Nonlinear Signal Distortion in WDM Transmission with 10- and 40-Gbit/s Channel Rates

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Abstract: *Extending WDM transmission distances between regenerators and increasing the channel bit-rates are required to achieve cost-effective terabit/s backbone networks. However, the achievable performance is limited the fibre nonlinearity, with high optical launch powers and short pulse widths leading to nonlinear distortion of the signals. In this paper, we report new results of split-step Fourier simulations of WDM transmission, investigating the effects of both intra- and inter-channel nonlinear distortion for 10- and 40-Gbit/s channel rates.*

1. Introduction

Backbone optical networks with terabit/s link capacities will be required to deal with the demand for bandwidth brought about by the growth in data communications and a cost-effective technique to achieve such data-rates is wavelength division multiplexing (WDM). With the next generation of WDM systems employing >100 channels, the limited scalability of electronically regenerating and routing the signals is driving the development of all-optical networking techniques, in which the signals remain in optical form across the network, and optical add-drop multiplexers and cross-connects are used to route individual channels.

All-optical transmission over long distances requires the careful optimisation of the link design, most importantly the tailoring of the fibre group velocity dispersion, to avoid significant signal distortion. The majority of the world's networks utilise standard single mode fibre (SSMF), with dispersion D = 17 ps/nm/km. This limits the error-free transmission distance of a 10 Gbit/s signal to around 60 km due to pulse broadening. However, dispersion compensating fibre (DCF, D = -100 ps/nm/km) or dispersion compensating fibre gratings can be placed in the link to recompress the pulses, allowing greatly extended range, as shown in Fig. 1.

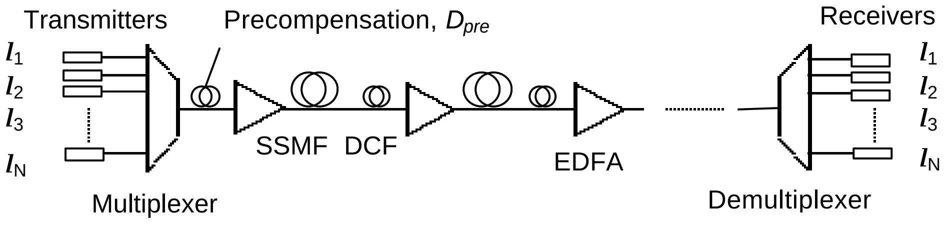

Figure 1: WDM transmission system configuration, employing SSMF, in-line DCF dispersion compensation, and erbium-doped fibre amplifiers (EDFA).

A further limiting effect is the fibre Kerr nonlinearity, the intensity dependence of the refractive index, which leads to self-phase modulation (SPM), in which the signal pulse distorts its own phase, $\Delta f = gP_s(z)\Delta z$, during transmission over distance Δz, where g is the fibre nonlinear coefficient and $P_s(z)$ is the optical power. Additionally, cross-phase modulation (XPM), $\Delta f = 2gP_p(z)\Delta z$, occurs due to the power $P_p(z)$ of neighbouring WDM channels or neighbouring pulses in the same channel. The frequency shifted components of the signal propagate with altered transmission velocities, Δv_g, due to the fibre dispersion, $\Delta v_g \propto D\Delta w$, where $\Delta w = df/dt$, resulting in intensity distortion in the detected signal.

A second effect of the Kerr nonlinearity is four wave mixing (FWM), in which nonlinear mixing of two optical frequencies w_1 and w_2 transfers power to new frequencies, $2w_1 - w_2$ and $2w_2 - w_1$ and this can lead to significant nonlinear cross-talk between WDM channels. The efficiency of the FWM process increases with the phase matching, and the problem of inter-channel FWM is solved by using a high local fibre dispersion to obtain a large velocity difference, Δv_g, between the channels. The dispersion of standard single mode fibre is sufficient to suppress FWM between WDM channels.

In this paper, the use of dispersion-managed soliton transmission techniques [1], in which the effect of SPM is balanced against the fibre dispersion, is investigated for STM-64 10 Gbit/s-based SSMF links. The dependence of the distortion on the average dispersion and the effect of inter-channel XPM on the soliton timing jitter for narrow WDM channel spacing are assessed. These results are then compared with the performance of STM-256 40 Gbit/s-based transmission over standard fibre and non-zero dispersion shifted fibre (NZDSF). It is shown that, since the dispersion-induced pulse broadening is rapid in the SSMF, significant performance limitation results from intra-channel XPM and a recently discovered effect, intra-channel FWM [2]. A new design technique minimising intra-channel nonlinear distortion in highly dispersed pulse transmission is described.

2. 10 Gbit/s-based transmission

Initially, a 10 Gbit/s-based system was considered. The modelled link consisted of 60 km spans of SSMF (loss a = 0.21 dB/km), each post-compensated with DCF. The approximation of noiseless amplifiers was used to allow the effects of fibre nonlinearity alone to be assessed. Input pulses, with T_{FWHM} = 36 ps, encoded with a random 128-bit sequence, were prechirped [1] using precompensation of D_{pre} = -170 ps/nm (Fig. 1) and transmission through the link with a launch power into each span of +5.7 dBm per channel was calculated using the split-step Fourier technique. Soliton transmission was achieved by using undercompensation of 34 ps/nm per span, giving an average dispersion of 0.57 ps/nm/km. The transmission of a single channel over 40 spans was first calculated and the resulting eye opening values, normalised to the input value, are plotted in Fig. 2. The pulses were compressed due to the interaction of SPM and the average anomolous dispersion, leading to a 20 % increase in the vertical eye opening after transmission. The signal eye diagram after 40 spans is shown in Fig. 1a, showing negligible distortion due to soliton-soliton interaction.

Next, the transmission performance dependence on the value of the average dispersion was investigated. The residual dispersion per span was reduced to 0 ps/nm by increasing the length of the DCF so that each span was exactly compensated. The phase distortion due to SPM was no longer balanced by dispersion and from the eye diagram after 30 spans (Fig. 1b) it can be seen that the calculated transmission distance was limited by the resulting pulse broadening and break-up. For wideband WDM soliton transmission, this highlights the importance of compensating the dispersion slope (typically ~0.06 $\mathrm{ps/nm^2/km}$ in SSMF) over the bandwidth of the EDFA.

Following the single channel studies, simulations of WDM soliton transmission were carried out, investigating the effect of inter-channel XPM. The residual dispersion was reset to 34 ps/nm per span, and a channel spacing of 50 GHz was used, giving a spectral efficiency of 0.2 bit/s/Hz. Five co-polarised channels encoded with uncorrelated bit sequences were considered in the simulations, and the performance of the central channel was monitored. Fig. 2 shows the significant impairment of the signal due to XPM, with eye closure of 50 % occurring after only 12 spans. The frequency shifts caused by XPM lead to variations in the pulse propagation velocities, and hence pulse timing jitter in the received signal. This builds up to a standard deviation of 5.6 ps after 12 spans and is clearly seen in the signal eye shown in Fig. 2c following transmission over 15 spans.

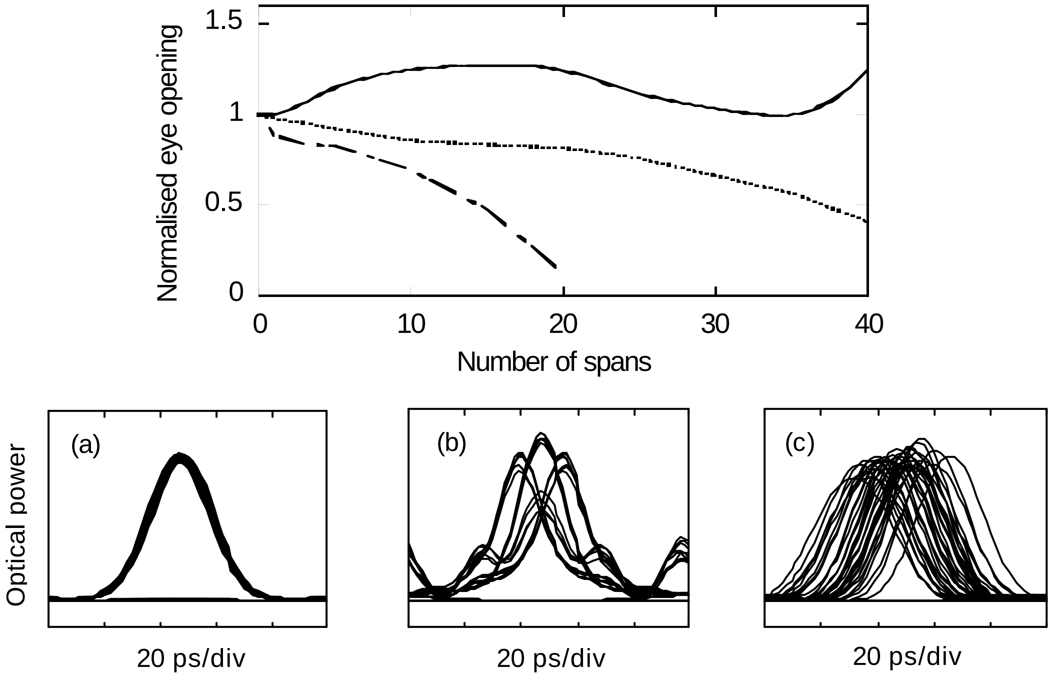

Figure 2: Eye opening for single channel 10 Gbit/s transmission over SSMF with 0.57 ps/nm/km (¾) and 0 ps/nm/km (xxxxx) average dispersion. Five channel 50 GHz-spaced WDM transmission (- -). Eye diagrams for (a) single channel soliton transmission (40 spans), (b) single channel transmission with zero average dispersion (30 spans) and (c) WDM soliton transmission (15 spans).

3. 40 Gbit/s transmission

The same dispersion-compensated multi-span link configuration with 60 km span length was used to investigate the performance of 40 Gbit/s per channel WDM transmission. An input pulse width of T_{FWHM} = 9 ps and launch power of +7.5 dBm per channel were used and the performance of SSMF and non-zero dispersion shifted fibre (NZDSF, D = 2 ps/nm/km) fibres were compared. The advantage of NZDSF is that, while the inter-channel FWM is suppressed due to the non-zero dispersion, the dispersive pulse broadening is much lower than in SSMF. The dispersion length, defined as the length over which the pulse broadens by a factor of $\sqrt{2}$, is 1.3 km in SSMF for 9 ps pulses compared to 11 km for NZDSF. Single channel soliton transmission over the dispersion-shifted fibre was simulated with precompensation of –24 ps/nm to optimise the pulse chirp and a residual dispersion of 3 ps/nm per span, giving an average dispersion of 0.05 ps/nm/km. Eye opening of 72 % after 40 spans was achieved, and the performance was limited by soliton-soliton interaction, due to intra-channel XPM.

In contrast, the single channel transmission distance through the SSMF link was limited to 13 spans for <3 dB eye closure. The optimum performance was obtained with –200 ps/nm precompensation and zero cumulative dispersion over the link. The dominant limiting effect was found to be FWM between dispersion-broadened neighbouring pulses. The blue-shifted trailing and red-shifted leading edges of the pulses overlap, and the small frequency difference between them results in similar propagation velocities and hence high FWM efficiency. When the DCF recompresses the pulses, the FWM products remain in the 'zero' time slots, in the form of 'shadow pulses'. This is observed in the eye diagram of the signal as an increased 'zero' level (Fig. 3b). Additional contribution to the eye closure is caused by the power depletion of the pulses contributing to the FWM, reducing the amplitude of the 'one' level.

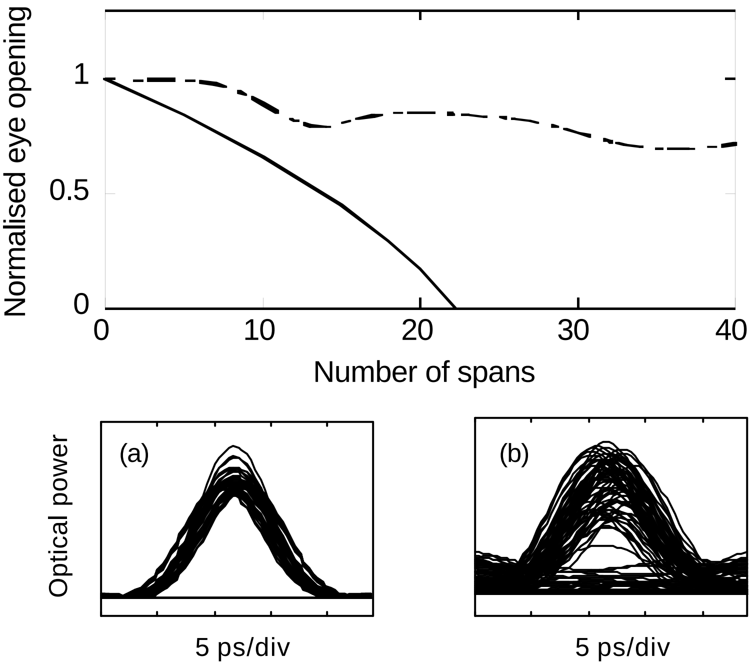

Figure 3: Eye opening for single channel 40 Gbit/s transmission over NZ-DSF (– –) and SSMF (¾). Eye diagrams for (a) NZ-DSF (25 spans) and (b) SSMF transmission (20 spans).

4. Improving the performance of 40 Gbit/s-based WDM transmission

The results of the previous section demonstrate that techniques to extend the transmission distance are required to realise all-optical networking of STM-256 channels over the installed standard fibre. One method is to optimise the signal shape before transmission to minimise the nonlinear interaction of neighbouring pulses. This can be achieved by optimally prechirping the pulses to achieve minimum width averaged over the nonlinear length of the system. This is achieved for an N span link by using a value of precompensation given by [3]

$$D_{pre} = \frac{-D_{SSMF}}{a} \ln\left(\frac{2}{1+e^{-aL}}\right) - \frac{ND_{res}}{2} \qquad (1)$$

where D_{SSMF} and a are the dispersion and loss of the transmission fibre, L is the span length and D_{res} is the residual dispersion per span. Simulations of a single channel 12 span system with D_{res} = 0 ps/nm were carried out, and the calculated average intra-channel FWM power (normalised to the signal peak power) and timing jitter are plotted in Fig. 4 for a range of precompensation values D_{pre}. The values minimising distortion due to FWM and XPM are close to the value D_{pre} = -220 ps given by (1). Simulations confirming (1) for a range of values of D_{res} are reported in [3]. Finally, multi-channel 40 Gbit/s transmission over the 12 span link was investigated to assess the impact of inter-channel XPM. Five channel transmission was simulated with 150 GHz channel spacing, giving a spectral efficiency of 0.26 bit/s/Hz. Fig. 4c shows the increased timing jitter of the central channel due to nonlinear interactions with neighbouring channels. Unlike with 10 Gbit/s WDM soliton transmission, the timing jitter increase due to the presence of the neighbouring channels is only a factor of 0.8. This can be explained by the increased signal velocity mismatch, due to the wider channel spacing, and the increased pulse broadening in the interfering channels, reducing the XPM distortion.

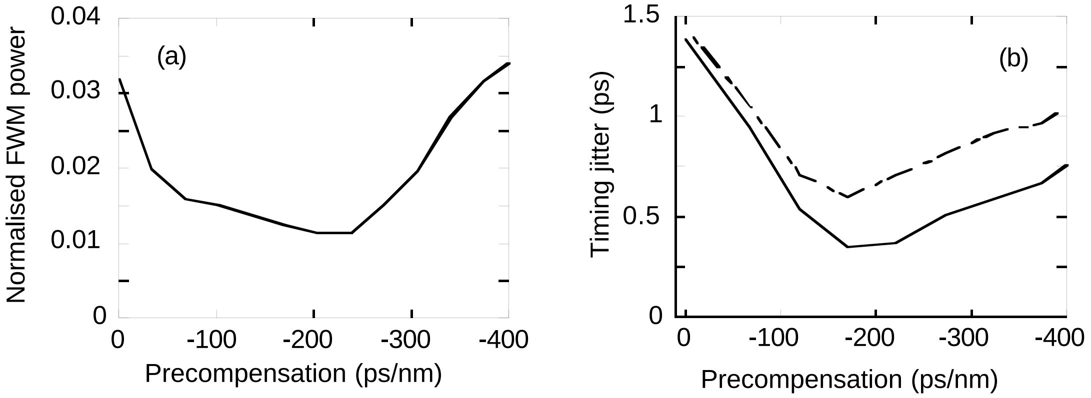

Figure 4: 40 Gbit/s transmission over 12 spans of SSMF: (a) Average FWM shadow pulse power, normalised to signal peak power, (b) Timing jitter for single channel (¾) and WDM transmission with 150 GHz channel spacing (- -).

5. Summary

The transmission performance of 10- and 40-Gbit/s-based WDM signals was assessed for links employing standard single mode and non-zero dispersion shifted fibres. Optimum performance with a +5.7 dBm single channel 10 Gbit/s signal over SSMF was achieved using an average dispersion of 0.57 ps/nm/km. With zero average dispersion, SPM distortion resulted in an eye closure of >3 dB after 40 spans. For WDM transmission with 50 GHz channel spacing, XPM-induced timing jitter resulted in 3 dB eye closure after only 12 spans. A NZ-DSF-based link with an average dispersion of 0.05 ps/nm/km gave the best results for single channel 40 Gbit/s transmission, with an eye closure of 72 % after 40 spans resulting from soliton-soliton interaction due to intra-channel XPM. The performance of SSMF links was shown to be limited by intra-channel four wave mixing, and a technique to minimise FWM and XPM by optimising the pulse shape using precompensation was demonstrated.

References

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