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Intra-Channel Nonlinear Effects in Dispersion Compensated DWDM Optical Networks

A. Nolasco Pinto [1,2], Paulo Almeida [1] and J. Ferreira da Rocha [1,2]

[1] Institute of Telecommunications, Aveiro Pole, [2] University of Aveiro, Campus de Santiago, 3810-193 Aveiro, Portugal, Phone: +351 234 377918; Fax: +351 234 377901; E-Mail: anp@det.ua.pt

Nonlinear effects in optical fibers are related to anharmonic motion of silica bound electrons under the influence of the light [1]. Even though silica is intrinsically not a highly nonlinear material, the waveguide geometry that confines light to a small cross section over long fiber lengths makes the waveguide behavior marked dependent of the optical field intensity. As today's optical telecommunication systems evolve to higher bit rates and distances increasing signal power is required, to keep the necessary signal-to-noise ratio, making the fiber nonlinear behavior the main hurdle to overcome, in order to send short optical pulses at a very high repetition rates over long distances, without considerable pulse distortion or timing uncertainty. In this work we consider a generic single channel of a DWDM optical network, where losses and dispersion are fully compensated. In this scenario the only limitations to the transmission capacity of our optical channel are the noise, the channel bandwidth and the fiber nonlinear effects. The limitations imposed by channel bandwidth and noise were addressed in a remarkable work published by Claude Shannon in 1948 [2] and represent a fundamental limit. However, before being able to approach the Shannon limit we must make the signal robust against the fiber nonlinear behavior. The main topic of this work is the study of effective nonlinear compensation techniques that allow the transmission, over standard step-index fibers (G.652), of 40 and 80 Gbit/s channels over distances greater than thousands of kilometers using less than 100 GHz of optical bandwidth in DWDM networks. An interesting solution for dealing simultaneously with the chromatic dispersion and fiber nonlinearities was present by the soliton systems [3]. However, for high bit rates, which mean very short optical pulses, in system where the local chromatic dispersion and attenuation are high, like in standard step-index fibers, is not simple to maintain stable solitons with hundreds of kilometers between optical amplifiers. Yet recent works have shown that is possible to compensate completely the fiber chromatic dispersion by cascading in the optical path devices that induce a frequency dependent delay with opposite signal to the one induced by the chromatic dispersion. Nevertheless the nonlinear induced signal distortions represent a serious limitation to the total optical length that the signal can travel before being electrically regenerated. In figure 1, we considered an ideal noiseless transmission system where all linear effects are full compensated. As can be seen, the fiber nonlinear behavior impose a maximum distance of 1200 km for a 40 Gbit/s optical signal, over G.652 fibers, before the need of being electrically regenerate, considering a 10^{-9} error rate floor. From figure 1 is clear that the limitations caused by nonlinear transmission takes several forms: one is pulse distortion, other is timing and amplitude jitter and finally is also seen in figure 1 some energy in 'zeros' that was transferred from neighbor pulses. These same results were observed in laboratorial trials [4-5] and the maximum attainable distance in [5] was 720 km using a span between amplifiers of 120 km. In [4] the use of pre-chirped pulses for fiber nonlinear behavior compensation was purpose and in [6] an expression for the pre-chirp value appropriate to maintain a single pulse stable transmission both in the time and frequency domain was derived. In [7] the timing jitter was related with the nonlinear pulse to pulse interaction seen in classical soliton systems and the shadow pulses that appears at the 'zeros' was described by a special case of four-wave mixing between different spectral components in a single channel. An analytical treatment of the four-wave mixing process was presented in [8] and [9]. In this work, after making clear the relations between the fiber nonlinear behavior and the several forms of signal distortions seen in figure 1, we propose a suitable configuration scheme, for maximizing the distance that the signal can travel in the optical domain and that allow the deployment of multiple wavelength high-speed all optical networks with switching functions. In order to analyze in detail the nonlinear effects in this kind of systems we derived a mathematical description for the propagation of a strongly dispersed field in a single mode optical fiber, starting from the modified nonlinear Schrödinger equation. Assuming a solution around the linear one we obtain (1), for the propagation of two pulses U_1 and U_2, where ΔU is the perturbation induced in the linear solution due to the fiber nonlinear behavior. The first two terms in the right side of equation (1) are the usual SPM terms, the second two are responsible for the IXPM and the last two terms are

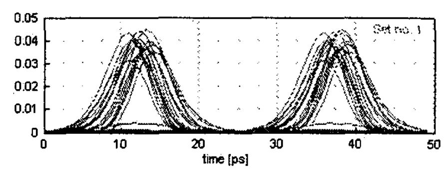

Figure 1 - Eye diagram after transmission at 40 Gbit/s over 1200 km of G.652 fiber, using optical amplifiers separated by 100 km and chirped Bragg grating devices for fully dispersion compensation.

the cause of the IFWM. It is also important to point out that in systems, where the pulses remain in its time slot during the propagation $U_1 \cdot U_2 \approx 0$, which means that the terms related with IXPM and IFWM vanish, but this is not the case in here, due to the strong pulse broadening induced by high local chromatic dispersion. An interesting aspect of equation (1) is that it allows determination of the induced nonlinear perturbation, considering individually each nonlinear effect. The results show, see figure 2, that the perturbation induced by SPM has a symmetrical phase and is centered with the linear pulse; its effect is a small pulse shape distortion. In contrast, the IXPM induced perturbation has a non-symmetrical phase, which induces timing jitter. As the origin of this jitter is the pulses tails superposition this gives arise to non-gaussian timing jitter, as in the soliton systems [10]. The IFWM is the result of the cross product between the two waves and it gives rises to a shadow pulse in the 'zeros' and amplitude fluctuations in the 'ones'. The use of chirped pulses can be an effective way of nonlinear compensation, because as soon as the chirped pulses are launched into a fiber with a high value of dispersion its energy is spread for multiple times slots and in terms of power the signal is average making its almost flat. As the problem is the transmission medium response for different levels of signal intensity this signal is extremely robust

$$\frac{\partial \Delta U}{\partial z} + i \cdot \frac{\beta_2}{2} \cdot \frac{\partial^2 \Delta U}{\partial t^2} + \frac{\alpha}{2} \cdot \Delta U = i \cdot \gamma \cdot \left\{ |U_1|^2 \cdot U_1 + |U_2|^2 \cdot U_2 \right\} + i \cdot \gamma \cdot \left\{ 2 \cdot |U_2|^2 \cdot U_1 + 2 \cdot |U_1|^2 \cdot U_2 \right\} + i \cdot \gamma \cdot \left\{ U_1 \cdot U_2^* \cdot U_1 + U_2 \cdot U_1^* \cdot U_2 \right\} \quad (1)$$

against fiber nonlinear behavior. As we observed previously the IFWM is the more critical effect in terms of limiting the maximum attainable optical distance, however this process is quite sensitive to the phase mismatch between the involved signals and in this case the noise added to the signal by the optical amplifiers reduce its efficiency. In the scheme that we proposed the dispersion compensation devices compensate all the previously accumulated dispersion and the post-chirp value induced before the optical receiver is symmetrical to the pre-chirp induced at the optical source. Other research groups claims the advantages of leaving some residual dispersion in order to obtain a better nonlinear compensation effect. We agree with that for a point-to-point connection but that does not seem to be a suitable solution in a mesh optical network with optical switching functions where the signal can travel from different paths before reaching the receiver. In this scenario is difficult to know which is the amount of residual dispersion accumulated during the transmission that needs to be compensated at the receiver, although the value of the post-chirp is always the symmetrical of the pre-chirp value and is independent of the optical path.

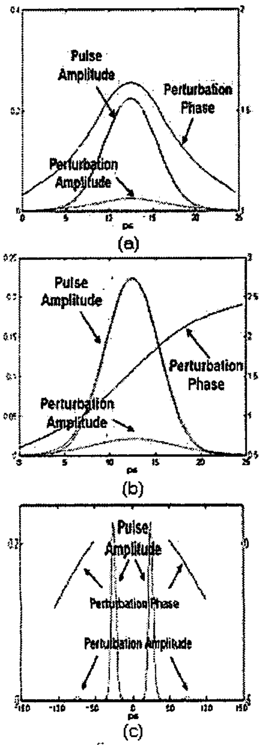

Fig. 2 - (a)- SPM; (b)- IXPM; (c)- IFWM.

Acknowledgments: This work was partially supported by Portugal Telecom Inovação (O-NODE project).

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