Quasi-Single-Mode Transmission for Long-Haul and Submarine Optical Communications

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Abstract: Single-mode transmission over few-mode fiber is investigated to enable larger effective area and higher nonlinear tolerance. Multipath interference generated during propagation is modeled. Transmission results illustrate benefits of hybrid spans and multi-subcarrier modulation formats.

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1. Introduction

Strong traffic growth in long-haul and submarine optical networks motivates a continuing drive to increase system capacity and increase system reach. A technology extensively studied to improve system performance is digital nonlinear compensation as a means of mitigating fiber nonlinear impairments [1]. However, such techniques are generally computationally expensive and only moderately effective. An alternative approach to increasing nonlinear tolerance is the use of optical fibers with larger effective area (A_{eff}). In practice, it can be difficult to balance large A_{eff} with bend loss performance. One path toward increasing fiber nonlinear tolerance is to relax a requirement for strict single-mode propagation, thus allowing the fundamental mode A_{eff} to be enlarged, while increasing the cutoff wavelength and allowing a lossy higher order mode. However, the existence of a second mode also introduces possible new impairments from mode coupling, namely multipath interference (MPI). We refer to the transmission of the fundamental mode only in a few-mode fiber in a system with conventional single-mode components such as optical amplifiers as quasi-single-mode (QSM) fiber transmission, and we examine some of the implications of this system type here. Digital signal processing (DSP) can be applied to mitigate the effects of MPI, as has been proposed and demonstrated [2-4]. Thus QSM fibers may offer a trade-off of increased linear impairments for reduced nonlinear impairments, which may be worthwhile if the linear MPI impairment can be more easily compensated in DSP.

In this paper, we review some recent research in quasi-single-mode transmission. We present modeling results of the effects of mode coupling and differential mode attenuation (DMA) on MPI. We also show recent experimental transmission results for QSM transmission over long distances with 200 Gb/s channels and prototype fiber.

2. Multipath Interference in a QSM Fiber Span

A phenomenological model for MPI generated during propagation of the fundamental mode in a two-mode fiber span has been developed based on power coupled-mode theory [5]. The model assumes that light is launched into only the fundamental LP_{01} mode at the beginning of a span and that mode coupling will occur on a distributed and continuous basis throughout the span. The mode coupling is governed by an average coupling coefficient κ (km^{-1}) that is dependent on the difference in phase velocities between the two modes and the transverse spatial profiles of the modes, among other things. The model yields the expression in Eq. 1 for MPI as a function of distance z into a span, where $\Delta\alpha = (\alpha_{11} - \alpha_{01})$ is the DMA in units of km^{-1}. The expression in Eq. 1 has also been derived independently based on the expected impulse response [6]. MPI is defined as the ratio of the total crosstalk power to the average signal power at the receiver, MPI = $P_{xt,tot}$ /P_{sig}.

$$MPI(z) = \frac{(\Delta\alpha\cdot z - 1 + e^{-\Delta\alpha\cdot z})}{\Delta\alpha^2}\kappa^2 \qquad (1)$$

It can be shown that for very small $\Delta\alpha$, MPI(z) grows proportional to z^2, while for large DMA, MPI(z) grows linearly with distance [5]. Overall, MPI decreases with increasing DMA. Regardless of DMA, the total MPI at the end of a full link scales proportionally to the total number of spans. This is because any power in the LP_{11} mode is stripped out at the end of each span by the single-mode optical amplifier, and the spans are independent. This leads to differences in the total MPI at link end, depending on fiber DMA and span length. This is illustrated in Fig. 1(a) for a 3000 km link length and weak mode coupling with $\kappa = 0.001$ km^{-1}. For DMA values ≥ 1 dB/km, the total link MPI is essentially independent of span length. DMA also affects the effective maximum group delay addressed in MPI compensation DSP, illustrated in an example as the normalized number of equalizer filter taps in Fig. 1(b).

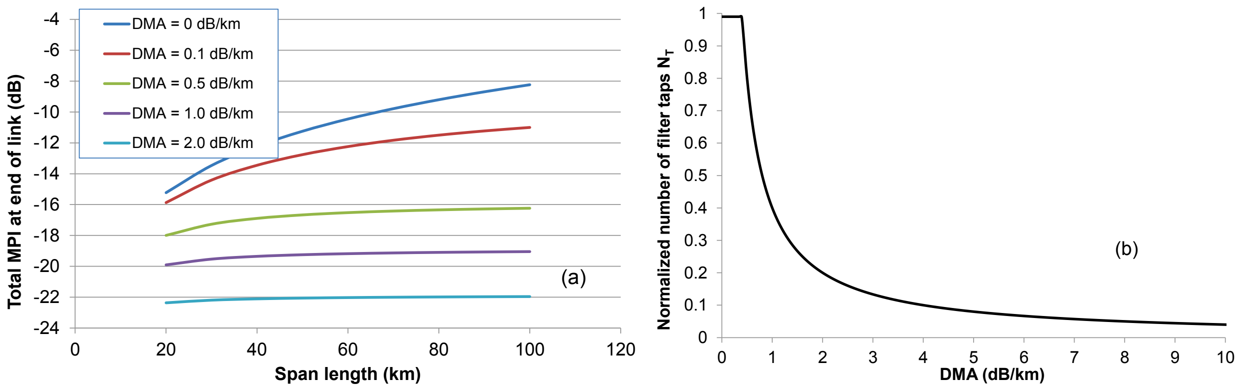

Fig. 1: (a) Total MPI as function of span length for 3000 km link. Coupling coefficient = 0.001 km^{-1}. (b) Normalized number of filter taps required for MPI compensation as a function of DMA.

3. Transmission Experiments

Recent experiments with quasi-single-mode transmission have been performed that help demonstrate the potential advantages and challenges of quasi-single-mode systems [4]. Two important findings demonstrated in this work were the benefits of using hybrid fiber spans and multi-subcarrier modulation formats. In the experiments, 101.8 km spans were constructed in a re-circulating loop. Spans comprised homogeneously of the few-mode fiber (A_{eff} ~ 200 μm^2) or of a large effective area single-mode fiber (A_{eff} ~ 150 μm^2), or in a hybrid configuration with ~51 km of the few-mode fiber followed by ~51 km of the single-mode fiber were studied. The hybrid spans were found to produce the best overall system performance because of the higher nonlinear tolerance afforded by the few-mode fiber in the first half of the spans, and the lower MPI generated by the hybrid spans in comparison to spans homogeneously comprised of the few-mode fiber. Modeling of hybrid spans suggests that optimal fiber ratios may depend on the relative fiber attenuations and level of MPI compensation. The experimental results obtained comparing the performance of the three different types of spans are shown in Fig. 2(a). Fig. 2(b) shows the relative MPI levels generated by transmission through the systems with different spans, illustrated by the CMA tap weights after 4060 km for the multi-subcarrier signal. The results in Fig. 2(c) demonstrate the better performance found with the multi-subcarrier modulation format compared to a single-carrier format with the same overall bit rate, afforded by more effective equalization per subcarrier with a smaller number of required filter taps.

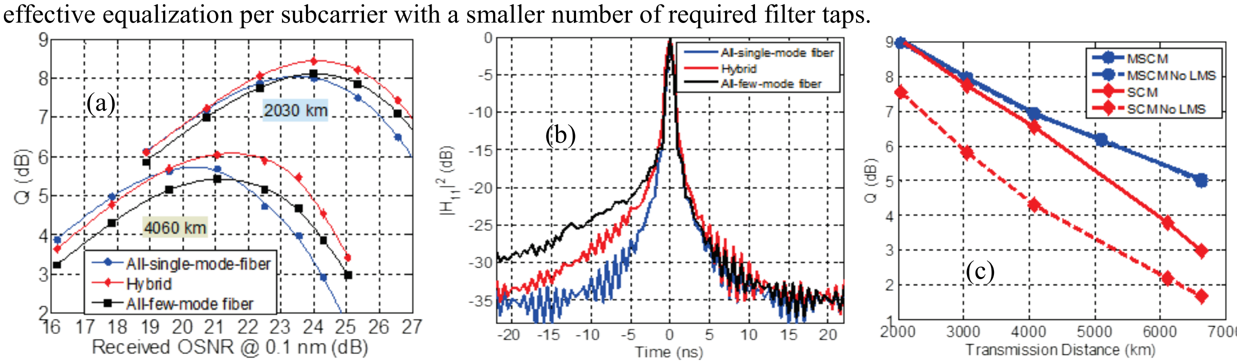

Fig. 2: (a) Q vs. OSNR for three span configurations. (b) CMA filter tap weights for multi-subcarrier format with different span configurations at 4060 km. (c) Q vs. distance with and without LMS equalization for single-carrier (SCM) and multi-subcarrier (MSCM) signal formats.

4. Summary

We have reviewed some issues involved with single-mode transmission over a few-mode fiber, or quasi-single-mode transmission. The potential benefits of larger effective area come at the expense of potentially increased linear impairments such as MPI. Recent transmission experiments highlight the advantages of multi-subcarrier signal formats with regard to MPI compensation via DSP, and hybrid fiber span configurations as a means of minimizing MPI and filter tap numbers.

5. References

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