Analytical model and Limitations on the Design Diagram for Soliton Systems

Zahariah Zakaria
Science and Maths Dept,
Faculty of Science, Technology and Human Development,
UTHM, Parit Raja, Batu Pahat 86400 Johor

***Abstract*— This paper considers the single channel soliton system where the predictions of the analytical models are compared with the numerical simulations of the system performance. To overcome the effect of loss in long-haul light wave systems, solitons should be amplified periodically to compensate for the losses. However even with the discrete periodic amplification, launching with the ideal, lossless peak power will not give the balance between non-linearity and dispersion required to create a soliton. In order to achieve the balance, average soliton system /guiding center soliton is used where a pulse with an enhanced peak power is launched so that the average power over the propagation between amplifiers is equal to the soliton power in a lossless system. In order to improve the performance in propagation of soliton systems, it is necessary to resist signal to noise ratio (SNR) degradation and Gordon-Haus jitter accumulation. This is done using the guided soliton system where the system has in-line filters which prevent the frequency of the soliton from drifting as a result of the accumulated ASE noise and hence suppress the GH jitter. The effect of modifying the existing rule of thumb formulae is presented in terms of a design diagram. This is then compared to the numerical simulations. A series of design diagram with Gordon-Haus (GH) jitter, signal to noise ratio (SNR) and soliton collapse limited transmission is also introduced. The same study has been repeated for guided soliton systems.**

Keywords- Guiding center soliton system; guided soliton system; EDFA; GH timing jitter; SNR

1.0 INTRODUCTION

This work will look at a single channel soliton system where the predictions of the analytical models are compared with the numerical simulations of the system performance. We look at the example of the design diagram and when certain effects are dominant. We describe the methodology for the numerical simulations and the systems to be used for the simulations.

The effect of fibre loss becomes the major unsatisfactory feature for long-distance propagation of soliton in fibres. Hasegawa and Kodama [1,2,3] have proposed several methods to overcome the effect of loss in long-haul light wave systems. Mollenauer et al [4,6] materialized in experiments the concept of Raman amplification using the fibre Raman gain to reshape the soliton. Solitons should be amplified periodically using either lumped or distributed amplification [6,7,8]. The lumped amplification scheme in which Erbium Doped Fibers Amplifiers, EDFAs are periodically placed along the fibre link to compensate for the losses, is now considered. However even with this discrete periodic amplification, launching with the ideal, lossless peak power will not give the balance between non-linearity and dispersion required to create a soliton. In order to achieve this balance we need to use a guiding center soliton or average soliton system [6],[7],[8] where a pulse with an enhanced peak power is launched so that the average power over the propagation between amplifiers is equal to the soliton power in a lossless system. In this way the non-linearity and the dispersion are exactly balanced over the entire fibre span. This warrants transmission of optical solitons, however at some distances minor disturbance like amplified spontaneous emission, ASE starts to accumulate and deteriorates the transmission [9]. To overcome such effects, the guided solitons where the system has in-line filters which prevent the frequency of the soliton from drifting as a result of the accumulated ASE noise and hence suppress the GH jitter, was introduced

1.1 Main Limitations for an Amplified Soliton

The development of the EDFA was a major breakthrough in the field of communication. Loss-induced broadening in fibre is unfavourable especially when solitons are used in optical transmission. Solitons need to be amplified periodically to restore their energy. Nakazawa et al. [10] first demonstrated soliton transmission with EDFA in the late 80s. The limitations imposed by EDFAs to the propagation of an amplified soliton are Gordon Haus (GH) Effect, Amplified Spontaneous Emission (ASE) Noise Accumulation, Periodic Attenuation and Amplification of Soliton (average soliton limit) and Interaction between Solitons (Soliton collapsed, SC)

The Gordon-Haus effect i.e.

$$T_{FWHM} >> \frac{1.763}{18\langle\sigma_t^2\rangle_{\max}} \frac{(G-1)}{f_{LM} L_A T_0} \mu\hbar\omega_0 \gamma |\beta_2| L_T^3$$

and the average soliton limit i.e.

$$\tau_{FWHM} >> \sqrt{L_A \beta_2}\,,$$

establish a lower limit for the pulse width

The upper limit for the pulsewidth is established by the interaction between solitons (soliton collapsed) which is given by,

$$T_{FWHM} << \frac{1.763}{2B\ln\left(\frac{4L_T}{z_0}\right)}$$

and the ASE limit i.e.

$$\tau_{FWHM} << \left(\frac{\beta_2}{\gamma\,\mu\,\hbar\omega_0 SNR^2_{\min}}\frac{G\ln G}{(G-1)^2}\frac{B}{B_e}\frac{L_A}{L}\right)$$

where $SNR_{\min}$ is the minimum acceptable signal to noise ratio for the system[11,12].

1.2 Soliton Transmission Control

In this work, a filter is inserted after an amplifier, typically 10 times larger than the bandwidth of the pulse train spectrum. The filter can be thought of as applying a restoring force in frequency space in such a way that if the spectrum of a single soliton pulse drifts away from the original frequency then it passes through the filter off-center and this will reduce the energy in such a way that the mean of the spectrum will move toward the filter center. The ASE noise components incorporated into the soliton are not filtered out by the action of the fixed frequency guiding filter. However the ASE noise power increases considerably and it can reach levels that are not acceptable at the receiver. Therefore the ASE noise continues to accumulate as before and the SNR limits still apply. For soliton transmission control in the time domain, a sinusoidal shaping function is applied to the soliton pulses. The effect of the sinusoidal modulation is to provide a restoring force in the time domain which moves the soliton to the peak of the modulation. Thus, control techniques are designed to reduce the soliton jitter [13,14].

2.0 NUMERICAL IMPLEMENTATIONS – CONCEPT OF A DESIGN DIAGRAM

Consider Figure 1.1 below. We start with the design diagram which consists of a transmitter, a series of fibres with amplifiers in the channel and a receiver. Optical amplifiers are placed periodically along the fibre link to compensate losses between the amplifiers. The parameters we are interested to look at are the pulsewidth, τ of the Gaussian pulse from the transmitter, dispersion, D of fibre and the spacing L_A between amplifiers. To consider the soliton transmission control (guided soliton), filter is inserted after every amplifier in Figure 1.1.

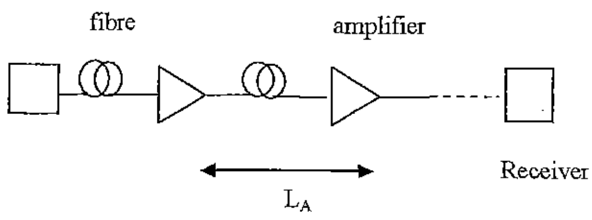

Figure 1.1 Fibre links with periodic loss compensation through optical N amplifiers

In this work, we formulate analytically all the limitations imposed in the system using a design spreadsheet in excel. Analytically we look at the Q factor for a soliton system with fixed amplifier spacing but different values of the input pulse width. The pulse width values should span the curves plotted in the design diagram. Next we vary the dispersion value and repeat for different pulse width. Later we carry out the similar process with different amplifier spacing. We then compare the results of the analytical and the numerical as described below.

For the purpose of the numerical simulation, we use the mqocss optical communication systems simulator written by Dr Marc Eberhard of Aston University. A PRBS of 128 bits in a time window of 12.8 ns and a numerical resolution of 2^{13} bins is generated and is modulated by a range of FWHM Gaussian pulses with respective peak power from the analytical model, with a rise time of 12.5 ps, 30 dB modulation depth and no insertion loss. It finally transmitted along the fibre link. The numerical simulation of the propagation is equivalent to the recirculating loop technique which consists of a fibre span and an amplifier. The actual transmission fibre in the loop is chosen to be 35, 50 and 70 km to give a total propagation distance of 3500 km i.e. a-100, -70 and -50 spans each. The loss was set to the standard value of 0.2 dB/ km. Usually the simulation jobs are repeated many times to see how the value of Q changes. We look at Q = 6 border at the end of propagation distance which is at every 3500 km.

We first describe the design diagrams for a fixed bit rate of 10 Gbit/s and allow the propagation distance to increase from 1000 km to 4000 km. Next we will keep the propagation distance fixed at 1000 km and allow the bit rate to increase from 5 Gbit/s to 20 Gbit/s. Second, we look at the variation of pulse width with dispersion at respective amplifier spacing.

The system performance is reported in terms of the Q factor which is commonly used to represent the performance of the optical systems in the presence of amplifiers, with and without the in-line filters.

3.0 RESULTS AND DISCUSSION

Design diagram can help to identify possible operating ranges for amplified soliton systems so that conflicting restrictions stated are respected. For example, a design diagram to see the variation of pulse width (which refers to various effects of limitations) with amplifier spacing when propagation distance and bit rate are kept fixed, respectively. Figures 1.2-1.3 show the pulse width as a function of amplifier spacing necessary to achieve acceptable system for 10 Gb/s and 3500 km system length for average soliton. The plots show impairments arising from design limitations namely GH jitter, ASE, average soliton limit and soliton-soliton interaction. The region of a safe operation would be the intersection region below SC and ASE limits and above GH jitter. The shaded area in figures 1.2-1.3 denotes the permissible pulse width for propagation which is based purely on the analytical predictions. It can be concluded the permissible area of propagation is getting smaller as the propagation distance increases at a fixed bit rate. The inset in each figure shows the position of GH and ASL limitations (as it is too small a difference in pulse width). In figure 1.4, propagation fails as there is no intersection between the curves as the ASE is lower than GH limit.

There is also a drop in permissible area of propagation as the bit rate increases from 5 to 10 Gbit/s as shown in figures 1.5-1.6 when the propagation distance is kept fixed.

A plot in figure 1.7 shows the propagation limitations for different amplifier spacings in analytical for respective amplifier spacing. The upper bound on the pulsewidth (i.e. dispersion below 0.17 ps/ km nm) is due to ASE and above that dispersion, is bounded by soliton collapse, SC. The lower bound is all bounded by GH jitter limitation.

Plots in figure 1.8 describing the pulsewidth versus dispersion with their respective amplifier spacing for a numerical method. For each plot the peak pulsewidth is at around dispersion 0.2 ps/km nm. It can be noted from the plot that the longer the amplifier spacing the smaller the value of its maximum dispersion. Also as the amplifier spacing increases the area under the curve decreases while maintaining the same limitations i.e. GH jitter, ASE and soliton collapse.

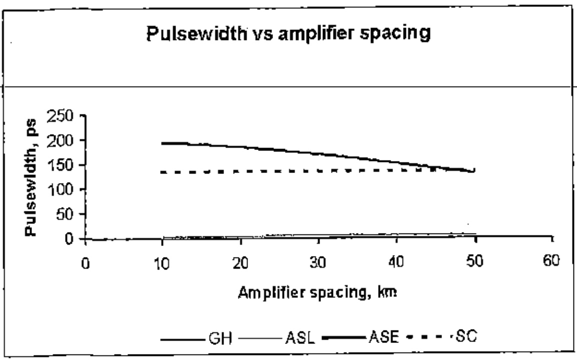

Figure 1.2: propagation distance = 2000 km

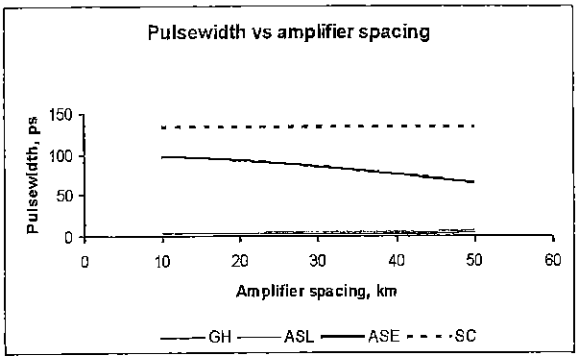

Figure 1.3: propagation distance = 4000 km

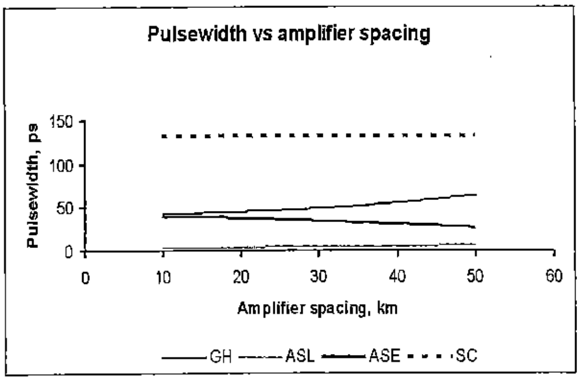

Fig 1.4 Lt=10000 km- no intersection! There is where there is no combination of system parameters that satisfies all the criteria.

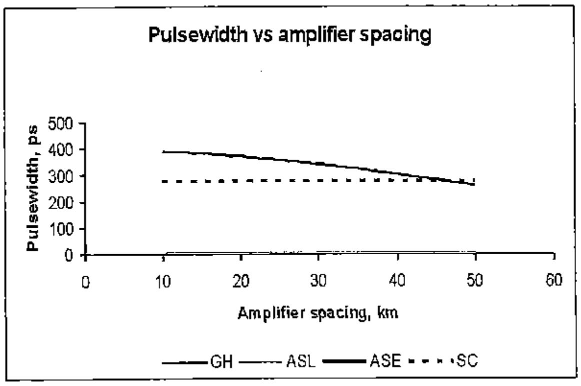

Figure 1.5: Bitrate = 5 Gbit/s

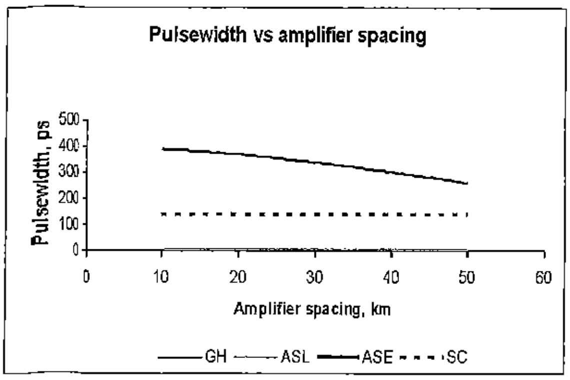

Figure 1.6: Bitrate = 10 Gbit/s

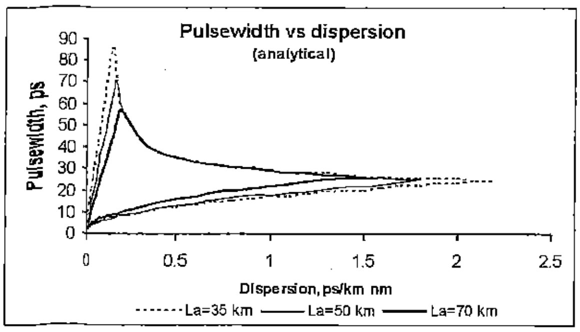

Figure 1.7 analytical plots for pulsewidth versus dispersion for different amplifier spacings in analytical method

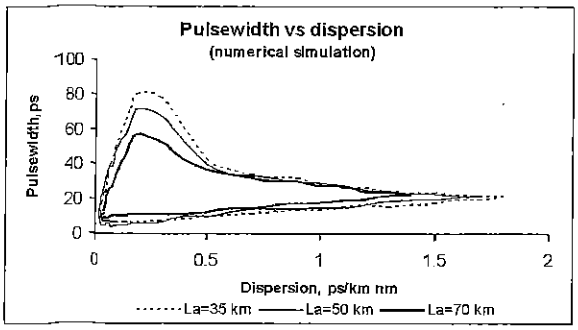

Figure 1.8 Numerical plots for pulsewidth versus dispersion for different amplifier spacings in numerical method

The use of filters decreases the GH limitations i.e. the GH effect is decreased and this then leads to an increase in the range of the allowed parameters and also increases the dispersion both analytical and numerical simulation. This is shown in figures 1.9 and 1.10 for $L_a = 50$ km [15]. From these plots there is not much reduction in timing jitter when in-line filters are used except at higher dispersion but the trend follows. Based on the previous simulations that have been published [16,17] the filtering works much better when the underlying GH is small.

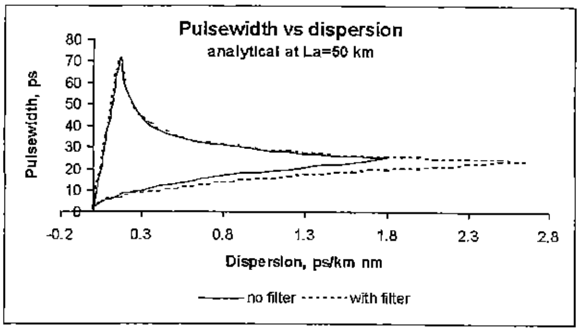

Figure 1.9 Analytical plot for pulsewidth versus dispersion for L_a = 50 km

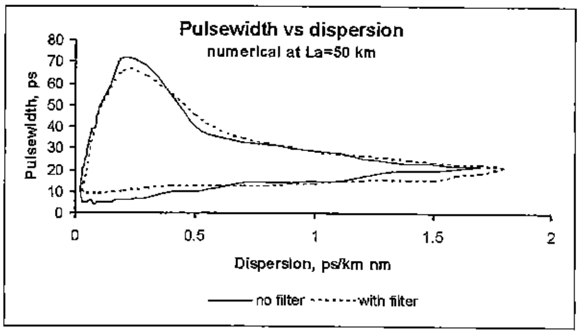

Figure 1.10 Numerical plot for pulsewidth versus dispersion for L_a= 50 km

The eye diagram in figure 1.11 is for system parameters corresponds to a point on a design diagram close to the limit imposed by the GH effect. It shows clearly the position jitter of the pulses as predicted by the GH effect. Figure 1.12 shows the improvement when in-line filters can reduce the effect of GH at the end of 3500 km propagation of fibre system. The benefit of filters is evident by reducing the GH jitter and limiting the degradation due to instability induced by the periodical amplification [7].

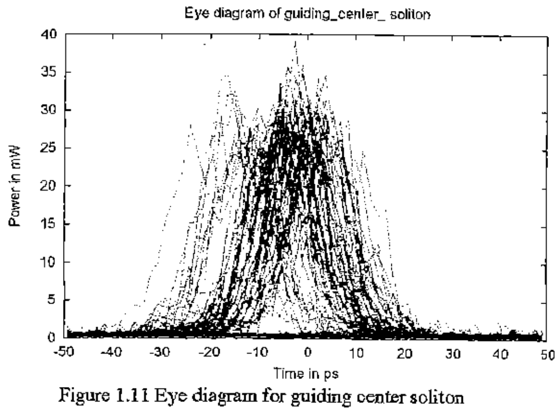

Figure 1.11 Eye diagram for guiding center soliton

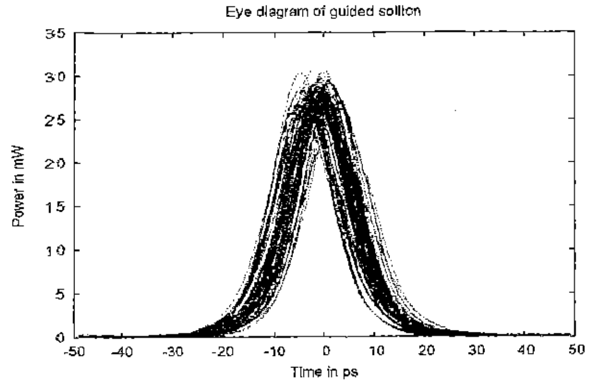

Figure 1.12 Eye diagram for guided soliton

3.0 CONCLUSION

In the average soliton system, a pulse with a specific peak power is launched in to the fibre so that the average power over the propagation between amplifiers is equal to the soliton power in a lossless system. The ratio of the initial peak power to the lossless soliton power is given by *(G ln G)/(G-1)* where *G* is gain. The limitations on the system operating parameters such as dispersion, amplifier spacing and pulse width, were shown both in numerically generated and analytically generated plot.

In the guided soliton system, filters are inserted into the systems in order to yield a substantial reduction of the GH effect. This reduction was demonstrated by comparing the eye diagrams before and after the insertion of the filters. The inclusion of filters introduces an increase in loss through the insertion loss as well as through the effect of filtering. The losses must be compensated for by increasing the gain in the amplifier. The increase in gain leads to the generation of more noise. These studies showed that analytically the timing jitter is reduced significantly when filters are inserted and the eye diagrams show significantly reduction in jitter.

Acknowledgments

The work done in this article was undertaken in Aston University, UK. The author wishes to thank Prof K.J. Blow and Dr M.A. Eberhard of Photonic Research Group, Electronic Engineering Dept. School of Engineering and Applied Science, Uni. of Aston, Birmingham, UK for the supervision.

References

[1] Y. Kodama, A.H., *Amplification and reshaping of optical solitons in glass fiber - III. amplifiers with random gain.* Opt. Lett., 1983. **8**: p. 342.

[2] A.Hasegawa, *Amplification and reshaping of optical solitons in a glass fiber - IV: Use of stimulated Raman process.* Opt. Lett, 1983. **8**: p. 650.

[3] A.Hasegawa, *Numerical study of optical soliton transmission amplified periodically by the stimulated Raman process.* Appl. Opt., 1984. **23**: p. 3302.

[4] L.F.Mollenauer, R.H.S., M.N.Islam, *Experimental demonstration of soliton propagation in long fibers: loss compensated by Raman gain.* Opt. Lett, 1985. **10**(229).

[5] L.F.Mollenauer, J.P.G., M.N.Islam, *Soliton propagation in long fibers with periodically compensated loss.* IEEE J. Quantum Electron, 1986. **QE-22**: p. 157.

[6] A.Hasegawa, Y.K., *Guiding Center Soliton in Optical Fibre.* Opt. Lett., 1990. **15**(24): p. 1443-1445.

[7] L.F.Mollenauer, S.G.E., H.A.Haus, *Long-Distance Soliton Propagation using Lumped Amplifiers and Dispersion Shifted Fiber.* Journal of Lightwave Technology, 1991. **9**(2): p. 194-197.

[[8] K.J.Blow, N.J.D., *Average soliton Dynamics and the operation of soliton systems with lumped amplifiers.* IEEE photonics Technology Letters, 1991. **3**(4): p. 369.

[9] J.P.Gordon, H.A.H., *Random walk of coherently amplified solitons in optical fiber transmission.* Optics Letters, 1986. **11**(10): p. 665-667.

[10] M.Nakazawa, Y.K., K.Suzuki, *Soliton amplification and transmission with Er3+-doped fiber repeater pumped by GaInAsP laser diode.* Elec. Lett., 1989. **25**: p. 199-200.

[11] E. Iannone, F.M., A. Mecozzi, and M. Settembre, *Nonlinear Optical Communication Networks.* 1998: Wiley, New York.

[12] G.P.Agrawal, *Fiber-Optic Communication Systems.* 3rd ed. 2002: John Wiley and sons, New York.

[13] Mecozzi, A., Moores,J.D,Haus,H.A, *Modulation and filtering control of soliton transmission.* J. Opt. Soc. Am., 1992. **9**: p. 1350-1357.

[14] A.Mecozzi, J.D.M., H.A.Haus,Y.Lai, *Soliton transmission control.* Opt. Lett, 1992. **16**(23): p. 1841-43.

[15] K.J. Blow, S Turitsyn, S Derevyanko, J Prilepsky,Z Zakaria, *Soliton in optical communication.* Int. conference on Engineering and Computational Maths, Hong Kong Polytech Uni. 2009.

[16] Marcuse, D., *Simulations to demonstrate reduction of the Gordon-Haus effect.* Optics Letters, 1992. 17(1): p. 34-36.

[17] Francesco Matera, M.S., *Comparison of performance of optically amplified transmission systems.* J. Lightwave Technology, 1996. **14**(1): p. 1-12.