling promising technologies for ultra long-haul dense wavelength-division-multiplexing systems due to their potential to provide high transmission capacity while maintaining large enough optical signal-to-noise ratios [1-2]. All Raman amplification also enables signal transmission over a single ultra wide band avoiding the necessity for band splitters and combiners required for C-L EDFA systems and provides better performance due to reduced number of loss elements.

In those systems apart from amplifier spontaneous emission (ASE) noise, especially those with all-Raman amplifiers, multipath interference (MPI) [3-8] becomes an important factor in performance degradation. Although the problem of the evolution of MPI has already been solved [9-10] the problem of properly including it in Q-factor calculation or power penalty determination is still an open issue. A number of models have been proposed so far [3-8]. These models are more or less the improvement, or just implementation, of the Gaussian crosstalk model proposed in [7]. This model gives satisfying results, as will be shown latter in the text, when the MPI crosstalk level is much smaller than the observed channel level devided by $2Q^2$. Also Gaussian crosstalk model is valid just for NRZ, rectangular shape of optical filter transfer function and integrate and dump electrical filter.

We proposed a novel MPI model independent on the MPI crosstalk level, modulation format and optical and electrical filter choice. Model includes the influence of the optical and electrical filter transfer functions as well as the intersymbol interference (ISI).

Due to the fact that double Rayleigh-back scattering, which is a main source of MPI, occurs in an optical fiber due to small inhomogeneities or microscopic variations in the refractive index, that reflections may occur on splices and poor connectors [3] and the fact that these sources are independent of each other, we model MPI as a stationary process with an autocorrelation function determined from the measured power spectral density (PSD) function.

Additive white Gaussian noise (AWGN) is commonly used to describe ASE noise [12]. In contrast to terrestrial communication links, a typical undersea fiber communications system operates at a signal power below 0 dBm (even less than -3 dBm) per channel for Nx10 Gb/s systems, with relatively short amplifiers spacing (less then 45 km) and properly chosen dispersion compensated fiber pairs to minimize the influence of the fiber nonlinearities and dispersion [12]. The validity of the AWGN fiber channel model in considering ASE noise was confirmed for such applications through experiments [12].

However, in most terrestrial optical communication systems the AWGN assumption is not completely accurate. For example in terrestrial long-haul wavelength division multiplexing (WDM) systems, due to the interaction of fiber nonlinearities and dispersion, the WDM carriers can act as a set of pumps, and the amplifier spontaneous emissin noise spectral components can be selectively amplified. In other words the noise enhancement is much higher in certain spectral regions. This gain introduced by these effects is known as a parametric gain [13]. In this case the ASE noise is neither white nor Gaussian. Moreover, an optical filter colors the white (ASE) noise in every amplifier stage, even in the absence of parametric gain what justifies our non-white noise assumption.

II. Model Description

The electrical field of an observed channel at the optical filter input for n^{th} bit slot can be written as

$$\boldsymbol{E}_{\mathrm{n}}(t)=\sum_{k=-\infty}^{\infty}\boldsymbol{E}_{n,k}\left(t-cT-(n-1)T+kT\right), \qquad (1)$$

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where the slot n electrical field with ISI coming from k^{th} time slot can be written in the form of Jones vector as

$$\boldsymbol{E}_{n,k}(t) = \begin{bmatrix} E_{x,n,k}(t) \\ E_{y,n,k}(t) \end{bmatrix} =$$

$$= \begin{bmatrix} \sqrt{d_{n+k}\,(1-p)P}\, g_{n+k}(t) + N_x^{ASE}(t) + N_x^{MPI}(t) \\ \sqrt{d_{n+k}\, pP}\, g_{n+k}(t) e^{j\Phi} + N_y^{ASE}(t) + N_y^{MPI}(t) \end{bmatrix}, \quad (2)$$

where: $N_x^{ASE}(t)$ and $N_x^{MPI}(t)$ are the complex representations of ASE noise and MPI, respectively; having the same state of polarization as the observed channel signal. $N_y^{ASE}(t)$ and $N_y^{MPI}(t)$ are the noise components of ASE and MPI, respectively; orthogonal to the signal state of polarization. P is the peak power per channel, $d_n \in \{r, 1\},\ 0 < r < 1$ is the information content (r-the extinction ratio). $g_n(t)$ is the n^{th} bit pulse shape that could vary from bit to bit depending on the fiber nonlinearity and dispersion, and modulation statistics as well. Both ASE noise components and the MPI components are considered to be colored Gaussian. The power spectral density of ASE noise is determined by the EDFA output filter, while that of MPI by the signal spectrum. To determine the spectrum of MPI the spectrum of an isolated pulse was observed, properly normalized so that its power be equal to the average MPI power, and each spectral component was uniformly randomized in phase. The state of polarization is described by power splitting ratio p ($0 \le p \le 1$) and phase difference Φ between y- and x-polarization components. Centering factor c takes a pulse position with respect to bit frame into account, T is the bit duration. The summation (1) takes into account the influence of the neighboring bits, that is ISI.

Typical receiver configuration, consisting on the optical filter, photodiode, electrical filter, sampler and decision circuit is observed.

The optical and electrical filters are modeled as Gaussian filters with the eighth and the first order, respectively.

To compute the Q-factor we apply expressions reported in our previous paper [11].

III. Q-FACTOR DEGRADATION DUE TO MPI

The system penalty coming from MPI was estimated in [3-8] using the Gaussian Crosstalk model. This model assumes that the signal-MPI beating dominates MPI-MPI beating. Starting from [7] the power penalty, defined as increase in received optical power in the presence of MPI (P_s') to have the same Q-factor as in the absence of MPI (P_s)) follows

$$-10\log_{10}\frac{P_s}{P_s'} = -10\log_{10}\frac{2}{1+\sqrt{1+2Q^2\varepsilon}}, \quad (3)$$

with ε being the MPI crosstalk level. Under assumption that $\varepsilon << 1/(2Q^2)$ and applying the Taylor expansion the well-known expression for power penalty follows

$$-10\log_{10}\frac{P_s}{P_s'} = -10\log_{10}\left(1-\frac{1}{2}Q^2\,\varepsilon\right). \quad (4)$$

Due to the fact that the light is scattered randomly in all directions and that it could appear at any point during transmission in long-haul link, and that different MPI sources are uncorrelated with different phases we assume that MPI signal is an average of mark- and space-state bits from direct signal and it is depolarized. Similarly as previous models we also assume that MPI is a stationary process, but with a non-flat power spectral density determined by the signal spectrum.

Results of Monte Carlo simulation are illustrated in Figs. 1-4 for the most popular modulation format in long-haul communications, chirped-return-to-zero (CRZ). Long-haul transmission with 10 Gb/s per channel is observed with redundancy from FEC of 23%. In all calculations the non-ideal extinction ratio r of 12 dB is assumed, while the Q-factor in the absence both ASE noise and MPI (determined by transmitter and receiver electronics), also known as 'back-to-back' noise is set to Q_{BB}=23 dB. (With OSNR is denoted the optical signal-to-noise ratio, and R is the photodiode responsivity). The Q-factor dependence on normalized electrical filter bandwidth B_e/R_b (B_e-electrical filter bandwidth, R_b-bit rate) for different optical filter bandwidths B_o and fixed AM depth m and PM index θ confirms the existence of the optimum electrical filter bandwidth. It lies in the region [0.4,0.7] depending on the optical filter bandwidth and PM index. As optical filter bandwidth increases Q-factor becomes less sensitive to the electrical bandwidth choice. For optical filter bandwidths greater than $3R_b$ the electrical filter can be even omitted without too much degradation in performance.

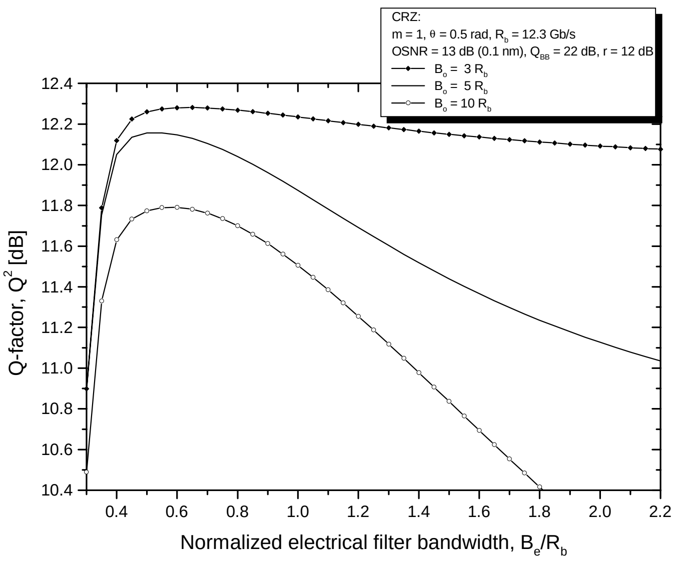

Fig. 1. Q-factor in the absence of MPI vs. electrical filter bandwidth for CRZ with a phase modulation index of 0.5 rad

The performance degradation coming from MPI, defined as the ratio in Q-factor in the presence Q and absence of MPI Q_0,

$$\Delta Q = -20\log_{10}\frac{Q}{Q_0}\,[\mathrm{dB}] \qquad (5)$$

is illustrated in Figs. 2-3. Results shown in Fig. 2 (a) corresponds to the hybrid Raman/EDFA chain, while those in Fig. 2 (b) to all-Raman based systems. That all-Raman based systems are much more sensitive on MPI than hybrid amplifiers can be concluded from given figures. Also, the greater the phase modulation index is, the smaller Q-factor degradation due to MPI is, Fig. 3 suggests.

The comparison between the proposed model and Gaussian crostalk model is shown in Fig. 4, for Q-factor being set to 15.56 dB (bit-error rate is then 10^{-9}). Previously reported Gaussian crosstalk model gives reasonable results when the crosstalk coming from MPI is less than -20 dB. For greater crosstalk levels Gaussian crosstalk model overestimates the degradation coming from MPI.

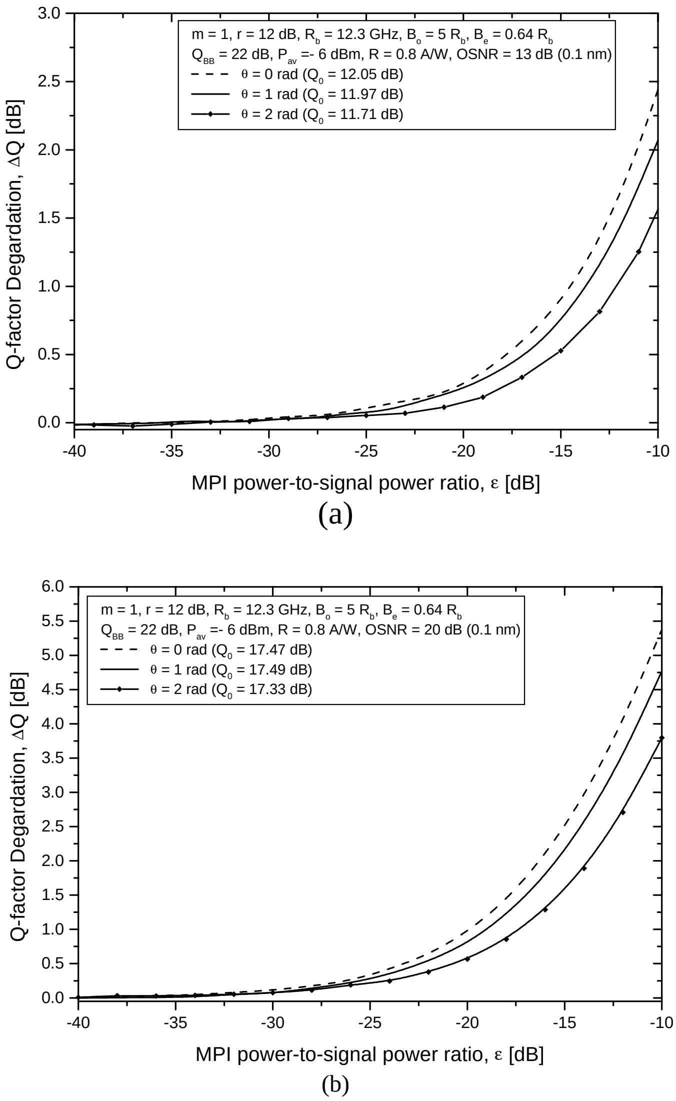

Fig. 2. Q-factor degradation due to MPI for CRZ with different phase modulation indexes for: (a) OSNR =13 dB in 0.1 nm, (b) OSNR = 20dB in 0.1 nm

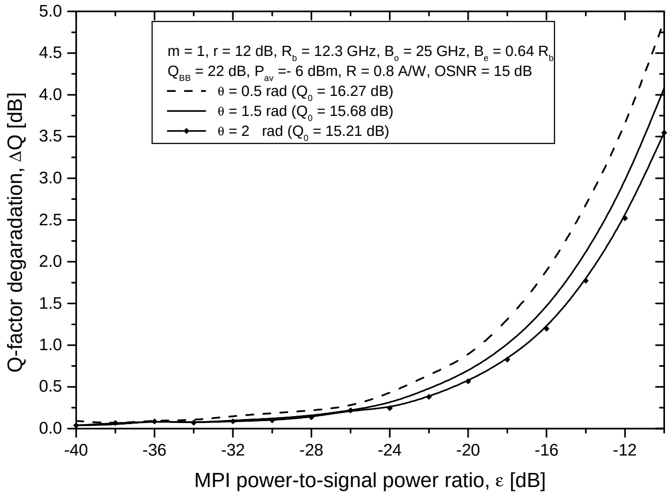

Fig. 3. Q-factor degradation due to MPI for CRZ and different values of phase modulation index

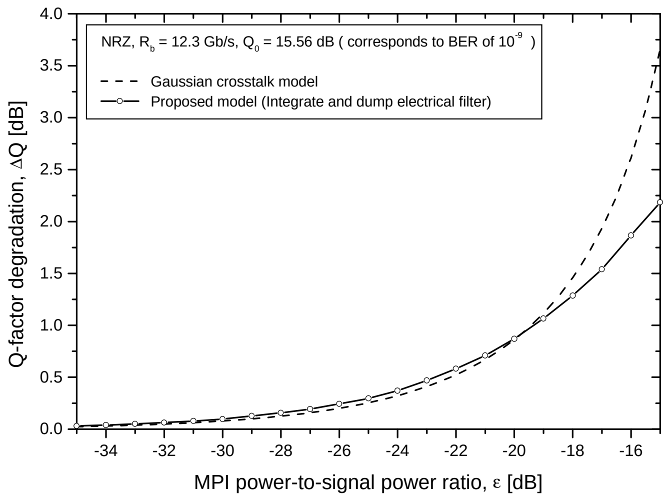

Fig. 4. Comparison of proposed and Gaussian crosstalk model

IV. Conclusion

A novel MPI model independent on MPI crosstalk level, modulation format, optical and electrical filter choice is proposed in this paper. MPI and ASE noise impact on receiver performance is considered taking into account the transfer functions of optical and electrical filters, intersymbol interference and receiver noise. ASE noise components are colored Gaussian with PSD determined by EDFA output filter. The MPI is considered as a stationary process with the power spectral density determined by the signal spectrum. It was shown that for the crosstalk levels greater than -20 dB Gaussian crosstalk model fails. While Gaussian crosstalk model is valid just for NRZ, rectangular shape of optical filter transfer function and integrate and dump electrical filter, the proposed model is general and valid for any modulation type and any optical-electrical filter pair.

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