# Hybrid fiber links using quasi-single-mode fibers

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***Abstract*—We evaluate the performance of coherent optical communications systems using hybrid spans, composed of quasi-single-mode (QSM) and single-mode fibers (SMFs). We study how the optimum fiber splitting ratio per span increases with the span length, the QSM fiber effective area, and the residual multipath interference at the receiver.**

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

## I. INTRODUCTION

The spectral efficiency of contemporary coherent optical communication systems is limited by fiber nonlinearities [1]. Nonlinear distortion mitigation and compensation techniques for long-haul optical communications systems have been studied extensively over the past few years [2]-[3].

Among other techniques, large-effective-area fibers can be deployed to reduce nonlinear distortion due to the Kerr effect [4]-[5]. Quasi-single-mode (QSM) fibers, especially, have larger effective areas for the $LP_{01}$ mode than conventional single-mode fibers (SMFs). It is possible to launch optical signals exclusively in the fundamental mode of QSM fibers. However, higher-order modes are excited due to random coupling along the optical link. Light in higher-order modes interferes with the signal in the fundamental mode. This effect is referred to as multipath interference (MPI) [5].

A compromise between fiber nonlinearities and MPI can be achieved by combining QSM and SMF segments in each span to reduce nonlinear distortion and minimize MPI interference simultaneously. The splitting ratio between the QSM fiber and the SMF can be adjusted to obtain the best system performance.

To find the optimum fiber splitting ratio, Monte Carlo simulation can be used. In this paper, we compute the fiber splitting ratio of hybrid fiber links for a large set of different optical fibers and system parameters. We study how the optimum fiber splitting ratio increases with the span length, the QSM fiber fundamental mode effective area, and the level of MPI compensation at the coherent optical receiver.

## II. SIMULATION SETUP

Fig. 1 depicts the block diagram of a representative long-haul coherent optical communication system for QSM transmission with hybrid fiber spans. It is composed of a concatenation of $N_s$ identical spans. Each span has length $\ell_s$ and is comprised of 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 $\beta_2$ or, equivalently, its chromatic dispersion parameter $D$, and its attenuation coefficient $\alpha$. The three splices between dissimilar optical fibers are denoted by $\otimes$ in Fig. 1. At the end of each span there is an optical amplifier with gain $G$ equal to the span loss and noise figure $F_A$.

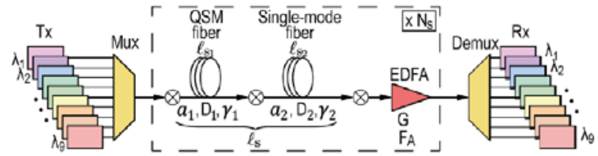


Fig. 1. Representative long-haul coherent optical communications system with hybrid fiber spans.

Nine channels are wavelength division multiplexed (WDM) and transmitted through the fiber link. Each channel consists of two polarization division multiplexed (PDM), quadrature amplitude modulated (QAM) signals with ideal square-root raised cosine (SRRC) pulses. The WDM channel spacing is approximately equal to the channel symbol rate $R_s$. We evaluate the performance of the center WDM channel at wavelength $\lambda$.

The simulation parameters are listed on Table I. For simplicity, splice losses and splice-induced MPI are neglected.

TABLE I. SIMULATION PARAMETERS

| Parameter | Symbol | Value |
|---|---|---|
| Modulation format | | PDM-16QAM |
| Symbol rate | $R_s$ | 32 GBd |
| WDM channels | $N_{ch}$ | 9 |
| WDM channel spacing | $\Delta f$ | $R_s$ |
| Link length | $L$ | 6,000 km |
| Span length | $R_s$ | 120 km |
| Attenuation coefficients | $\alpha_1, \alpha_2$ | 0.155 dB/km |
| QSM fiber $LP_{01}$ mode effective area | $A_{eff1}$ | 350 $\mu m^2$ |
| SMF $LP_{01}$ mode effective area | $A_{eff2}$ | 150 $\mu m^2$ |
| Power coupling coefficient | $\kappa$ | $10^{-3}$ km$^{-1}$ |
| Differential mode attenuation (DMA) | $\Delta\alpha$ | 2 dB/km |
| Nonlinear refractive index | $n_2$ | $2.1\times10^{-20}$ m$^2$/W |
| GVD parameter | $\lvert\beta_2\rvert$ | 26.6 ps$^2$/km |
| EDFA noise figure | $F_A$ | 5 dB |

The effective optical signal-to-noise ratio ($OSNR_{eff}$) is used to fit the numerical results. The $OSNR_{eff}$ at the receiver can be well described by the analytical relationship [5]

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

where $\tilde{\alpha}$ 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 $\tilde{\alpha}, \tilde{\beta}, \tilde{\gamma}$ depend on the fiber and system parameters.

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In the simulation, MPI is modeled as an additive white Gaussian noise with zero mean and variance $\tilde{\beta}P$. 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 $\kappa$ satisfies the relationship $\kappa\ell_{s1} \ll 1$. Then, the MPI coefficient $\tilde{\beta}$ is given by [5] (with a sign correction)

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

where Δα is the differential mode attenuation (DMA).

## III. Representative Results and Discussion

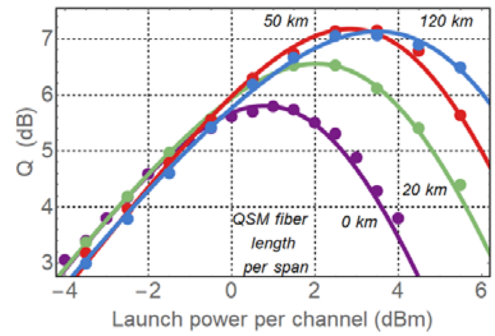
This Section shows representative results for a 6,000 km system with 120 km spans, each composed of two fiber segments with effective areas of 350 μm² and 150 μm², respectively. We first examine the variation of the Q-factor as a function of the launched power per WDM channel (Fig. 2). Two extreme MPI cases are shown: (a) When MPI is not compensated; and (b) When complete equalization of MPI-induced intersymbol interference is achieved. In Fig. 2(a), the optimal Q-factor initially increases as the length of QSM fiber per span increases. For QSM fiber segments longer than about 50 km, however, the impact of MPI dominates and the optimal Q-factor decreases. The best combination of optical fibers, leading to optimal system performance, consists of about 50 km of QSM fiber, followed by 70 km of SMF fiber. The use of this fiber combination yields an optimal Q-factor $Q_0 = 7.2$ dB without MPI compensation. The percentage of QSM fiber per span varies with the span length and the fundamental mode effective areas of the two fiber segments. If the MPI-induced ISI can be fully compensated, the optimal Q-factor monotonically increases with the QSM fiber length, as shown in Fig. 2(b). The peak optimal Q-factor is equal to 7.8 dB and is obtained using 120 km QSM fiber per span.

Next, 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. Fig. 3 shows plots of the optimal Q-factor $Q_0$ as a function of the QSM fiber length per span for different MPI compensation ratios. The best fiber configuration depends on the residual MPI level at the receiver. For 0% MPI compensation, the best configuration is roughly 50% QSM fiber and 50% SMF in each span. However, as MPI compensation increases, the percentage of QSM fiber per span increases. At 100% compensation, the best system performance is achieved by solely using QSM fiber.

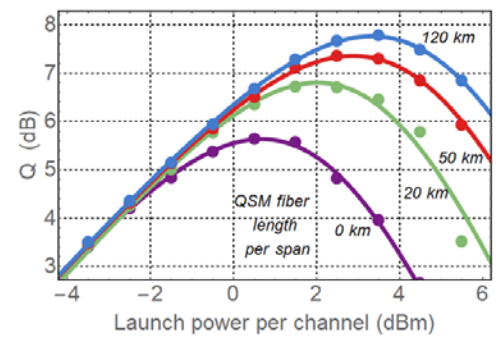
Comprehensive results for other span lengths and different fiber characteristics will be presented at the conference.

## IV. Conclusion

Monte Carlo simulation was used to compute the optimum hybrid fiber configuration per span with high accuracy. We studied how the optimum fiber splitting ratio increases with the span length, the QSM fiber fundamental mode effective area, and the level of MPI compensation at the coherent optical receiver.




(a)




(b)

Fig. 2. *Q-factor vs launch power for different splitting ratios of QSM fiber vs SMF per span. a) No MPI compensation; b) Full MPI compensation (Symbols: Points: Monte Carlo simulations; Lines: Least squares fitting using (1)).*

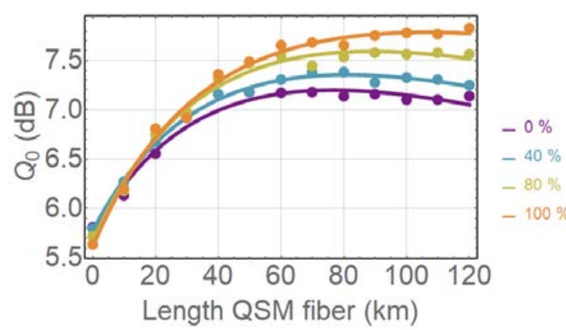



Fig. 3. *Optimum Q-factor* $Q_0$ as a function of the *QSM fiber length per span for different MPI compensation levels.*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