SOLITON COMMUNICATION SYSTEMS: PERFORMANCE SIMULATION AND EVALUATION

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Abstract
This paper uses computer simulations to evaluate the performance of amplified soliton systems in long haul and/or high-speed transmissions, using proprietary numerical models for both the nonlinear optical fiber and the optical receiver. Eye diagrams are used to assist in the analysis of the results.

I - Introduction

In recent years, optical communication technology has experienced steadfast progress, stimulated by an increasing demand for telecommunication services. Researchers and designers of optical systems and networks find themselves in a permanent quest for new techniques to augment the capacity and flexibility of the existing communication facilities to meet the requirements of high capacity and/or long haul transmissions. As a result, there exists a strong competition between linear and nonlinear transmission systems. The classic NRZ – IM/DD linear transmission systems combined with the WDM technology cover a vast range of applications, which include transmission distances of up to 10,000 km, and aggregated rates of up to 100 Gb/s. These systems are currently in commercial operation, but are in general limited to rates of 2.5 – 5 Gb/s per channel in long distance transmissions. A large number of optical carriers would then be required to yield 100 Gb/s. On the other hand, nonlinear RZ systems, i. e. amplified soliton systems, have already reached a considerable state of maturity, thus representing a true alternative to high capacity communications. In long distance transmissions, each channel of a nonlinear RZ system can support rates of up to 10 Gb/s.

Despite being a mature technology, amplified soliton systems are as yet not deployed commercially. The main reason for this is the fact that optical solitons suffer from the severe *Gordon-Haus* effect [1], which results from the mixing of the signal and the amplified spontaneous emission (ASE) noise generated by the Erbium-doped fiber amplifiers (EDFAs) used to compensate for the losses of the fiber segments in a communication link. The mixing of signal and noise produces a jitter on the arrival times of the pulses, thus limiting the capacity of amplified soliton systems.

This paper presents an evaluation of the performance of soliton systems, considering their application in long haul and/or high-speed transmissions. The system performance is evaluated through comprehensive numerical simulations. Numerous papers are found in the literature on this subject, for example [2], that employ a perturbational theory to investigate how a soliton is affected by the accumulation of ASE noise. However, this approach only establishes theoretical limits for the adequate operation of amplified soliton systems. These limits are obviously restricted to the validity of the perturbational theory. The numerical models used in this paper do take into account the nonlinear interactions between the solitons and the ASE noise generated by the optical amplifiers.The main results are presented in the form of eye diagrams, allowing for an immediate evaluation of both the timing jitter and the degradation of the system's signal-to-noise ratio (SNR).

II - Description of a Soliton System

The block diagram in Figure 1 depicts a generic IM/DD optical communication system.

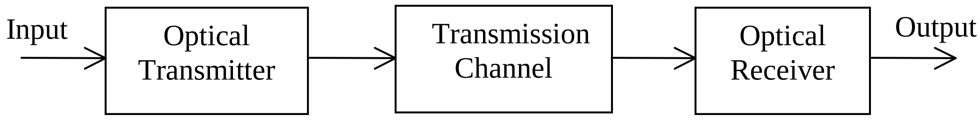

Figure 1: Block diagram of a generic optical communication system.

In this work, the optical transmitter is a laser diode with direct modulation, so that the frequency chirp at the laser output can be neglected. The digital input signal is composed of a 64-bit sequency – ‘0001 0000 1100 0101 0001 1100 1001 0110 0110 1001 1110 1010 1110 1101 1111 1000’. Each bit ‘1’ is represented by a first order soliton. For the purpose of the simulations, 256 time samples per bit are taken, so that the overall time window comprises 16,384 samples. To avoid collision between neighbouring pulses, only 20% of each bit slot is actually occupied by the pulse.

The transmission channel is composed of segments of monomode optical fiber, each followed by an EDFA. A simplified model is used for the amplifier, which is treated as a multiplier, and generated ASE noise is represented by a complex random variable with Gaussian distribution, which is then added to the spectral components of the pulses at the amplifier output. The real and imaginary parts of the complex Gaussian variables have zero mean, and their variance is made equal to the average white noise power contained in each component of the Fourier spectrum [3]. The amplifier gain is assumed to be flat all over the frequency band of interest. The signal thus obtained is propagated along the fiber segments with the split-step Fourier method [4].

The optical receiver consists basically of a photodiode, an electric filter, and an optical filter. The received optical signal usually is directly converted into an electric current. The transfer function of the electric filter is given by $H_{el}(\omega) = \exp\left[-4(\ln 2)\,\omega^2/B_{el}^2\right]$, where B_{el} represents the FWHM bandwidth of the filter. In certain situations, a Fabry-Perot optical filter is inserted at the receiver input, before the photodiode, to reduce the presence of the ASE noise. The transfer function of the optical filter is given by $H_{ot}(\omega) = (1 + j2\omega/B_{ot})^{-1}$, where B_{ot} is the filter FWHM bandwidth. It is worth mentioning that the phase of the optical filter is responsible for only a time shift of the pulse, and so just the real part of the transfer function is considered here. For the nonlinear systems under study the bandwidths of both the electric and optical filters must be chosen judiciously. The performance of the system is usually evaluated by the probability of wrongly identifying a bit, the bit-error rate (BER). In this work, a BER of 10^{-9} is considered thoughout.

III - Results

The numerical models described in the previous section were used to simulate soliton systems operating in realistic conditions. One of the main objectives of the simulations was to evaluate to what extent the timing jitter due to the *Gordon-Haus* effect and the accumulation of ASE noise limited the performance of soliton systems, and also to test the theoretical bounds found in the literature [1].

Initially, a soliton system was considered with the following parameters: fiber loss α = 0.2 dB/km, fiber chromatic dispersion parameter $\beta_2 = -2$ ps^2/km, spacing between optical amplifiers (or length of the fiber segments) L_{amp} = 40 km, 1/e pulse width T_0 = 10 ps, optical carrier wavelenght λ_c = 1550 nm.

Figure 2 shows the timing jitter as a function of the transmission distance (measured in terms of the number of optical amplifiers) for a system operating at a rate B = 2.5 Gb/s. This figure also shows the timing jitter as calculated via a first order perturbational analysis [1], and the maximum allowed standard deviation for a BER of 10^{-9}. For distances up to 12,000 km (300 amplifiers), the agreement between the numerical and the analytical values is quite good. For longer distances, the two sets of results deviate increasingly. In practice, these systems would be restricted to a maximum distance of about 8,000 km, so that the maximum timing jitter limit of 22 ps is respected

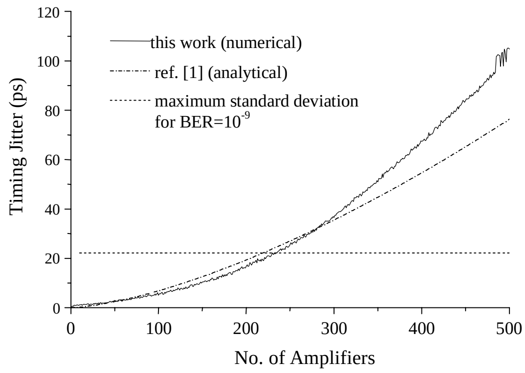

Figure 2: *Timing jitter* versus transmission distance (measured by the number of optical amplifiers) for a soliton system operating at a rate B=2.5Gb/s (T_0=10ps, $\beta_2 = -2$ ps^2/km, α= 0.2dB/km and L_{amp}=40km).

Figure 3 shows the eye diagrams associated with the system in Figure 2, for a transmission distance of 6,000 km. In this figure, different bandwidths were considered for the electric filter, ranging from 1.25 GHz to 3.75 GHz. Figures 3 (a) and (b) indicate that if the filter bandwith is narrower than the transmission rate the pulse sequence is destroyed at the receiver, as the pulses invade the neighbouring bit slots. Figures 3 (c) and (d) show that cleaner eye diagrams are obtained when the filter bandwidth is equal to or greater than the transmission rate.

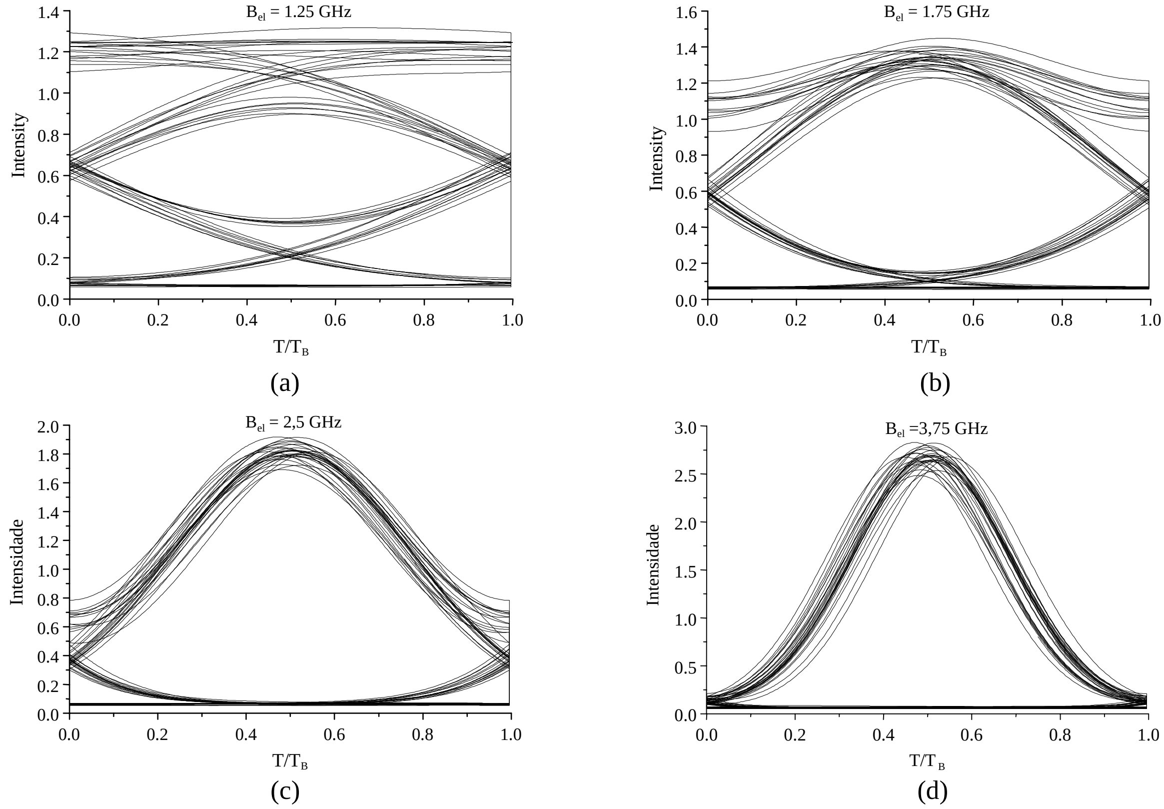

Figure 3: Eye diagrams for the system described in Figure 2, for a transmission distance of 6,000 km. The electric filter bandwidths are: (a) 1.25 GHz (B_{el} = 0.5B), (b) 1.75 GHz (B_{el} = 0.7B), (c) 2.5 GHz (B_{el} = B) e (d) 3.75 GHz (B_{el} = 1.5B), while the optical filter bandwidth is B_{ot} = 200GHz.

The diagram in Figure 3 (c) allows for a safer identification of the bits “1” and “0”, as a threshold level can easily be established. A 200 GHz Fabry-Perot optical filter was used in the simulations. It was observed that the optical filter bandwidth had little or no effect on the eye diagram, as the spectral width of a soliton pulse train is quite narrow, around 15 GHz, in contrast to the Gaussian pulse trains used in linear NRZ system. The function of the optical filter at the receiver input is to limit the ASE noise outside the signal bandwidth, which is small in this example.

Extensive simulations indicated that the fiber chromatic dispersion parameter β_2 plays a crucial role on the design of an optical communication system. Figure 4 shows the timing jitter as a function of the transmission distance for a soliton system with the same parameters as before, except for β_2 = – 0,1 ps^2/km. The agreement between the numerical and analytical results is satisfactory only for distances up to 6,000 km (150 amplifiers), approximately half the maximum distance allowed for a system operating at this same rate (B = 2.5 Gb/s) with β_2 = – 2 ps^2/km (Figure 2). Beyond 6,000 km the timing jitter grows rapidly, with an oscillatory and noisy structure. The curve representing the analytical result remains below the maximum value allowed for the timing jitter at the receiver, for all transmission distances.

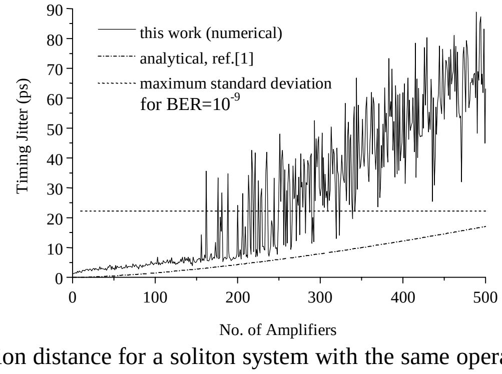

Figure 4: Timing jitter versus transmission distance for a soliton system with the same operating conditions as in Figure 2, except for β_2 = – 0,1 ps^2/Km.

It is true that a reduction of the β_2 parameter contributes to a reduction of the timing jitter but, at the same time, it also provokes a reduction of the signal power [3]. In consequence, the accumulation of ASE noise along the amplifier cascade becomes more pronounced and results in severe degradation of the system performance. The nonlinear interaction between signal and noise is taken into account by the numerical model but not by the analytical one, and that explains the deviation of the two curves in Figure 4.

Figures 5 show eye diagrams corresponding to the system in Figure 4, for a transmission distance of 4,000 km (100 amplifiers). As the interaction between signal and ASE noise is now very intense, due to the small value of the chromatic dispersion parameter, different bandwidths, ranging from 50 GHz to 200 GHz, were considered for the optical filter at the receiver input, to test its influence on the overall system performance. In these figures, the bandwidth of the electric filter was set equal to the transmission rate, i.e. $B_{el} = 2.5\ \text{GHz}$. Other values were tested, and the same general behaviour as mentioned before was observed. Figures 5 indicate that now the optical filter bandwidth does influence the overall performance, and the narrower filters yield cleaner eye diagrams, as a larger portion of the ASE noise is eliminated. Even so, Figures 5 indicate a severe deterioration of the system's signal-to-noise ratio, in comparison with the system represented in Figure 3 (with a larger chromatic dispersion parameter).

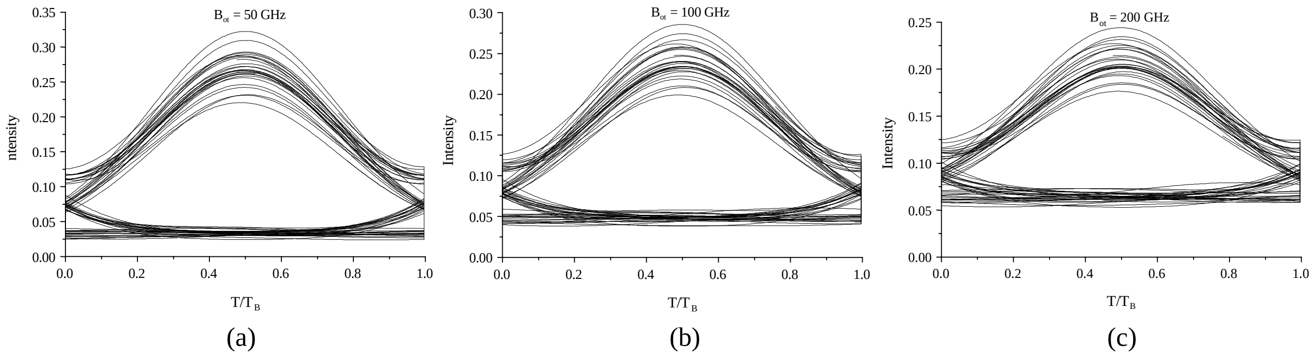

Figure 5: Eye diagrams for the system described in Figure 4, for a transmission distance of 4,000 km (100 amplifiers). The optical filter bandwidths are: (a) 50 GHz, (b) 100 GHz, (c) 200 GHz, while the electric filter bandwidth is B_{el} = 2.5 GHz.

IV - Conclusion

This paper presented an evaluation of amplified soliton systems for application in long haul and/or high-speed optical communication networks, based on realistic numerical simulations.

The results were presented in the form of eye diagrams, affording a prompt evaluation of both the timing jitter due to the *Gordon-Haus* effect and the degradation of the system's signal-to-noise ratio. The simulations indicate that the chromatic dispersion parameter of the optical fiber plays an crucial role on the system performance, and that the characteristics of both the optical and electric filters of the receiver must be chosen judiciously. Although not mentioned here, the numerical models developed also allow for the accommodation of soliton control techniques, such as dispersion management or sliding frequency filtering, thus providing a true simulation tool for soliton systems.

V - References

1. J. P. Gordon and H. A. Haus, "Random Walk of Coherently Amplified Solitons in Optical Fiber Transmission", Opt. Lett., vol. 11, pp 665-667, 1986.
2. N. J. Smith e N. J. Doran, "Evaluating the Capacity of Phase Modulator-Controlled Long-Haul Soliton Transmission", Optical Fiber Technol., vol. 1, 1995, pp 218-235.
3. P. B. Harboe, "Amplified soliton systems: a feasibility study for application in long haul and/or high-speed optical communications", PhD Dissertation, Pontifical Catholic University of Rio de Janeiro, Brazil, 2000.
4. P. B. Harboe, and J. R. Souza, "Evaluation of the performance of exponentioal operators for the simulation of pulse propagation in optical fibers by the split-step Fourier method", Proc. 4th Int. Conf. on Millimeter and Submillimeter Waves and Applications, pp 139-140, San Diego – CA, 1998.