Nonlinear Intra-Channel Effects in Dispersion-Managed Data Transmission Systems

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Abstract: It is shown that nonlinear intra-channel effects imposed a limit to the transmission capacity of pulse-overlapped dispersion-managed systems. However, using pre and post-compensation techniques, thousand of kilometers at 40 Gbit/s under standard step-index fibers with 100 km amplifiers span are achievable.

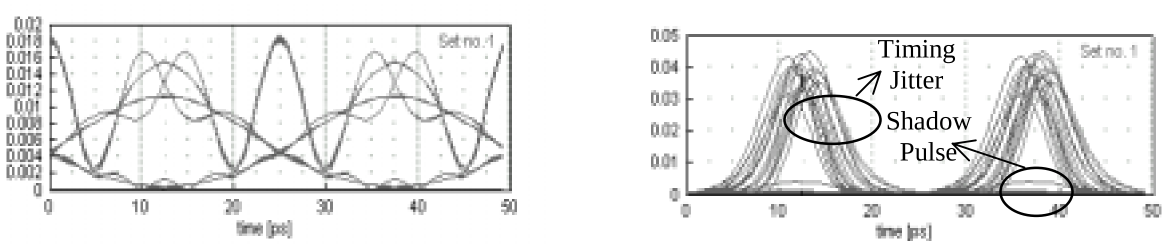
OCIS codes: (060.2330) Fiber optics communications; (060.5530) Pulse propagation and solitons

1. Introduction

As today's optical communication systems evolve to higher bit rates and distances, chromatic dispersion and nonlinear effects in the optical fibers present serious limitations. The dispersion and nonlinear length are frequently used as merit figures to compare the relevance of both effects [1]. In this ways it is possible to define three operation regions. One in which the dispersion length is much greater than the nonlinear length, another in which both lengths are of the same order and finally one in which the dispersion length is smaller than the nonlinear length. Several fiber based nonlinear optical devices operate in the first region, taking advantage of the nonlinear behavior of the optical fiber to process the signal. In the second region, the soliton region, it is possible to propagate short optical pulses without shape distortion, using the nonlinear Kerr effect to balance the chromatic dispersion. However for high bit rates, 40 Gbit/s and above, this regime it is not practical in standard step-index fibers (G.652) due to the high chromatic dispersion in the wavelength window around 1.5 μm. In fact, to get stable transmission and to satisfy the conditions for average soliton transmission, amplifier spacing is required to be shorter than the soliton period, which, for high bit rates in G.652 fibers, is of the order of few kilometers. This is a very strong limitation for practical implementations of high-speed optical soliton systems on standard single mode fibers. The last region, where the dispersion length is much smaller than the nonlinear length, is the more promising for transmission at 40 Gbit/s and above over G.652 fibers. In this region the dispersion plays the main role, however by using appropriate dispersion management techniques, usually by means of dispersion compensation fiber sections or by chirped fiber Bragg grating devices, it is possible to extend the transmission distance well behind the dispersion length [2].

2. Pulse-Overlapped Dispersion-Managed Data Transmission

In figure 1, we present two eye diagrams; the first, figure 1a, was obtained after 2 km of a G.652 fiber for a 40 Gbit/s system without dispersion compensation. The second, figure 1b, was obtained, after 1 200 km, for the same system, using a chirped fiber Bragg grating before each amplifier, in order to completely compensated the chromatic dispersion. In both cases a bit-error rate (BER) better than 10^{-9} was achieved.



(a) (b)

Figure 1 – For a 40 Gbit/s system, it was possible to extend the transmission distance from 2 km (a) to 1 200 km (b) using a completely chromatic dispersion compensation scheme, based on chirped fibre Bragg grating devices.

It is obvious from figure 1, that with a proper dispersion compensation technique it is possible to upgrade the actual point-to-point terrestrial G.652 fibre based systems to 40 Gbit/s per channel, without any electro-optic generation stage, as long as the total optical length remains in the order of hundreds of kilometres. However, for long or higher-bit rates systems the timing jitter and the shadow pulses, seen in figure 1b, are important limitation factors. In this work we discuss the origin of this effects and we show that with a proper compensation scheme that takes into account the intra-channel nonlinear effects, it is possible to extend the total system length from 1 200 km to 2 600 km.

3. Intra-Channel Nonlinear Effects

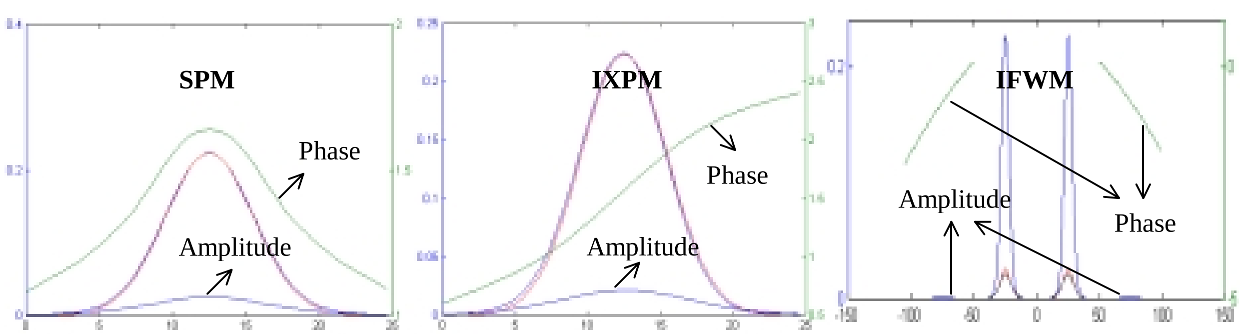
In the system previously analysed, see figure 1, all the linear effects are fully compensated; the attenuation is compensated by the optical amplifiers and the dispersion by the chirped fibre Bragg gratings. So, the degradation effects seen in figure 1b should be due to the Kerr nonlinear effect. If we take into account that, in this system, the dispersion length is 500 m and the nonlinear length 10 km, we can considerer the nonlinearities as a small perturbation and we can write the propagation solution of the nonlinear Schrödinger equation as the superposition of a linear wave with a nonlinear perturbation, $u = u_0+\Delta u$, where u_0 is the linear solution and Δu it is the nonlinear perturbation. Doing that we obtain the following equation for the nonlinear perturbation around u_0.

$$i \cdot \frac{\partial \Delta u}{\partial z} - \frac{\beta_2}{2} \cdot \frac{\partial^2 \Delta u}{\partial t^2} + \gamma \cdot |u_0|^2 \cdot u_0 = 0 \qquad (1)$$

If we consider the propagation of two pulses, $u_0=u_1+u_2$, we end up with the following equation

$$\begin{aligned} \frac{\partial \Delta u}{\partial z} + i \cdot \frac{\beta_2}{2} \cdot \frac{\partial^2 \Delta u}{\partial t^2} &= i \cdot \gamma \cdot \left\{ |u_1|^2 \cdot u_1 + |u_2|^2 \cdot u_2 \right\} \longrightarrow \text{SPM} \\ &+ i \cdot \gamma \cdot \left\{ 2 \cdot |u_2|^2 \cdot u_1 + 2 \cdot |u_1|^2 \cdot u_2 \right\} \longrightarrow \text{IXPM} \\ &+ i \cdot \gamma \cdot \left\{ u_1 \cdot u_2^* \cdot u_1 + u_2 \cdot u_1^* \cdot u_2 \right\} \longrightarrow \text{IFWM} \qquad (2) \end{aligned}$$

In equation (2) we have identified the terms that originate the pulse self-phase modulation (SPM), the intra-channel cross-phase modulation (IXPM) and the intra-channel four-wave mixing (IFWM). We also should point out that in systems, where the pulses remain in its time slot during the propagation $u_1 \cdot u_2 \approx 0$, and the terms related with IXPM and IFWM vanish, but this is not the case in here, due to the strong pulse broadening induced by chromatic dispersion during propagation. An interesting aspect of equation (2) is that it allows determination of the nonlinear perturbation, considering individually each nonlinear effect. We should point out that equation (2) is a linear equation for Δu.



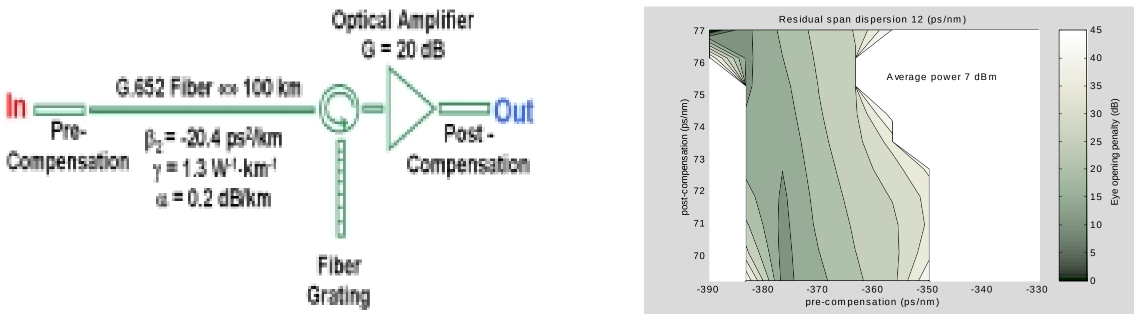
(a) (b) (c)

Figure 2 – Nonlinear perturbation induced considering individually each nonlinear effect.

The results obtained, after solving equation (2) considering individually each nonlinear effect, show that the perturbation induced by SPM has a symmetrical phase and it is centred with the pulse, see figure 2a, its effect is a small pulse shape distortion. In contrast, the IXPM induced perturbation has a non-symetrical phase, see figure 2b, which originates the induced timing jitter. The IFWM arise from the cross product between the two waves and it gives rise to a shadow pulses, see figure 2c. Due to the strong temporal broadening suffered by the pulses the IFWM it can be efficient between tens of pulses [3, 4].

4. Compensation Techniques

In order to compensate both the dispersion and the nonlinear intra-channel effects we use the configuration presented in figure 3a. Although, in figure 3a, the post-compensation fibre appears after the optical amplifier it is not present in all optical amplifier stages. It is only present before the optical receiver. The same happens with the pre-compensation section that it is only present after the optical pulse source. In order to obtain an optimum operation point we tried several values for the chirp, induced by the pre and post compensation fibres, and for the residual dispersion in the span, see figure 3b.



(a) (b)

Figure 3 – Compensation scheme for both the chromatic dispersion and the nonlinear intra-channel effects (a). Eye opening penalty obtained for different chirp values induced by the pre and post compensation fibre (b).

As shown in figure 4, with a pre-compensation of 377 ps/nm, a post-compensation of 70 ps/nm and a residual span dispersion of 12 ps/nm, we were able to propagate a 40 Gbit/s optical signal over 2 600 km of G.652 fibre, with a separation between amplifiers of 100 km and with a BER better than 10^{-9}.

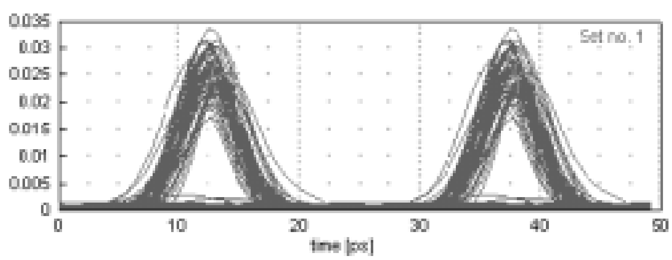


Figure 4 – Eye diagram, after 2 600 km of G.652 fibre, for a 40 Gbit/s signal with dispersion and intra-channel nonlinearity compensation.

Acknowledgement: The financial support from European Commission (IST/ ATLAS project) and Portugal Telecom Inovação (IT/P115 – Camada WDM project) is grateful acknowledge.

5. References

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