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PERFORMANCE COMPARISON BETWEEN ANALYTICAL ANALYSIS AND NUMERICAL SIMULATIONS FOR AVERAGE SOLITON SYSTEM.

Zahariah Zakaria
Maths & Science Dept
Faculty of Science, Technology and Human Development
Universiti Tun Hussein Onn Malaysia
zahariah@uthm.edu.my

This paper presents the comparison between analytical results and computer simulated results showing the performance of soliton transmission in optical fibre optics. A study of average soliton systems with 50 km amplifier spacing is presented both analytically and numerically. 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.

Keywords: Amplified soliton; EDFA; GH effect; ASE; Soliton collapse.

1. INTRODUCTION

The development of the Erbium Doped Fibre Amplifier 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 [1] first demonstrated soliton transmission with EDFA in the late 80s. This section will look at the limitations imposed by EDFAs to the propagation of an amplified soliton.

2. MAIN LIMITATIONS FOR AN AMPLIFIED SOLITON

2.1 Gordon Haus, GH Effect

One of the main limiting factors arising from the introduction of amplification is the amplified spontaneous emission (ASE) added at the amplifiers. The ASE noise remains a serious limitation of soliton systems; it manifests through a reduced signal-to-noise ratio and an increased timing jitter at the optical receiver [2]

The origin of timing jitter can be understood as follows. The ASE noise of the amplifiers used in the system adds random fluctuations in amplitude, frequency and temporal position of the pulse. Fluctuations in frequency affect the group velocity and hence the speed with which the pulse propagates through the fiber. Since the ASE induced fluctuation in the frequency is random, the transit time through the fiber link is also random. Temporal fluctuations directly lead to timing jitter [2][3] This fluctuation in the arrival time of a soliton is called the *Gordon-Haus timing jitter* [4].

To summarise, T_{FWHM} is the full width at half maximum of the pulse, the Gordon-Haus effect then establishes a lower limit for the pulse width i.e.

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

2.2 Amplified Spontaneous Emission, ASE Noise Accumulation

Another main problem resulting from the introduction of amplification comes from the required signal to noise ratio at the receiver. The accumulation of the ASE noise along the fibre link can severely degrade the electrical signal-to-noise ratio, SNR at the receiver. The SNR is a measure of the mean square current due to signal/soliton divided by the mean square current due to ASE noise and can be written as,

$SNR = \dfrac{\left\langle i^2_{soliton}\right\rangle}{\left\langle i^2_{sp}\right\rangle}$ establishes the upper limit for pulsewidth i.e.

$$\tau_{FWHM} << \left(\frac{\beta_2}{\gamma\ \mu\ \hbar\omega_0 SNR^2_{\min}} \frac{G\ln G}{(G-1)^2} \frac{B}{B_e} \frac{L_A}{L}\right)1.763 \qquad (2)$$

where $SNR_{\min}$ is the minimum acceptable signal to noise ratio for the system.

2.3 Periodic Attenuation and Amplification of Soliton

Fibre losses lead to soliton broadening. This problem of loss is overcome by periodic amplification along the propagation line. The amplifiers will restore the soliton energy to its initial value after propagating to a certain distance. However the same peak power launched, does not give a required balance between nonlinearity and dispersion over the entire span. This introduces to the concept of average soliton where the soliton power is increased by a factor of $G\ln G/G-1$, G is the gain of the amplifier which compensates for the losses of the fibre segment so that the average power in one amplification period coincides with the power of a fundamental soliton in the absence of fibre losses.

The condition $L_A << L_D$ is required to operate within this average-soliton regime i.e.

$$L_A << L_D = \frac{\tau_0^2}{\left|\beta_2\right|}$$

or the average soliton limit is given by,

$$\tau_{FWHM} >> \sqrt{L_A\beta_2}\,FWHM \qquad (3)$$

2.4 Interaction between Solitons

The reduction of the time separation between the pulses allows for an increase of the transmission rate. However a smaller separation may lead to interaction between adjacent solitons, so this will place a limit on the transmission rate that can be achieved.

To summarise, the upper limit for soliton propagation is given by,

$$L_T < \frac{L_{col}}{2} = \frac{z_0}{4}\exp\left(\frac{T_B}{2T_0}\right) = \frac{\pi}{16}\frac{1}{q_0^2 B^2 |\beta_2|}\exp\left(\frac{1.763}{2BT_{FWHM}}\right)$$

or

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

3. CONCEPT OF DESIGN DIAGRAMS

In this section, the concept of design diagram is shortly introduced to check that every condition for proper propagation of soliton is satisfied. In designing such a system, the required system length and the operating bit rate are the main considerations [6],[7]. We start with the design diagram which consists of a transmitter, a series of fibres with amplifiers and a receiver. 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. The values of the parameters must be chosen such that an acceptable bit error rate of the system is possible and the pulse propagation is successful to the end of propagation distance. There must be compromises made in the system design brought about by the requirements of low timing jitter on the arrival at the detector, high signal to noise ratio and consideration on the collapse of the soliton. For example Gordon-Haus jitter requires a wide pulse width whilst a short pulse width is required to reduce the soliton-soliton interaction. Figure 1 shows optical amplifiers are placed periodically along the fibre link to compensate fibre losses between two amplifiers.

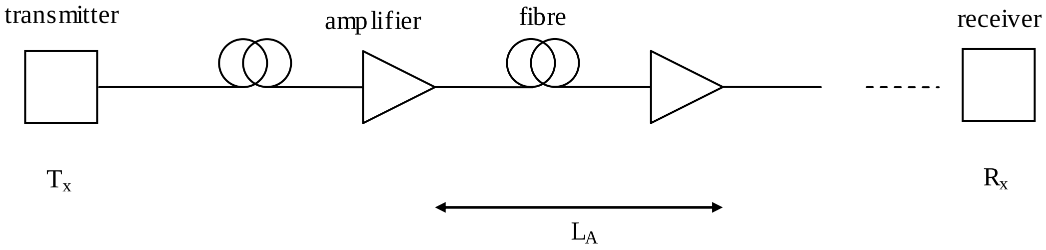

Figure 1: Fibre links with periodic loss compensation through optical N amplifiers

Figure 2 shows the pulsewidth as a function of amplifier spacing necessary to achieve acceptable system for 10 Gb/s and 3500 km system length for average soliton and guided soliton respectively. The plots show impairments arising from design limitations namely GH jitter, ASE, average soliton limit and soliton-soliton interaction, SC (soliton collapse). The region of a safe operation would be the intersection region below SC and ASE limits and above GH jitter and average soliton limitations.

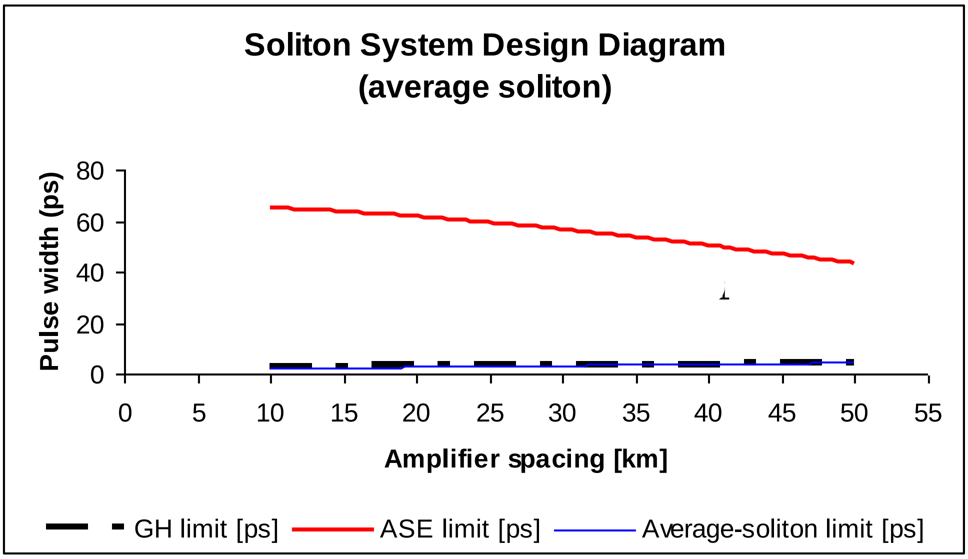

Figure 2: Soliton design diagram for 3500 km system length for average soliton.

3.1 Analytical Simulations

In this part, equations on main limitations for an amplified soliton are used to analytically simulate this average soliton system. Those limitations are due to Gordon-Haus effect, ASE noise accumulation, periodic attenuation and amplification of soliton and interaction between solitons or soliton collapse. In the design diagram, we fix the amplifier spacing and set the dispersion and look at the series of pulsewidth which show the propagation is successful i.e. the Q value is above 6. We repeat for other dispersions. Again we look at a plot of pulsewidth versus dispersion for a fixed amplifier spacing, i.e. 50 km.

As shown in figure 3, the upper bound on the pulsewidth is due to ASE, for D<0.17 ps/km nm and to soliton collapse for D>0.17 ps/km nm. The lower bound is all bounded by GH jitter limitation [8],[9].

3.2 Numerical simulations and system parameters

For the purpose of this simulation, we use the mqocss optical communication systems simulator written by Dr Marc Eberhard of Aston University, and a sample of a configuration file (the XML code) describing the communication system operating at

10 Gbit /s and employing soliton-like pulses. A PRBS of 128 bits in a time window of 12.8 ns and numerical resolutions 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. 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 50 to give a total propagation distance of 3500 km i.e. 70 spans each. The loss was set to the standard value of 0.2 dB/ km. The nonlinearity in the system is assumed to be described by the pure Kerr effect, the effective area of the fibre was set to 72 μm^2. Dispersion was set from as low as 0.3 ps/ km nm to as high as 2.5 ps/ km nm (as referred to a design diagram) and there is no dispersion slope (second order dispersion). In a typical configuration of 50 km amplifier span, the gain in amplifier would be 10 dB to compensate for the round trip loss of the loop of 10 dB. In the receiver an optical Gaussian filter with 20 GHz bandwidth is inserted before the detector. An optical signal passes through this detector then is filtered by an electrical Bessel filter with 8 GHz bandwidth. Noise is normally generated by the amplifiers which add noise to the transmitted signal during amplification. Each time the amplifier works, it generates a random noise signal that is different but has the same average power. Therefore the results should differ a little bit each time the simulation is run. 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.

Figures 4 describe the pulsewidth vs dispersion with a fixed amplifier spacing respectively [8],[9]. 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.

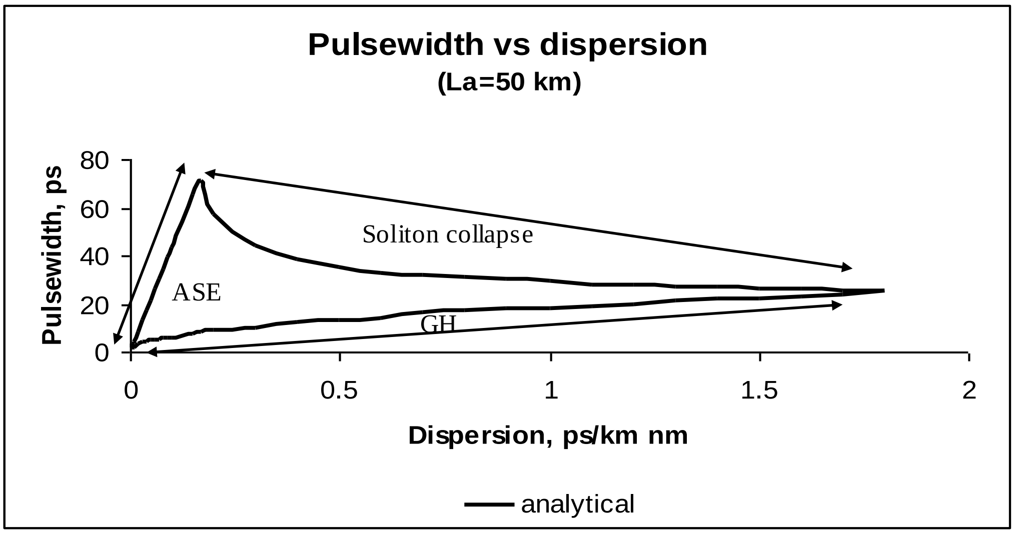

Figure 3: Analytical plot with its limitations at La=50 km

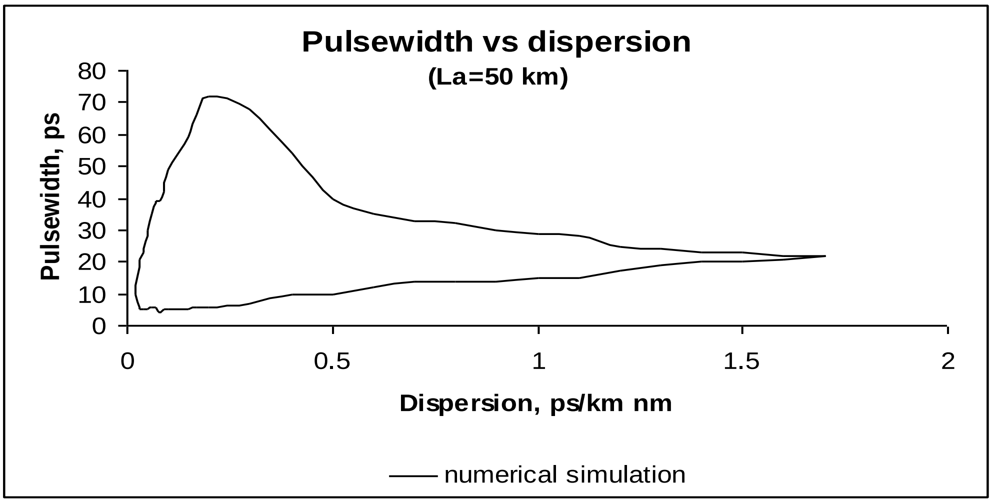

Figure 4: Q=6 contour plot of pulsewidth vs dispersion for numerical simulation at La=50 km

5.6 Conclusion

It has been shown that at small values of dispersion, the upper bound on the pulsewidth is due to ASE as the soliton peak power is very low. Whilst for higher values of dispersion, it is bounded by soliton collapse. The lower part of the curve is bounded by GH jitter as its limitation throughout the dispersion span. These limitations should be shown in the eye diagrams representing their positions on the pulsewidth versus dispersion plots.

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