Performance of Coherent Optical Communication Systems With Hybrid Fiber Spans

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Abstract *We theoretically study the performance of coherent optical communication systems using quasi-single-mode fiber in the beginning of each span, to reduce the bulk of nonlinearities, followed by single-mode fiber, to limit multipath interference penalty within acceptable levels.*

Introduction

Quasi-single-mode (QSM) fibers exhibit very large effective areas that result in a dramatic reduction of fiber nonlinearities but suffer from the existence of a higher-order leaky mode other than the fundamental propagation mode[1-4]. The exchange of power between the fundamental mode and the higher-order mode in QSM fibers gives rise to multipath interference (MPI)[1-4]. MPI can lead to severe deterioration of the performance of coherent optical communication systems and must be electronically equalized[5] to maximize the benefits stemming from nonlinearity reduction.

Simultaneous reduction of fiber nonlinearities and MPI in coherent optical communication systems can be achieved by using hybrid fiber spans, consisting of the concatenation of QSM fiber with a smaller effective area single-mode fiber (SMF)[3,4]. In this approach, a section of QSM fiber is placed in the beginning of each span, in order to reduce the bulk of nonlinearities, followed by a section of SMF, to reduce the remaining fiber nonlinearities while avoiding excessive MPI penalty. The relative lengths of QSM fiber and SMF must be optimized to maximize the system performance.

In principle, such optimization can be performed numerically using Monte Carlo simulations. However, the latter are typically extremely time-consuming due to the use of the computationally-intensive split-step Fourier algorithm for the solution of the Manakov equation. For this reason, it is preferable to first use an analytical model to approximately calculate the optimum fiber configuration and then refine this preliminary solution by simulation.

The nonlinear Gaussian noise model[6] provides an analytical first-order perturbation solution of the Manakov equation. Signal distortion due to the Kerr nonlinearity is treated as a zero-mean, complex Gaussian additive noise. The variance of the latter is calculated in closed-form from fiber and system parameters[6].

In its original formulation, the nonlinear Gaussian noise model[6] is restricted to coherent optical communication systems using a single fiber type. Recently, we extended this formalism to model coherent optical communication systems with hybrid fiber spans[3] comprising a combination of QSM fiber and single-mode fiber per span. In this paper, we use Monte Carlo simulation to validate this model. We show that it predicts the optimum hybrid fiber configuration per span with excellent accuracy.

Analytical model

The nonlinear noise variance σ_{NL}^2 at the center of the WDM spectrum, in an optical bandwidth equal to the symbol rate R_s , is given by[3]

$$\sigma_{NL}^2 = \frac{16}{27}\frac{N_s P^3}{R_s^2} \iint_{-B_0/2}^{B_0/2} df_1 df_2 \left| \gamma_1 \frac{1 - e^{-(a_1 + i\Delta\beta_1)\ell_{s_1}}}{a_1 + i\Delta\beta_1} + \gamma_2\, e^{-(a_1 + i\Delta\beta_1)\ell_{s_1}} \frac{1 - e^{-(a_2 + i\Delta\beta_2)\ell_{s_2}}}{a_2 + i\Delta\beta_2} \right|^2 \quad (1)$$

where N_s is the number of fiber spans, P is the launch power per WDM channel, B_0 is the WDM bandwidth, ℓ_{s_k} is the k –th fiber segment length per span, a_k is the attenuation coefficient, γ_k is the fiber nonlinear coefficient, $\Delta\beta_\mathrm{k}\,(f_1, f_2)$ is the propagation constant mismatch for $k = 1, 2,$ respectively, and $\ell_s = \ell_{s_1} + \ell_{s_2}$ is the total span length.

MPI crosstalk is also modeled, for simplicity, as a complex white additive Gaussian noise with zero mean and variance proportional to the launch power per WDM channel. An explicit expression for the MPI noise variance as a function of the system parameters is given in[2,3].

Simulation setup

The simulation setup is shown in Fig. 1. We consider a 6,000 km long coherent optical communication system with 9 Nyquist WDM channels, each carrying 32 GBd PDM-16QAM.

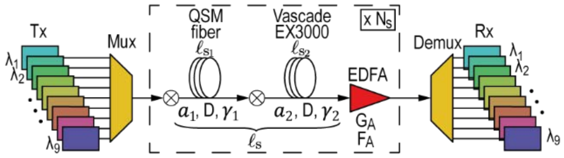

Fig. 1 Simulation setup.

For Nyquist pulse shaping at the sampling instant at the receiver, the transmitter and the receiver use square-root-raised-cosine matched filters. To maximize spectral efficiency while avoiding spectral overlap, the roll-off factor is $\beta = 0.01$ and the channel spacing is $\Delta f_{ch} = (1+\beta)R_s$. The QSM fiber has effective area $A_{eff,1}$= 200 μm², average coupling coefficient κ = 10^{-3} km^{-1}, differential mode attenuation Δα = 2 dB/km, and fundamental mode attenuation coefficient (including the excess loss coefficient[2]) a_1 =0.155 dB/km. For the single-mode fiber segment, we consider the use of Corning® Vascade® EX3000[3,4] fiber with an effective area $A_{eff,2}$=150 μm² and attenuation coefficient a_2 =0.155 dB/km. The resulting nonlinear coefficients are γ_1 = 0.43 W^{-1} km^{-1} and γ_2 = 0.57 W^{-1} km^{-1}, respectively. The dispersion parameter for both fiber types is D = 20.855 ps/(nm.km). The erbium-doped fiber amplifiers (EDFAs) have noise figure F_A = 5 dB and gain G_A equal to the span loss.

We evaluate the Q-factor vs. launch power for the central WDM channel using three different methods: (a) Monte Carlo simulation using direct error counting; (b) The nonlinear Gaussian noise model for hybrid fiber spans described in the previous section; (c) The nonlinear interference noise (NLIN) model for single fiber type spans[7,8].

Results and discussion

Fig. 2(a),(b) show plots of the Q-factor as a function of the launched power per WDM channel for a coherent optical system with 60 km spans using various configurations of QSM fiber and Vascade EX3000 fiber, with and without MPI equalization, respectively. We observe that the numerical results (points) qualitatively follow the predictions of the Gaussian nonlinear noise model for hybrid fiber spans (broken lines of the same color). However, there is a discrepancy between the analytical and numerical results of about 0.7 dB at the optimum Q-factor. For instance, according to the Gaussian noise model, the best hybrid fiber configuration per span consists of about 10 km of QSM fiber in the beginning of each span, followed by 50 km of Vascade EX3000 fiber. The performance of this hybrid fiber configuration yields an optimum Q-factor Q_0 of 9.4 dB, which is almost equivalent to using Vascade EX3000 alone. The numerical results in Fig. 2(a) confirm that this is indeed the case but that Q_0 =8.7 dB. In the presence of full MPI equalization (Fig. 2 (b)), analytical and numerical results indicate that the optimum performance is achieved using solely QSM fiber at each span. Nevertheless, the optimum Q-factor provided by the nonlinear Gaussian noise model is 10.2 dB whereas the numerically-calculated optimum Q-factor is 9.5 dB.

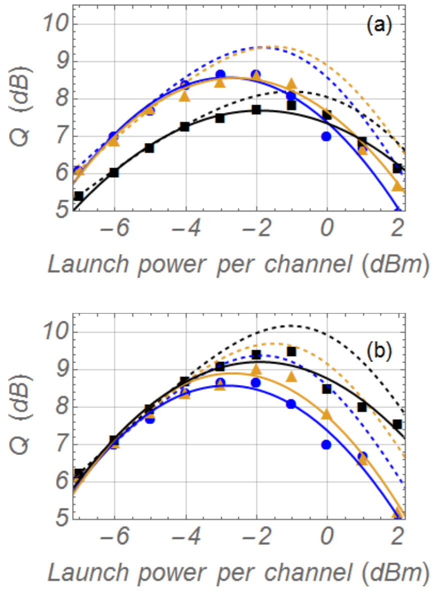

Fig. 2 Q-factor as a function of the launched power per WDM channel for a coherent optical system with 60 km spans using various combinations of QSM fiber and Vascade EX3000 fiber (a) without and (b) with MPI equalization. (Symbols: circles: Vascade EX3000 fiber only, squares: QSM fiber only, triangles: 10 km QSM fiber-50 km Vascade EX3000 fiber, broken lines: nonlinear Gaussian noise model, solid lines: NLIN model or polynomial fit for hybrid spans).

Similar behavior is observed for 100 km spans (Fig. 3). In Fig. 3 (a), in the absence of MPI equalization, both numerical and analytical results indicate that the optimum Q-factor is achieved by using about 25 km of QSM fiber in the beginning of each span, followed by 75 km of Vascade EX3000 at the end of each span. In Fig. 3(b), for full MPI equalization, the best system performance is achieved again by using solely QSM fiber for each span. In the latter case, the optimum Q-factor predicted by the nonlinear Gaussian noise model is 8.2 dB which differs slightly from the numerical prediction of 8 dB. In other cases, the numerically-calculated optimum Q-factor is about 0.5 dB below the analytical prediction. We conclude that the Gaussian nonlinear noise model of the previous section is appropriate for predicting the optimum fiber configuration but not the optimum Q-factor.

Fig. 4 shows plots of the optimum Q-factor Q_0 as a function of the QSM fiber per span ℓ_{s_1} in a coherent optical system with 100 km spans in the absence of MPI compensation. We observe that numerical results follow well the shape of the analytical curve despite the 0.5 dB difference in the predicted optimum Q-factor. As a result, the Gaussian nonlinear noise model for hybrid fiber spans accurately predicts the normalized optimum QSM fiber length ℓ_{s_1}/ℓ_s as a function of the percentage of MPI compensation (Fig. 5).

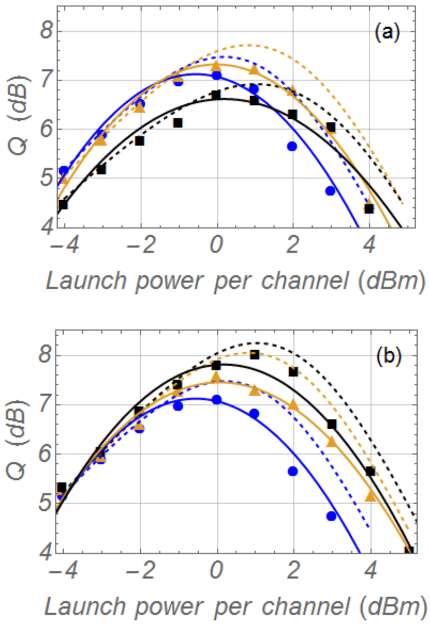

Fig. 3 Same as Fig. 2 for 100 km spans. (All symbols are the same as in Fig. 2 except for the triangles: 25 km QSM fiber-75 km Vascade EX3000 fiber).

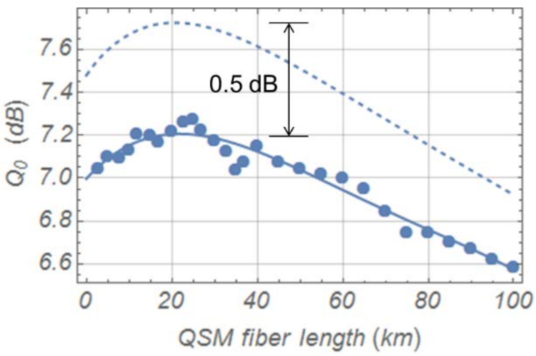

Fig. 4 Optimum Q-factor $\boldsymbol{Q_0}$ as a function of the QSM fiber length $\boldsymbol{\ell_{s_1}}$ per span in a coherent optical system with 100 km spans in the absence of MPI compensation. It is worth noting that the maximum is relatively broad so that varying the fiber splitting ratio around its optimal value changes the optimum Q-factor only slightly. (Symbols: Dashed line: nonlinear Gaussian noise model, points: Monte Carlo simulation, solid line: polynomial fit).

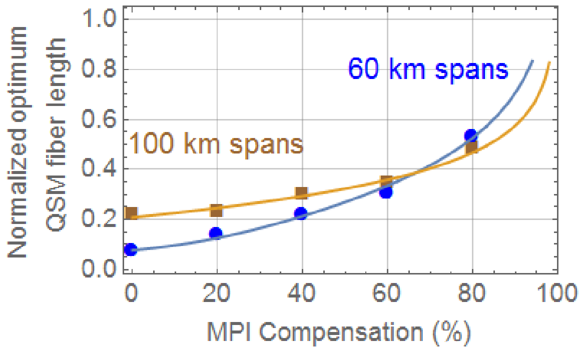

Fig. 5 Normalized optimum QSM fiber length per span $\boldsymbol{\ell_{s_1}/\ell_s}$ vs. the level of MPI compensation. (Symbols: lines: nonlinear Gaussian noise model, points: Monte Carlo simulation).

Conclusions

We proposed and validated an analytical model for the performance evaluation of coherent optical communication systems with hybrid fiber spans. The model represents the nonlinear distortion and multipath interference in coherent optical communication systems as Gaussian noises. The model predicts the optimum hybrid fiber configuration per span with excellent accuracy.

Acknowledgements

The authors would like to thank W. A. Wood of Corning for fruitful discussions.

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