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10 Gbit/s Long Haul Soliton versus NRZ Optical Transmission in the 1300nm Window

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Abstract—We have compared the operation and applicability of soliton transmission systems versus NRZ (Non Return to Zero) transmission systems for the 1300nm optical window. For a different number of in-line amplifiers the BER (Bit Error Rate) curves of both transmission systems have been simulated. For both systems the same fibre dispersion and attenuation has been assumed and all amplifier gains have been chosen so that the fibre losses are compensated for. In case of the soliton system an extra dispersion shifted fibre has been located directly after the laser diode to unchirp and compress the laserpulses. With respect to the BER simulations, soliton and NRZ transmission systems are expected to be competitive. Transmission exhibiting an error probability below 10^{-9} is attainable for both systems. Under equal circumstances, we conclude from our simulations that soliton systems show better BER performance than NRZ systems beyond 450 km. Owing to the dispersion compensating properties soliton transmission systems are advantageous when long haul transmission is considered. However, NRZ transmission is both a well established and relatively simple technique and can be more readily implemented.

I. INTRODUCTION

Since the introduction of standard single mode fibre (SSMF) more than 55 million kilometers has been installed. At present 2.5 Gbit/s data transmission has become a commercial standard. In the near future the increasing demand for more network capacity can be satisfied by introducing 10 Gbit/s transmission systems. The very low dispersion in the 1300 nm window of SSMF makes a 10 Gbit/s system attractive. Considering the recently achieved progress in the development and use of quantum-well laser amplifiers (QWLAs) [1], [2], [3], attenuation of over 50 km of SSMF can be easily compensated for, making repeaters superfluous. Recently, more and more promising experimental results are being published on NRZ [4] [5] as well as soliton transmission. Even 20 Gbit/s soliton transmission over 200 km [6] has been realised as well as 2×10 Gbit/s wavelength division multiplexed NRZ transmission over 63.5 km [5]. As solitons can be multiplexed easily in the time domain it is more likely that for higher bitrates (i.e. ≥ 40 Gbit/s) soliton systems will be preferred to NRZ systems whose maximum bitrate is limited by the maximum achievable electrical bandwidth in current electronics. Although the literature available on soliton as well as NRZ systems is extensive, theoretical study on long

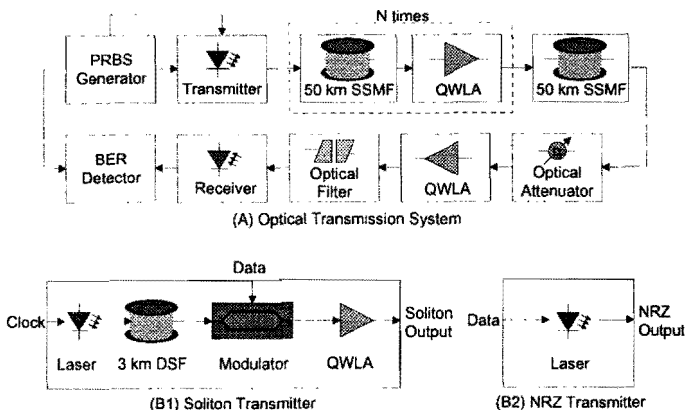


Figure 1: Optical Transmission System (A), Soliton Transmitter (B1), NRZ Transmitter (B2)

haul transmission systems with cascaded QWLAs is not yet complete. The effects of amplifier saturation, ASE and timing jitter on system performance still need investigation. In this paper we compare the performance between a 10 Gbit/s NRZ system [4], [5] and a 10 Gbit/s soliton system theoretically by means of computing bit error rate (BER) curves.

II. TRANSMISSION MODEL

Figure 1 shows the NRZ and soliton transmission system. In the case of NRZ transmission the laser diode is directly modulated with the PRBS signal. The soliton system requires a more complex transmitter. Chirped near-soliton pulses are generated by gain switching of the laser diode and unchirped and compressed in the dispersion shifted fibre after which the optical modulator modulates the data on the soliton train. Finally, the power is boosted by a QWLA up to a level where nonlinear effects compensate dispersion effects in the SSMF. Both soliton and NRZ transmission systems are built up out of eight different components figure 1, namely QWLAs, fibres, a laserdiode, a photodiode, a PRBS generator, a BER detector, a filter and an attenuator. The soliton system needs an additional modulator. Therefore nine models are needed for a theoretical description of both systems.

QWLA model

The model used to describe the QWLAs is based upon the rate equations in [7] and [8], where the z-dependency has been eliminated by integration over the amplifier length L . The ASE is wavelength dependent [4], namely:

$$P_{out}(\tau, \lambda) = P_{in}(\tau, \lambda)e^{h(\tau, \lambda)} + h \frac{c^2}{\lambda^3} \frac{NF}{2} e^{h(\tau, \lambda)} d\lambda \quad (1)$$

with

$$h(\tau, \lambda) = \int_0^L g(z, \tau, \lambda) dz, \quad (2)$$

$$\varphi_{out}(\tau, \lambda) = \varphi_{in}(\tau, \lambda) - \frac{1}{2} \alpha_H h(\tau, \lambda) \quad (3)$$

and

$$\frac{\partial h(\tau, \lambda)}{\partial \tau} = - \frac{h(\tau, \lambda) - g_0(\lambda)L}{\tau_c} - \frac{\sum_{\lambda_i} \frac{\lambda_i}{\lambda} P_{in}(\tau, \lambda_i) / P_{sat}(\lambda)}{\tau_c} \cdot (e^{h(\tau, \lambda)} - 1), \quad (4)$$

where τ_c is the carrier lifetime, $P_{sat}(\lambda)$ represents the $1/e$ saturation output power, $g_0(\lambda)L$ represents the small signal amplifier gain, $h(\tau, \lambda)$ is the time dependent amplifier gain, α_H is the linewidth enhancement factor, $d\lambda$ is the wavelength discretisation stepsize, h is Planck's constant, c stands for the velocity of light, NF is the fibre coupled noise figure, and $P_{in}(\tau, \lambda_i)$ represents the total input power to each amplifier, i.e. the sum of input signal power and ASE originating from the previous amplifiers. τ is the reduced time with respect to a reference plane moving with the signal ($\tau = t - \frac{z}{v_g}$, with v_g the group velocity). The amplifier is assumed to have zero reflecting input/output facets and to be polarization independent. The gain is assumed to have a Gaussian shaped spectrum. The equations are numerically solved using *Euler forward* iteration.

Fibre model

Propagation in the fibre is described by the nonlinear Schrödinger equation [9],

$$\frac{\partial A}{\partial z} = -\frac{\alpha}{2} A - \frac{i}{2} \beta_2 \frac{\partial^2 A}{\partial \tau^2} + i\gamma |A|^2 A, \quad (5)$$

where A is the slowly varying envelope of the optical signal, α represents the losses in the fibre, γ is the nonlinearity parameter and $\beta_2 = -D \frac{\lambda^2}{2\pi c}$ is the dispersion parameter. D is the dispersion. Eq. 5 is numerically solved using the *split-step Fourier* method.

Laser diode model

The model employed is a simple Fabry Perot model

where the z-dependence has been eliminated [10]. Laser pulses are generated by gain switching of the laser diode. After transmission through a dispersion shifted fibre, the pulses closely resemble soliton pulses. In the case of NRZ modulation the signal shows an extinction ratio and slopes equal to experimentally observed values.

Photodiode model

The optical signal is converted to the electrical domain by the photodiode as described by [11]. A quantum efficiency of 0.8 is taken. The model includes shot noise, signal-spontaneous beat noise, spontaneous-spontaneous beat noise and thermal noise. The electrical bandwidth is 10.2 GHz and the thermal noise is adjusted, so that the receiver has a sensitivity of -13.7 dBm at 10 Gbit/s NRZ and a BER of 10^{-9} , in agreement with measured data (figure 2).

Optical filter

The optical filter is assumed to be square and sufficiently broad with respect to the signals bandwidth. The optical filter reduces the ASE by allowing only a small fraction of the ASE spectrum to pass. The effective bandwidth of the filter is 2 nm and the filter introduces a loss of 2 dB.

Optical attenuator

The optical attenuator is used primarily to attenuate the signal in order to compute BER values for different receiver input powers.

Optical modulator

The optical modulator has only functionality in the soliton system. Its purpose is to modulate the soliton train. When the modulator is excited by a logical one, a raised-cosine window is opened letting a soliton pass. When a logical zero is applied, a window of smaller amplitude is opened, attenuating the soliton. The optical modulator introduces a loss of 5 dB. The roll-off factor of the raised cosine function is $\beta = T_b/2$, with T_b the bit time. The extinction ratio i.e. the ratio between the peak power of a logical one and a logical zero is equal to $ER = 20$.

PRBS generator and BER detector

The PRBS generator generates a $2^7 - 1$ pseudo-random bit sequence. The BER detector computes the optimum BER for a number of detection thresholds and sampling times, assuming a gaussian distribution for all noise sources. The BER is obtained by averaging over all $2^7 - 1$ bits. We emphasize that the clock of the PRBS generator is used to sample the received data and that there is no clock recovery at the receiver.

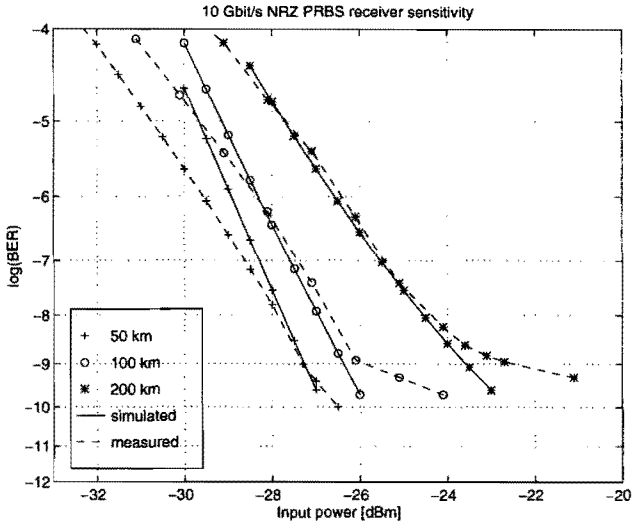


Figure 2: Measured and simulated BER curves in absence of clock recovery, $ER = 6$

III. COMPUTER SIMULATIONS

At 1300 nm the 50 km SSF sections exhibit a loss of $\alpha = 0.4$ dB/km and a dispersion of $D = 0.6$ ps/km/nm and a nonlinearity parameter of $\gamma = 2.1$ W/km. The 3 km dispersion shifted fibre exhibits a loss of $\alpha = 0.4$ dB/km and a dispersion of $D = -17$ ps/km/nm. The QWLAs are adjusted to a gain of 22.5 dB at the signal wavelength of $\lambda = 1310$ nm, almost equal to the loss of the 50 km fibre span. A 60 nm gain bandwidth was assumed. The fibre to fibre noise figure of the amplifier was estimated at 9 dB. For the 3 dB saturation output power $P_{sat,3dB} = 10$ dBm was assumed. The linewidth enhancement factor was estimated at $\alpha_H = 5$. For the gain-recovery time $\tau_c = 200$ ps was taken. Using the NRZ or soliton transmitter a power of 2 dBm or 6 dBm respectively, is launched into the first fibre section. All computer simulations were carried out with the same algorithms. The only difference between the NRZ and soliton simulations is the number of sample points per bit. Because the phase of the solitons is of major importance, 256 sample points per bit were used for soliton simulations while 20 sample points sufficed in the case of NRZ simulations. Figure 2 shows measured and simulated NRZ BER-curves with an extinction ratio of $ER = 6$. The good agreement between the measured and theoretical curves validates our model.

IV. DISCUSSION

Figure 3 depicts the simulated BER-curves for NRZ and soliton transmission over 150 km and 200 km. The higher receiver input power of the soliton signal is due to the amplifier in the soliton transmitter,

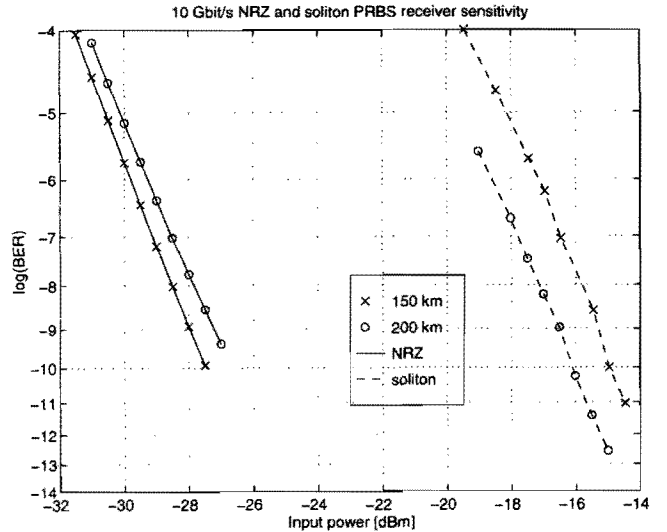


Figure 3: Simulated NRZ and soliton BER curves in absence of clock recovery, $ER = 20$

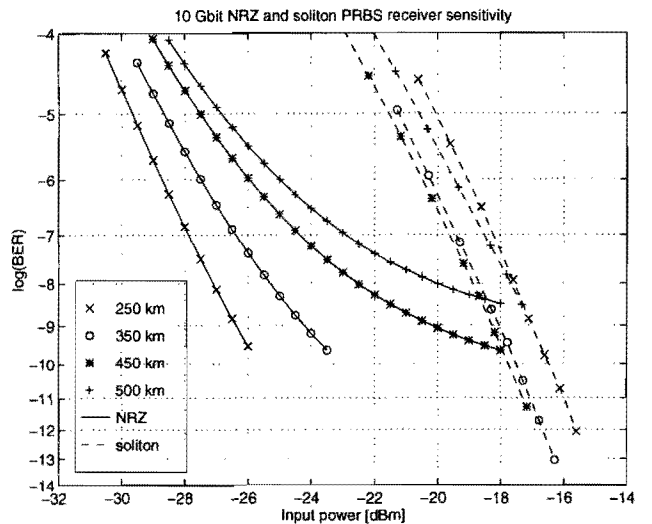


Figure 4: Simulated NRZ and soliton BER curves in absence of clock recovery, $ER = 20$

therefore better BER performance is expected. Additional simulations reveal that this different behaviour can be explained by the absence of clock recovery. As solitons are sensitive to timing jitter caused by saturation and soliton interaction, timing jitter is expected to be the most likely cause. In contrary to NRZ transmission it can be clearly seen that in the case of soliton transmission at 200 km a better BER is obtained with less input power than at 150 km. The same result is obtained for longer transmission links, presented in figure 4. However, after 450 km no further improvement is observed. Additional simulations show that the improvement of the soliton signal could be explained by lesser non-linear effects in the fibre caused by saturation of the amplifiers resulting in a broadened pulse which is less sensitive to timing jit-

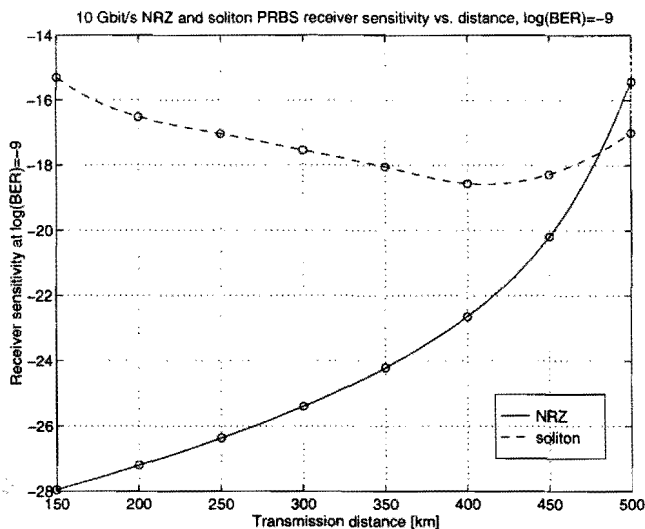


Figure 5: Receiver sensitivity versus transmission distance at $BER = 10^{-9}$

ter, resulting in a better BER. The degradation after 450 km is probably caused by less dispersion compensation due to diminishing output power caused by saturation of the amplifier by ASE. By placing an additional ASE-filter at 450 km we expect to increase the maximum transmission distance at a $BER = 10^{-9}$. In contrary to NRZ transmission soliton transmission simulations did not reveal BER floors however. Figure 5 shows that the receiver sensitivity of the NRZ system at $BER = 10^{-9}$ in contrary to the soliton system is strongly dependent on the transmission distance due to built up ASE. Only after 450 km the soliton system shows a better sensitivity. When a BER of 10^{-12} is required, a soliton system is preferred when more than 350 km needs to be bridged.

V. CONCLUSION

A transmission model has been presented for simulation of NRZ and soliton systems. With respect to the simulated BER curves we expect soliton transmission to be superior to NRZ when long haul transmission systems beyond 450 km are considered. Timing jitter caused by soliton interaction and saturation of the QWLAs is expected to seriously degrade the performance of soliton transmission systems and therefore needs further investigation. The relatively complex transmitter makes NRZ systems preferable to soliton systems.

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