Modeling Long-Haul Optical Networks with Quasi-single-mode Fibers

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Abstract. Few-mode fibers (FMFs) with weak mode coupling which are used to transmit signals predominantly in the fundamental mode are referred to as quasi-single-mode (QSM) fibers. QSM fibers can be designed to have much larger effective areas for the fundamental propagation mode than conventional single-mode fibers (SMFs). Signal transmission over the fundamental mode of QSM fibers can reduce distortion arising from the fiber Kerr nonlinearity. Random light coupling, however, among QSM fiber modes leads to multipath interference (MPI). Simultaneous reduction of nonlinear distortion and MPI can be achieved by using hybrid fiber spans, each composed of a QSM fiber segment to restrict nonlinear distortion, followed by an ultra-low-loss, large-effective-area SMF segment to suppress MPI.
In this invited paper, we review modeling and simulation tools that can be used for the design and optimization of coherent optical communication systems and networks with hybrid QSM fiber/SMF spans. We show that the precise selection of the fiber splitting ratio per span is not critical for the system performance and can be calculated with sufficient accuracy using a modified version of the nonlinear Gaussian noise model for hybrid fiber spans.

Keywords: Multipath interference (MPI), optical communications, optical fiber, quasi-single-mode (QSM) transmission.

1 Introduction

Kerr nonlinearity in single-mode fibers (SMFs) places a ceiling on the spectral efficiency of contemporary optical communication systems [7]. To overcome this limitation, several techniques for nonlinear distortion mitigation and compensation in long-haul optical communications systems have been proposed over the past few years [2], [1].

A promising nonlinear distortion mitigation strategy uses the fundamental propagation mode of FMFs to establish single-mode links with reduced nonlinear distortion due to the Kerr effect [17], [16], [5], [18], [13], [15], [19], [6], [8]. This technique is called quasi-single-mode (QSM) transmission. By extension, FMFs with weak mode coupling which are used to transmit signals predominantly in the fundamental mode are referred to as quasi-single-mode (QSM) fibers.

Launching light in the fundamental mode of an ideal, straight, perfectly-cylindrical FMF results, in principle, in pure single-mode propagation without coupling to higher-order modes. In practice, however, there always exists random coupling from the fundamental mode to higher-order modes and vice versa because of fiber irregularities. This leads to the generation and propagation of a multitude of copies of the signal waveform across the fiber link. Due to modal dispersion, these echoes propagate at various group velocities and interfere either constructively or destructively with the main signal propagating on the fundamental mode. This effect is referred to as multipath interference (MPI) [14], [10].

A compromise between fiber nonlinearities and MPI can be achieved by resorting to a combination of a large effective mode area QSM fiber and a smaller effective mode area SMF [15], [19], [4]. The QSM fiber is placed at the beginning of the span where signal power is greatest to restrict nonlinear distortion, followed by an SMF segment to suppress MPI. We can adjust the splitting ratio between QSM fiber and SMF to maximize the system performance.

Monte Carlo simulation can be commonly used to compute the optimum fiber splitting ratio. The main drawback of this approach is that it often requires excessive computational resources to evaluate the performance of a large number of candidate fiber configurations and select the best among them. This is due to the high computational complexity of the numerical solution of the Manakov equation using the split-step Fourier algorithm. A preferable alternative would be to use an approximate analytical model to either compute the optimum fiber splitting ratio directly or, at least, to limit the parameter space prior to running Monte Carlo simulations.

The nonlinear Gaussian noise model [11], [12] provides an analytical first-order perturbation solution of the Manakov equation in the absence of polarization mode dispersion (PMD) and polarization-dependent loss (PDL). In this regime, signal distortion due to the Kerr nonlinearity resembles a zero-mean, complex Gaussian additive noise. The variance of the latter is calculated in closed-form from fiber and system parameters [11], [12].

In its original formulation [11], [12], the nonlinear Gaussian noise model is restricted to coherent optical communication systems using a single fiber type per span. Recently, we extended this formalism to model coherent optical communication systems with hybrid fiber spans [4] comprising a combination of QSM fiber and SMF per span. In [9], we used Monte Carlo simulation to validate this model. We showed that it can predict the optimum hybrid fiber configuration per span with sufficient accuracy.

The purpose of this article is to review modeling and simulation tools that can be used for the performance evaluation and optimization of coherent optical communication systems with hybrid QSM fiber/SMF spans. Using these tools, we show that the optimum fiber splitting ratio per span increases with the percentage of MPI compensation at the coherent optical receiver. The peak system performance, however, is a slowly-varying function of the fiber splitting ratio. Therefore, the precise selection of the fiber splitting ratio per span is not critical and can be calculated with sufficient accuracy using the above-mentioned modified version of the nonlinear Gaussian noise model for hybrid fiber spans.

2 Theoretical model

2.1 System topology

Fig. 1 depicts the block diagram of a representative long-haul coherent optical communication system for QSM transmission with hybrid fiber spans. The transmission link of total length L is composed of a concatenation of N_s identical spans. Each span has length ℓ_s and comprises two fiber types. Each fiber type is characterized by its LP_{01} mode effective area A_{eff}, its nonlinear index coefficient n_2, its group velocity dispersion (GVD) parameter β_2 or, equivalently, its chromatic dispersion parameter D, and its attenuation coefficient a. In what follows, indices 1, 2 stand for the first and second fiber segment per span, respectively. For instance, the optical fiber lengths of the two segments are ℓ_{s_1}, ℓ_{s_2}, and their effective mode areas are A_{eff_1}, A_{eff_2}, respectively. The three splices between dissimilar optical fibers denoted by $\otimes$ in Fig. 1 have losses χ_1, χ_2, and χ_3, respectively. The optical fiber is followed by an optical amplifier of gain equal to the span loss $G = \chi_1^{-1}\chi_2^{-1}\chi_3^{-1}e^{a_1\ell_{s_1}+a_2\ell_{s_2}}$ and noise figure F_A.

We consider wavelength division multiplexing (WDM) and polarization division multiplexing (PDM) based on ideal Nyquist channel spectra. The latter are created using square-root raised cosine filters with zero roll-off factor at the transmitter and the receiver. Furthermore, we assume that the WDM signal is a superposition of an odd number N_{ch} wavelength channels with spacing $\Delta f = R_s$. We denote by P the total average launch power per channel (in both polarizations) and by R_s the symbol rate. We want to evaluate the performance of the center WDM channel at wavelength λ.

2.2 Analytical performance evaluation

Effective optical signal-to-noise ratio (OSNR) The performance of coherent optical systems without in-line chromatic dispersion compensation is related to the *effective* optical signal-to-noise ratio ($\mathrm{OSNR}_{\mathrm{eff}}$) at the receiver input. This quantity takes into account the amplified spontaneous emission (ASE) noise, the MPI, and the nonlinear distortion. All the above effects can be modeled as independent, zero-mean, complex Gaussian noises with a good degree of accuracy. More specifically, the $\mathrm{OSNR}_{\mathrm{eff}}$ at a resolution bandwidth $\Delta\nu_{\mathrm{res}}$ can be well described by the analytical relationship [10]

$$\mathrm{OSNR}_{\mathrm{eff}} = \frac{P}{\tilde{a} + \tilde{\beta}P + \tilde{\gamma}P^3}, \tag{1}$$

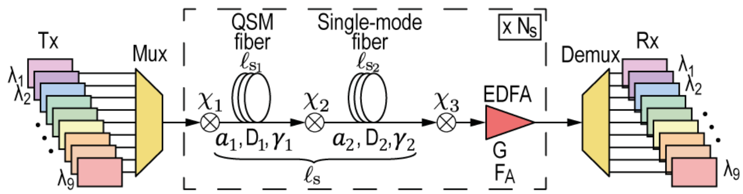


Fig. 1: Representative long-haul coherent optical communications system with hybrid fiber spans.

where $\tilde{a}$ is the ASE noise variance, $\tilde{\beta}P$ is the crosstalk variance due to MPI, and $\tilde{\gamma}P^3$ is the nonlinear noise variance. The coefficients $\tilde{a}, \tilde{\beta}, \tilde{\gamma}$ depend on the fiber and system parameters.

Noise variances for systems with hybrid fiber spans Nonlinear noise accumulation for coherent optical communication systems using hybrid fiber spans can be modeled by extending the perturbation formalism of [11], [12]. Here, we consider ideal Nyquist PDM WDM signals with channel spacing equal to the symbol rate R_s. We obtain the following expression for the nonlinear noise coefficient $\tilde{\gamma}$

$$\tilde{\gamma} \cong \frac{16}{27} \frac{N_s^{1+\epsilon} \Delta\nu_{\mathrm{res}}}{R_s^3} \chi_1^2 \int_{-\frac{B_0}{2}}^{\frac{B_0}{2}} \int_{-\frac{B_0}{2}}^{\frac{B_0}{2}} \left| \gamma_1 \frac{1 - e^{-(a_1 + i\Delta\beta_1)\ell_{s_1}}}{a_1 + i\Delta\beta_1} \right.$$
$$\left. + \; \chi_2 \gamma_2 e^{-(a_1 + i\Delta\beta_1)\ell_{s_1}} \frac{1 - e^{-(a_2 + i\Delta\beta_2)\ell_{s_2}}}{a_2 + i\Delta\beta_2} \right|^2 df_1 df_2. \tag{2}$$

In (2), γ_m are the nonlinear coefficients, $\Delta\beta_m$ are the propagation constant mismatches of the two fiber segments per span, $m = 1, 2$, and ϵ is a fitting parameter.

For modeling MPI, we assume that the QSM fibers under consideration exhibit weak coupling between the fundamental mode group LP_{01} and the higher-order mode group LP_{11}, i.e., the power coupling coefficient κ satisfies the relationship $\kappa\ell_{s_1} \ll 1$. Then, the MPI coefficient $\tilde{\beta}$ is given by [10] (with a sign correction)

$$\tilde{\beta} = N_s \frac{\Delta\nu_{\mathrm{res}}}{R_s} \frac{(\Delta\alpha\ell_{s_1} - 1 + \mathrm{e}^{-\Delta\alpha\ell_{s_1}})\kappa^2}{\Delta\alpha^2}, \tag{3}$$

where $\Delta\alpha$ is the differential mode attenuation (DMA).

Finally, the ASE noise variance for arbitrary span lengths is given by [3]

$$\tilde{\alpha} = hf_0 N_s \left(GF_A - 1\right) \Delta\nu_{\mathrm{res}}, \tag{4}$$

where h is Planck's constant and f_0 is the center WDM channel carrier frequency.

2.3 Numerical simulations

In numerical simulations, we consider hybrid fiber spans composed of a hypothetical QSM fiber and a representative commercially-available, large-effective-area SMF. We assume an ideal Nyquist WDM signal composed of 9 wavelength channels, each carrying PDM 16-QAM. The simulation parameters are listed in Table 1. For simplicity, splice losses and splice-induced MPI are neglected.

Table 1: Simulation parameters

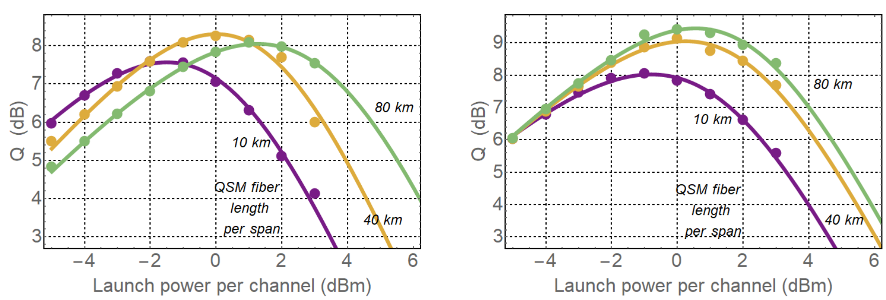
Parameter	Symbol	Value
Modulation format		PDM-16QAM
Symbol rate	R_s	32 GBd
WDM channels	N_{ch}	9
WDM channel spacing	Δf	R_s
Link length	L	6,000 km
Span length	ℓ_s	80 km
Attenuation coefficients	α_1, α_2	0.155 dB/km
QSM fiber LP_{01} mode effective area	A_{eff_1}	350 µm^2
SMF LP_{01} mode effective area	A_{eff_2}	150 µm^2
Power coupling coefficient	κ	10^{-3} km^{-1}
Differential mode attenuation (DMA)	$\Delta\alpha$	2 dB/km
Nonlinear refractive index	n_2	2.1×10^{-20} m^2/W
GVD parameter	$\lvert\beta_2\rvert$	26.6 ps^2/km
EDFA noise figure	F_A	5 dB

We evaluate the Q-factor vs. launch power for the central WDM channel using two different methods: (a) Monte Carlo simulation using direct error counting; and (b) The nonlinear Gaussian noise model for hybrid fiber spans described earlier.

3 Results and discussion

In this section, we compute the optimal fiber splitting ratio per span that maximizes system performance. In particular, we investigate how this ratio depends on the degree of MPI equalization at the coherent optical receiver.

System performance for 80 km spans At the beginning, we examine the variation of the Q-factor as a function of the launched power per WDM channel for a coherent optical system composed of 80 km spans. Fig. 2a and Fig. 2b show numerical results for two extreme MPI cases: (i) when MPI is not compensated; and (ii) when complete elimination of the MPI-induced intersymbol interference (ISI) is achieved using adaptive equalization at the coherent receiver, respectively. Different color curves correspond to different length combinations of QSM fiber and large-effective-area SMF. In Fig. 2a, the best combination of optical fibers leading to optimal system performance consists of about 40 km of QSM fiber at the beginning of each span, followed by 40 km large-effective-area SMF at the end of each span. The use of this fiber combination yields an optimal Q-factor $Q_0 = 8.3$ dB, which is better than that achieved with the two other displayed fiber configurations. In Fig. 2b, where we assume that there is complete equalization of MPI-induced ISI at the coherent optical receiver, the best system performance is achieved using only QSM fiber at each span. The optimal Q-factor obtained by this fiber configuration is 9.5 dB.



(a)

(b)

Fig. 2: Q-factor as a function of the total launch power per channel. (a) No MPI compensation; (b) 100% MPI compensation. (Symbols: Points: Monte Carlo simulations; Lines: Least squares fitting using (1) with $\tilde{a}, \tilde{\beta}, \tilde{\gamma}$ as unknown parameters.)

System performance for various MPI compensation levels Fig. 3 shows plots of the optimum Q-factor Q_0 as a function of the QSM fiber length per span ℓ_{s_1}. Curves from bottom to top correspond to progressively larger levels of MPI compensation at the coherent optical receiver. For 0% MPI compensation, about 50% of each span is QSM fiber. As MPI compensation increases, the fraction of QSM fiber per span increases. At 100% compensation, the best system performance is achieved by using exclusively QSM fiber. We observe that the proposed nonlinear Gaussian noise model given by (1)-(4) describes fairly well the numerical results.

It is worth noting that Q_0 is a slowly-varying function of the QSM fiber length ℓ_{s_1} in a wide region around the peak. For instance, in the absence of MPI compensation, the system performance changes by only 0.1 dBQ when the QSM fiber length varies in the range 22–61 km. This weak dependence of Q_0 on the QSM fiber length implies that it is not critical to determine the fiber splitting ratio per span with utmost accuracy. The nonlinear Gaussian noise model can be used to compute the fiber splitting ratio per span with sufficient accuracy even without exact knowledge of the value of the fitting parameter ϵ. For instance, in the absence of MPI compensation, using the nonlinear Gaussian noise model with $\epsilon = 0$ yields an optimum QSM fiber length $\ell_{s_1} = 31$ km, which results in less than 0.1 dBQ decrease from the maximum performance.

These general trends persist independent of the choice of the QSM fiber LP_{01} mode effective area and the fiber span length. The above results reveal that, in spite of the generation of MPI, the use of QSM fiber is beneficial.

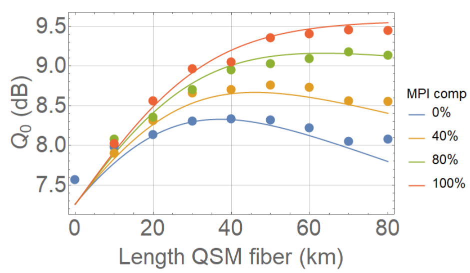


Fig. 3: Optimum Q-factor $\boldsymbol{Q}_0$ as a function of the QSM fiber length $\ell_{\boldsymbol{s_1}}$ per span. (Symbols: Points: Monte Carlo simulations; Lines: Least squares fitting using (1)-(4) with ϵ as an unknown parameter. Here $\epsilon \simeq 0.2$.)

4 Conclusion

The aim of this article was to review modeling and simulation tools that can be used for the performance evaluation and optimization of coherent optical communication systems with hybrid fiber spans, comprising a combination of QSM fiber and a large-effective-area SMF per span. Monte Carlo simulation was used to compute the optimum hybrid fiber configuration per span with high accuracy. We showed that the optimum fiber splitting ratio per span increases with the percentage of MPI compensation at the coherent optical receiver. For instance, for a transatlantic system with 80 km spans, in the absence of MPI compensation, it is best to use equal lengths of QSM fiber and SMF per span. In contrast, for full MPI compensation, the optimum system performance is achieved by using exclusively QSM fiber.

In addition, we analytically evaluate the performance of the aforementioned optical communication systems with hybrid QSM fiber/SMF spans. Nonlinear distortion and multipath interference are represented as additive white Gaussian noises. We extended the original nonlinear Gaussian noise formalism to model systems with hybrid fiber spans. The analytical model predictions qualitatively explain the numerical simulation results. The value of the analytical model lies in its simplicity. It helps us understand the interplay among various physical parameters. Most importantly, it can be used to compute the fiber splitting ratio per span with sufficient accuracy.

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