Bit Error Probability Simulation for RZ-Coded Free Space Laser Links

Martin Pauer, Peter J. Winzer, Andras Kalmar

Introduction: In a return-to-zero (RZ) coded transmission system the optical pulses representing a mark are made shorter than the bit duration by a factor D, the duty cycle. ($D = 1$ corresponds to the non return-to-zero (NRZ) modulation format.) As has recently been pointed out [1, 2, 3], RZ coding offers improved sensitivity over NRZ coding for the same average optical input power, even if the receiver bandwidth is optimized for NRZ signals.

Degradations in the performance of any communication system can be attributed to noise or to intersymbol interference (ISI). In an optical receiver, noise contributions can either be *signal-independent* (e.g. electrical noise) or *signal-dependent* (e.g. beat noise between signal and amplified spontaneous emission (ASE), if optical preamplification is employed). Since there is no signal dispersion along the transmission channel in case of optical free space communication, ISI is introduced solely by bandwidth limitations within the receiver, especially if receiver bandwidths of the order of 0.5 times the data rate or less are considered. Because of ISI, reliable analytical calculations of BEP are problematic in general. However, if either the signal-dependent or the signal-independent noise term clearly dominates, it is possible to calculate the BEP from the SNR at the decision gate by taking the bit pattern that leads to worst case ISI [1, 3]; this method yields in many cases at least an upper bound for the BEP. Our calculations showed that, especially for the case where ISI has non-negligible influence *and* where the dominating noise contribution is signal-*dependent*, the average BEP cannot be obtained from an average SNR. Thus, the SNR does then *not* represent system performance adequately. Actually, our latest results indicate that the sensitivity gain found by simulations of the BEP is even *higher* than that predicted by our SNR-based calculations.

Simulation of BEP: Since the performance of a digital communication system is ultimately determined by its BEP rather than by some SNR values, we developed a computer program to accurately evaluate the performance of RZ-coded systems. In order to increase simulation speed, as it is necessary when varying a number of parameters, such as receiver bandwidth, number of photons/bit, or duty cycle, we chose a quasi-analytical method [4], where the estimation of BEP does not rely on the occurence of errors brought by the detection of simulated signal-waveforms corrupted by noise, but is based on the calculation of error probabilities. Therefore, reliable simulations can be carried out using a relatively short pseudorandom bit sequence, regardless of how small a BEP has to be simulated; the only condition for the sequence length is that all possible ISI patterns occur at least once. The sequence length we used was $2^{10} - 1$.

Our simulation first calculates the value of the noiseless signal current i generated by the photodetector at the decision gate, starting from a pseudorandom bit pattern, and taking into account ISI. Then, the variance σ_i^2 of the photocurrent, which comprises all signal-dependent and signal-independent noise sources, is determined. Again, ISI has to be included because of the signal-dependent noise term: its variance $\sigma_{i,dep}^2$ is given by the convolution of the optical input pulse $p(t)$ with the square of the impulse response of the receive filter, $h^2(t)$, as $\sigma_{i,dep}^2(t) = C(p * h^2)(t)$, where C is an appropriate constant[1]. This non-standard formula characterizes the non-stationarity of signal-dependent noise at each time instant (cf. Appendix of [3]).

Assuming a Gaussian distribution of the noise[2], BEP can be *calculated* from the simulated i and σ_i at each sampling instant. Finally, the estimate for the BEP is found as the average of the BEPs obtained for each received bit.

Sampling instant and decision threshold are automatically optimized within the program before the simulation is started: For a suboptimum decision threshold, we first determine the sampling instant by varying it relative to some starting value until a minimum average BEP is reached (averaging is performed over all possible BEPs resulting from different ISI patterns). At that sampling instant we then determine the decision threshold in the same way. This independent optimization can be done because the BEP can

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[1] Provided that $h(t)$ is normalized to unit area, C would equal the product of the photodiode's sensitivity S times the electron's charge e in a conventional direct detection receiver, whereas for optical preamplification, C would be $2N_{ASE}S^2$, with N_{ASE} being the power spectral density of the ASE-ASE beat noise in one polarization.

[2] Strictly speaking, this assumption is a simplification if signal-dependent (Poisson-distributed) noise dominates; but it is a commonly used approximation that yields reasonably accurate results [5].

be assumed to be a monotonic function of sampling instant and decision threshold with a global minimum [6].

Results: Figure 1 shows the simulated BEP for the case, that both signal-dependent ($\sigma^2_{i,dep}$) and signal-independent ($\sigma^2_{i,indep}$) noise terms are non-negligible. This noise situation is encountered, e.g., in an optically preamplified receiver with moderate component characteristics (cf. Figure caption). In (a) we show BEP as a function of b_e, the receiver bandwidth normalized to the data rate, for a constant average optical input power, with the RZ duty cycle as a parameter. The BEP reaches a minimum with respect to b_e, which represents the best compromise between degradation due to ISI and noise enhancement due to increased filter bandwidth. For higher duty cycles, this optimum bandwidth moves towards larger values of b_e.

Figure 1 (b) shows BEP as a function of optical input power at a relative receiver bandwidth $b_e = 0.6$, the optimum value for NRZ detection. In comparison with NRZ coding, a duty cycle of $D = 2$ yields a sensitivity improvement of $2.5dB$. For higher duty cycles, an asymptotic behaviour can be observed, which limits the achievable gain at a fixed bandwidth ($3.1dB$ in our example).

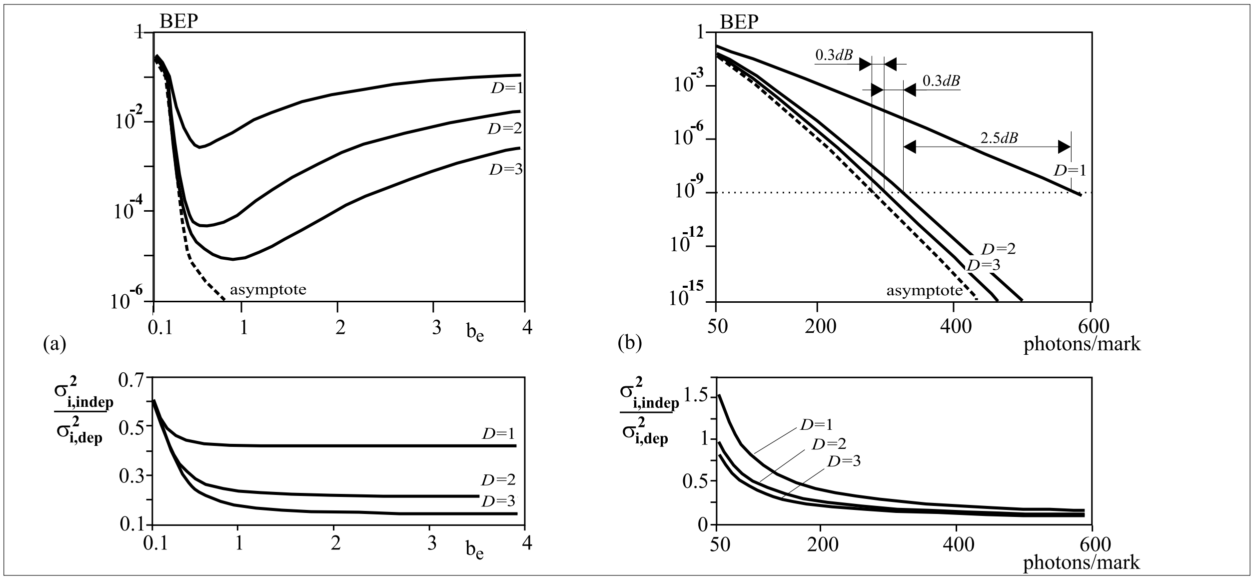

Figure 1: BEP and ratio of signal-independent to signal-dependent noise contributions of an optically preamplified receiver for different duty cycles D. $\lambda = 1.55\mu m$, data rate $R = 10Gbit/s$, ideal extinction ratio, photodetector responsivity $S = 0.8A/W$, $B_{opt} = 3nm$, $G = 30dB$, $F = 6dB$. In (a), receiver bandwidth is varied at a constant average receive power corresponding to 180 photons/mark. In (b), receiver bandwidth is kept constant at $0.6R$ and average receive power is varied.

References

[1] L. Boivin, M.C. Nuss, J.Shah, D.A.B. Miller, and H.A.Haus, *Receiver Sensitivity Improvement by Impulsive Coding*, IEEE Photon. Technol. Lett., **9**, 684-686, (1997).

[2] S. Tanikoshi, K. Ide, T. Onodera, Y. Arimoto, and K. Araki, *High sensitivity 10Gb/s Optical Receiver for Space Communications*, Proc. 17th AIAA International Communications Satellite Systems Conference, 178-183, (1998).

[3] P. Winzer and A. Kalmar, *Sensitivity enhancement of optical receivers by impulsive coding*, Journal of Lightwave Technology, **8**, 171-177, (1999)

[4] M.C. Jeruchim, *Simulation of communication systems*, Plenum Press, (1992)

[5] W.S. Wong, H.A. Haus, L.A. Jang, P.B. Mansen, M. Margalit, *Photon statistics of amplified spontaneous emission noise in a $10Gbit/s$ optically preamplified direct-detection receiver*, Opt. Lett., **23**, 1832-1834, (1998)

[6] M.R.N. Ribeiro, H. Waldmann, J. Klein, *Error Rate Patterns for the Modeling of Optically Amplified Transmission Systems*, IEEE Journal on selected areas in communication, **15**, 707-715, (1997)