Optimisation of 80 ´10Gbit/s Ultra long-haul DWDM systems

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Abstract: This paper outlines an approach to modelling ultra long-haul DWDM links taking into account spectral variations of gain and noise in EDFAs. A black-box model is used to describe EDFA gain and noise figure tilt and full nonlinear simulations are carried out using the split-step Fourier method. The effect of pre-emphasis and power optimisation is investigated for a typical ultra long-haul link of approximately 3000km.

1 Introduction

In recent years the deployment of terrestrial Ultra Long-Haul (ULH) optical transport systems capable of carrying many DWDM channels across distances in excess of 1500km without intermediate O-E-O regeneration [1] has helped lower the unit cost ($/Gbit/km) of long haul data transport [2]. ULH systems have been made possible by a number of technical advances outlined in [3] the key enabler being dispersion managed solitons, which uses group velocity dispersion (GVD) to balance the nonlinear effect of self-phase modulation (SPM) in optical fibre.

The Kerr nonlinear effect (intensity dependence of refractive index) leads to pulse broadening in the frequency domain (SPM-induced chirp). GVD introduces an opposing chirp which when the dispersion map in a link is carefully chosen, can balance and mitigate the SPM induced chirp. SPM and other Kerr nonlinear effects of four-wave mixing (FWM) and cross-phase modulation (XPM) set a higher limit on the optical channel power, whilst a lower limit is set by ASE noise due to optical amplification by EDFAs. Power variations in channels across the transmission band exist due to the non-flat gain spectrum of EDFAs, and stimulated Raman scattering (SRS) in optical fibre, which amplifies longer wavelength channels at the expense of shorter wavelength channels. SRS increases log-linearly with optical power (and hence channel count), so dynamic gain equalisation and input power pre-emphasis (changing the channel power profile at the input of the link) as shown in fig.1 is clearly required in future high capacity optical networks where channels are to be added/dropped instantaneously.

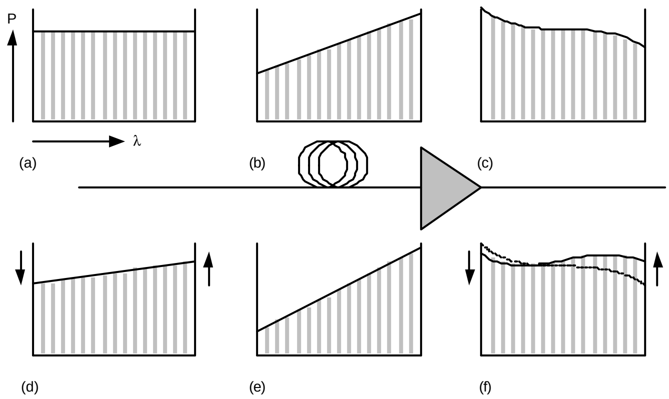

Figure 1. An illustration of the principle of input channel power pre-emphasis. Figs. (a), (b) and (c) show the evolution of a WDM signal through an optical fibre span and an EDFA using no pre-emphasis. Figs. (d), (e) and (f) show the same evolution but with pre-emphasis to equalise the net gain at the end of the transmission link.

This paper outlines a new approach to modelling ultra long haul systems taking into account the spectral dependence of gain and noise figure tilt in EDFAs in addition to dispersion and nonlinear effects. Modelling results are presented for an ultra long-haul system of approximately 3000km length showing the Q-value performance from full nonlinear simulations with varying average input channel power and pre-emphasis. Linear simulations (which are significantly less intensive in terms of computational time) are also carried out to determine if the optimum pre-emphasis calculated in that manner is close to the optimum calculated by the full nonlinear simulations.

2. Model outline

From a system design point-of-view the spectral dependence of gain and noise figure in an EDFA can be described using a black-box model as proposed in [4]. An advantage of this approach is that a detailed knowledge of the active gain medium and accurate data for the amplifier components is not required: only input-output test measurements of amplifier units. The model is based on the physics of an effective two-level laser system, meaning that it is valid for most commercially available EDFAs. From [4] the gain of an EDFA as a function of wavelength l and input power P_{in} can be derived as

$$G^{dB}\left(l, P_{in}\right) = G^{dB}_{ref}\left(l\right) + T_{l_{ref}}\left(l\right)\cdot a_T \cdot P^{dB}_{in} \qquad (1)$$

where $G_{ref}(\lambda)$ is the gain at a reference point $P_{in\ ref}$ = 0dBm and l_{ref} = 1546 nm, a_T is a constant. $T_{l\,ref}(\lambda)$ is a characteristic tilt function given by

$$T_{l_{ref}}\left(l\right) = \frac{G_1^{dB}\left(l\right) - G_2^{dB}\left(l\right)}{G_1^{dB}\left(l_{ref}\right) - G_2^{dB}\left(l_{ref}\right)} \qquad (2)$$

where G_1 and G_2 are the gains measured at different amplifier saturation conditions (input powers). $G_{ref}(\lambda)$ and $T_{l\,ref}(\lambda)$ can be modelled as third order polynomials by fitting to experimental measurements of gain against wavelength at various saturation conditions.

A similar expression for the spectral noise figure F is also derived from [4] as the spontaneous emission factor n_{sp}, with $F = 2n_{sp}$ (linear units)

$$n_{sp}\left(l, P_{in}\right) = n_{sp_0} + f\left(l\right)\cdot g\left(P^{dB}_{in}\right) \qquad (3)$$

where n_{sp0} is a constant and $f(\lambda)$ and $g(\mathrm{P_{in}})$ can be modelled as third and second order polynomials fits to experimental measurements. These models show good agreement with experimental measurements to ± 0.2 dB for the gain and ± 0.3 dB for the noise figure. The spectral variation of transmission and dispersion compensating fibre attenuation were modelled as quadratic and linear fits to experimental measurements.

The split-step Fourier method [5] was used to numerically solve the nonlinear Schrödinger equation (NLSE) for the propagation of pulses in optical fibre in the presence of nonlinearity and dispersion. Full nonlinear simulations are computationally intensive, especially when considering DWDM systems, as the simulation time increases with approximately N^2, where N is the number of channels [6]. Due to the long computation times involved in nonlinear simulations, it is only practical to simulate upto 6 neighbouring DWDM channels at a time, repeating the simulations at the middle and either end of the transmission band (1530, 1545 and 1560 nm in the C-band). A previous study [6] has shown this approach to be a valid approximation. Q-values were obtained as the worst of 6 channels averaging five different runs with random noise seeds using a 128-bit Pseudo Random Bit Sequence (PRBS). Linear simulations were carried out by setting the nonlinear coefficient to zero and by making a slight adjustment to the dispersion map.

3. System overview

The system studied carries 80×10 Gb/s channels in the C-band with a channel spacing of 50 GHz over a 2940km ULH link consisting of 35×84km spans (22dB loss) using return-to-zero (RZ) modulation. The fibre was standard SMF with in-line dispersion compensation using dispersion compensating fibre (DCF) on a per span basis. Pre and post compensation was optimised to provide 100% slope compensation. Dynamic gain equalising amplifiers were placed periodically along the link to correct for gain tilt and ripple variations and are capable of re-levelling the gain spectrum to any desired linear tilt profile.

4. Results

Full nonlinear simulations were carried out to calculate the worst channel Q-values in dB at the end of the link for varying input power per channel and pre-emphasis levels and are shown in fig. 2 (a). Results of simulations with no nonlinearity are shown in fig. 2 (b).

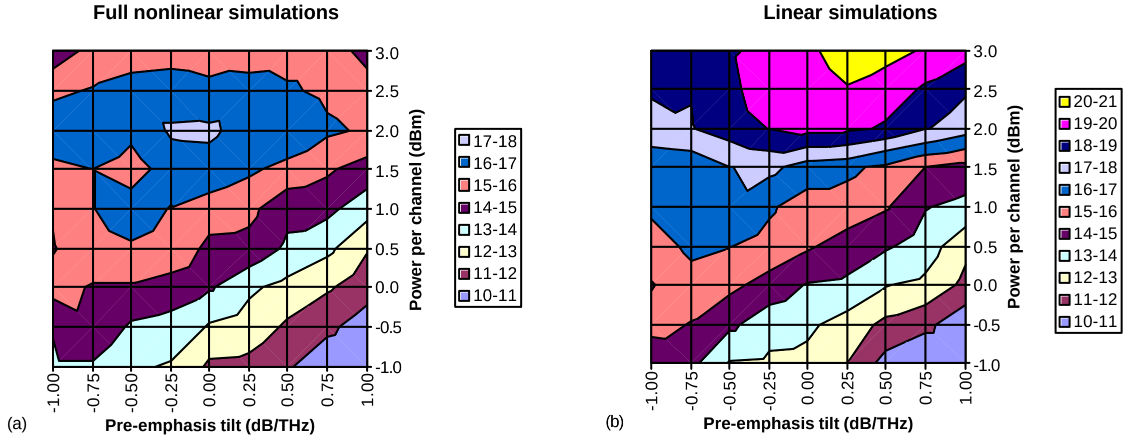

Figure 2. Q-value contour map for 35×84km span link using per span dispersion compensation for (a) full nonlinear simulations (b) linear simulations

Without nonlinearity as fig. 2(b) shows, simply increasing the power per channel gives a better Q performance due to improved OSNR, and as the power per channel is increased the pre-emphasis required to optimise Q becomes more positive. This is due to the increased SRS effect, which produces a negative tilt (in frequency) counterbalancing the positive EDFA gain tilt. However when taking into account full nonlinear propagation there is an upper limit to the input power of 2dBm, beyond which the signal deteriorates due to Kerr nonlinear effects. The lower threshold is due to a combination of OSNR requirements and a certain amount of nonlinearity, which is required to counterbalance the effects of GVD. From figs. 2 (a) and (b) an optimum pre-emphasis can be determined for each power level which results in optimising the Q-value of the worst effected channel across the band. Fig. 3 (a) shows the Q-value obtained from full nonlinear simulations using 3 different pre-emphases: the optimum pre-emphasis determined by nonlinear simulations, linear simulations and no pre-emphasis at all.

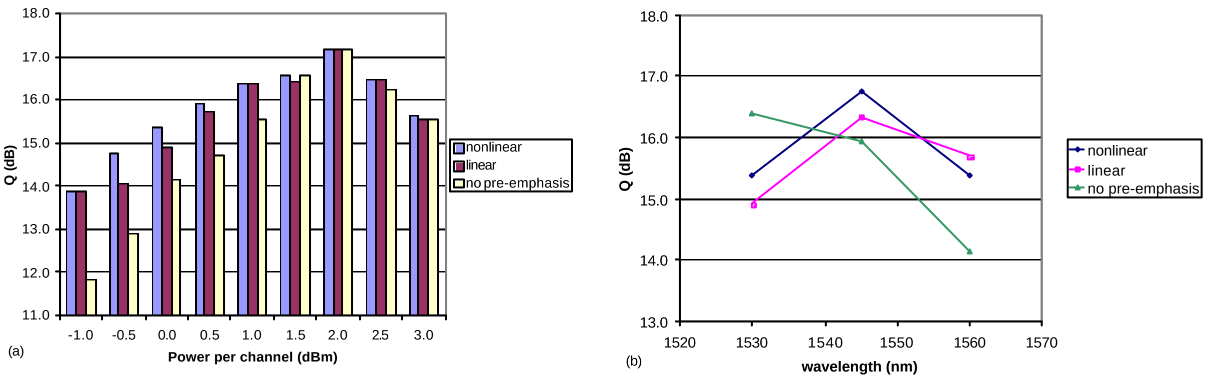

Figure 3. (a) Worst channel Q-values for the 35×84km span link with RZ modulation showing results obtained from full nonlinear simulations using the optimum pre-emphasis predicted by full nonlinear simulations, linear simulations and with no pre-emphasis. (b) example spectrum, showing Q-values from full nonlinear simulations using the optimum pre-emphasis predicted by full nonlinear simulations, linear simulations and with no pre-emphasis at 0dBm per channel

Fig. 3 (b) shows that at an input power of 0dBm per channel with no pre-emphasis the 1560nm channel suffers because of the low SRS tilt at this power, which is over compensated by the opposing EDFA gain tilt. Applying the correct pre-emphasis improves the performance of this channel to ensure a more constant BER across the band. There is a small penalty (<0.5dB) in the Q-value of the 1530nm channel when the pre-emphasis calculated from linear simulation is used.

Fig. 3 (a) shows that at the lower powers there is an appreciable difference between the performance with optimum pre-emphasis and that with no pre-emphasis but when the power level is at its optimum (2dBm) there is no difference between the performance. This is because the system is carefully designed so that SRS tilt in the fibre is balanced at the optimum input power with no pre-emphasis. There is little appreciable penalty between the Q-value performance using the optimum pre-emphasis calculated from linear simulations and that calculated from the full nonlinear simulations, the greatest being 0.7 dB at –0.5 dBm per channel and virtually no penalty around the optimum input power.

5. Conclusion

A new implementation of the split-step Fourier method of modelling lightwave propagation in optical fibre taking into account the spectral dependence of fibre attenuation, gain and noise figure in EDFAs as well as dispersion and nonlinearity was demonstrated. Full nonlinear simulations were carried out on a ULH link consisting of 35×84km spans using RZ modulation using per span dispersion compensation. Results show that using linear simulations to estimate the optimum pre-emphasis tilt for a given average input power per channel gives little or no appreciable Q penalty compared to the optimum pre-emphasis calculated from full nonlinear simulations. This result is quite significant and means that computationally less intensive simulations can be used to estimate the optimum pre-emphasis for a particular link. Future studies should aim to test this rule for different types of dispersion maps and different channel counts.

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