Performance Evaluation of Hybrid DBPSK-MPPM Technique in Long-Haul Optical Transmission

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Abstract: The performance of DBPSK-MPPM technique is evaluated in long-haul transmission using GN-model. The BER expression is extended to address fiber nonlinearity. Results show that fiber nonlinearity effects are more significant in DBPSK-MPPM than traditional ones.
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1. Introduction

Hybrid modulation techniques represent a window to solve the poor power efficiency of high order modulation schemes that are used to avoid optical capacity crunch in single-mode fibers (SMFs) [1]. We have introduced a hybrid differential binary phase shift keying-multipulse pulse position modulation (DBPSK-MPPM) technique that is based on spectrally-efficient direct-detection DBPSK (DD-DBPSK) along with an energy-efficient modulation scheme MPPM [2]. The performance of the hybrid DBPSK-MPPM technique has been evaluated under optical amplifier-noise limited transmission [2]. Recently, hybrid techniques have been investigated under long-haul optical transmission [3]. However, analytical assessment of the hybrid modulation performance in long-haul transmission has not been addressed yet. In long-haul optical transmission, fiber nonlinearity limits the system performance. There are many approaches for modeling the effects of fiber nonlinearity. One of the most reasonable models for addressing these nonlinear impacts on single-mode fibers performance is Gaussian noise model (GN-model). Its validation has been assured over a wide range of system scenarios [4, 5].

In this paper, we formulate an analytical expression for the total noise for nonlinear-dispersive optical transmission of single polarized DBPSK-MPPM technique. In addition, we characterize the impacts of fiber nonlinearity on the performance of DBPSK-MPPM technique and compare it with that of traditional schemes, specifically both DBPSK and MPPM techniques.

2. BER formula for DBPSK-MPPM long-haul transmission

The GN-model assumes that the nonlinear interference is statistically independent of both the transmitted signal and amplifier noise [4]. In addition, in order to apply the GN-model, a multiple DBPSK-MPPM transmitted signals (N_{ch}) are wavelength division multiplexed (WDM) at the transmitter. Then, a long-haul nonlinear-dispersive SMF is used as the transmission channel which consists of multiple spans. Each span is followed by an erbium-doped fiber amplifier (EDFA). At the receiver, the N_{ch} modulated signals are WDM demultiplexed and processed by separate DBPSK-MPPM demodulator. The total system noise variance σ^2 is formulated as:

$$\sigma^2 = \sigma_{\text{n}}^2 + \sigma_{nl}^2 = \left(F(G-1)h\nu + \frac{2}{\pi}\frac{\gamma^2}{|\beta_2|}\frac{L_{\text{eff}}^2}{L_{\text{eff,a}}}\left(\frac{MP_{tx}}{nB_{ch}}\right)^3 \operatorname{arcsinh}\left(\frac{3}{8}\pi^2 L_{\text{eff,a}}|\beta_2|B_\omega^2\right)\right) N_s B_n, \quad (1)$$

where σ_{n}^2 is the optical amplifier noise variance and σ_{nl}^2 is the nonlinear interference variance, which is formulated by following a similar procedure as in [4]. F is the amplifier noise figure, h is Plank's constant, ν is the center channel frequency, G is the EDFA gain that compensates the fiber span loss, β_2 is the group-velocity dispersion (GVD), γ is the nonlinearity coefficient, and B_{ch} is the channel bandwidth, which is equal to the sampling rate R_s at the Nyquist limit. $B_\omega = N_{ch}B_{ch}$ is the total WDM bandwidth with N_{ch} WDM channels. In addition, $L_{\text{eff}} = (1-e^{-\alpha L})/2\alpha$ and $L_{\text{eff,a}} = 1/2\alpha$ are the effective and the asymptomatic effective lengths of the fiber, respectively, with fiber physical length L and fiber loss coefficient α. P_{tx} is the average lunch power, M is the number of slots per frame, and n is the number of signal slots per frame. N_s is the number of fiber spans and B_n is the noise bandwidth.

We can extend the BER expression for hybrid DBPSK-MPPM technique to include the nonlinearity as [2]:

$$\mathrm{BER}_{\mathrm{Hybrid}} \leq \frac{1}{N+n}\left(\frac{\mathrm{SER}_{\mathrm{MPPM}}}{2}\left(\frac{2^N}{2^N-1}N+n\right)+(1-\mathrm{SER}_{\mathrm{MPPM}})\left(\mathrm{SER}_{\mathrm{MPPM}}\left(\frac{1}{2}-\mathrm{BER}_{\mathrm{DBPSK}}\right)+n\,\mathrm{BER}_{\mathrm{DBPSK}}\right)\right), \quad (2)$$

where $N = \left\lfloor \log_2 \binom{M}{n} \right\rfloor$ bits are encoded using the MPPM scheme and $(N+n)$ is the total number of transmitted bits each frame. $\mathrm{SER}_{\mathrm{MPPM}}$ is the symbol-error rates of MPPM data as given in [2], $\mathrm{BER}_{\mathrm{DBPSK}}$ is the bit-error rate of DBPSK data on top of the current MPPM frame and expressed as $\mathrm{BER}_{\mathrm{DBPSK}} = \frac{1}{2}\exp\left(-MB_nP_{tx}/2nB_{ch}\sigma^2\right)$.

3. Numerical Results

In our numerical evaluation of the performance of DBPSK-MPPM in long-haul transmission, we assume the following parameters: standard SMF with parameters $\alpha = 0.22\,\mathrm{dB/km}$, $D = 16.7\,\mathrm{n/km}$, and $\gamma = 1.3\,\mathrm{W^{-1}km^{-1}}$. The total fiber length is 1000 km with 100 km span length. An EDFA, that compensates the fiber span loss: $G = e^{2\alpha L_s}$ and has a noise figure of 6 dB. The WDM specifications are: $B_{ch} = R_S = 32\,\mathrm{GHz}$, a noise bandwidth of 12.48 GHz and $N_{ch} = 5$ [4].

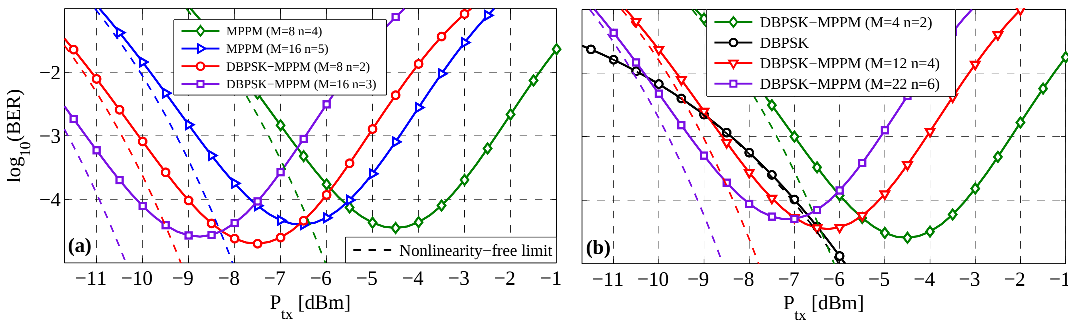

Fig. 1: BER versus average lunch optical power per channel for hybrid DBPSK-MPPM technique compared with both: a) traditional MPPM and b) traditional DBPSK, for both nonlinearity-free limited (dashed line) and nonlinearity limited (solid line) systems.

Figure 1 shows the BERs versus average launch optical power per channel for hybrid DBPSK-MPPM system compared with both (a) MPPM and (b) DBPSK traditional systems. Both M and n are chosen so as to ensure that all systems under comparison have the same transmission data rate and channel bandwidth. In linear operation (nonlinearity-free limit), the hybrid system performance is improved by increasing M as the energy efficiency of the system is improved. Specifically, at $\mathrm{BER} = 10^{-3}$ (forward-error correction (FEC) requirement), there is an improvement of about 2.5 dB for DBPSK-MPPM ($M = 16$ and $n = 3$) when compared to traditional MPPM ($M = 16$ and $n = 5$) system and an improvement of about 1.5 dB for the hybrid system ($M = 22$ and $n = 6$) when compared to traditional DBPSK.

After reaching a specific peak power, the nonlinearity becomes significant. Under the transmission of the same data rate at the same bandwidth and average launch optical power, the hybrid modulation system has high peak power per slot when compared to the traditional DBPSK and MPPM systems. This reduces the overall signal-to-noise ratio of the hybrid systems when compared to that of the traditional ones as the nonlinearity variance is proportional to $P_{peak}^3 = (MP_{tx}/n)^3$. Therefore, the DBPSK-MPPM system is affected rapidly by fiber nonlinearity than traditional DBPSK and MPPM systems. However, at FEC limit, after taking the fiber nonlinearity into consideration, this effect is not that sound and there is still an improvement of about 2.5 dB for DBPSK-MPPM ($M = 16$ and $n = 3$) when compared to traditional MPPM ($M = 16$ and $n = 5$) and an improvement of about 1 dB for the hybrid system ($M = 22$ and $n = 6$) when compared to traditional DBPSK.

4. Conclusion

Hybrid DBPSK-MPPM performance has been studied in long-haul nonlinear dispersive transmission using the GN-model. Our results reveal that, DBPSK-MPPM technique is less robust against fiber nonlinearity than traditional DBPSK and MPPM techniques. However, it outperforms them in both linear and FEC-limit nonlinear regions.

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