Paper

Impact of nonlinear optical phenomena on dense wavelength division multiplexed transmission in fibre telecommunication systems

Waldemar Szczęsny and Marian Marciniak

Abstract — In the paper results of analysis of nonlinear phenomena in optical fibres: Self-Phase Modulation, Cross-Phase Modulation, Four-Wave Mixing and Stimulated Raman Scattering and their influence on Dense-Wavelength Division Multiplexed system performance are reported. Different non-uniform optical channel allocation schemes based on ITU Recommendation G.692 100 GHz frequency grid are compared with uniform channel distribution. The level of nonlinear cross-talk is determined for different levels of the total optical power. As an example a 10 Gbit/s D-WDM dispersion-shifted single mode fibre link with dispersion-compensating fibres is envisaged. The directions for optimization of the system design in view of actual international standardization trends are pointed out.

Keywords — optical communications, WDM systems, nonlinear transmission.

Introduction

Dispersion-shifted fibres G.653 allow for better transmission parameters in single-channel transmission links due to very small dispersion value in third telecommunications window corresponding to 1.55 μm optical wavelength. However, in Wavelength Division Multiplexed (WDM) systems very small value of dispersion may cause a significant degradation of the systems due to nonlinear optical effects resulting from optical nonlinearity of silica glass. A high optical power level available with modern laser sources causes nonlinear interaction in fibres strongly efficient.

In WDM systems a nonlinear interplay between many different spectral components of the aggregate signal cases interchannel cross-talk. The nonlinear phenomena involved are: Self-Phase Modulation (SPM), Cross-Phase Modulation (XPM), Four-Wave Mixing (FWM) and Stimulated Raman Scattering (SRS).

In dispersion-shifted fibres the interchange of optical power between different propagating optical frequencies corresponding to the third telecommunication window is much stronger than in standard single mode fibres (G.652). The main causes of that are:

1. The effective area [2] of G.653 fibres are smaller then in G.652 fibres, a given power level results in a higher intensity in G.653 fibres than in G.652 fibres.

2. The low dispersion in G.653 fibres can results in low walk-off between bits in the different channels of WDM systems, also known as a phase matching condition. This means that a single 1 in the lowest wavelength channel will have a fair chance for seeing 1 bits in all the other channels throughout the part of the fibre, where the nonlinear interaction takes place.

Signal degradation caused by Stimulated Raman Scattering (SRS)

In the WDM systems SRS manifests itself as a depletion of the ”1” level in the lower wavelength channel, which depends on the signal in the higher wavelength, and a gain in the higher wavelength channel, that depends on the signal in lower wavelength channel.

The depletion introduced by SRS has unfortunate characteristic:

The depletion of a given ”1” is dependent on the signals that are other channels. This means that „drops” caused by SRS can occur on the timescale of an individual bit, which is much faster than the response time of the threshold setting in the receiver. The depth and the frequency of this drops will dictate the BER for the WDM system that is limited by SRS [1].

Phase modulation

Self-phase modulation (SPM) is the effect whereby the modulated optical signal induces a modulation in the fibres refractive index. SPM leads to considerable spectral broadening of propagating pulses. In a WDM system also a Cross-Phase Modulation (XPM) occurs. The total phase shift depends on the power in all channels and varies from bit to bit depending on the bit pattern of the neighbouring channels.

Four-Wave Mixing (FWM)

FWM generated a new wave at the frequency $f_{ijk} = f_i + f_j - f_k$, whenever three waves at frequencies f_i, f_j, and f_k co-propagate inside the fibre. For N channel system i, j and k can vary from 1 to N. In the case of equally spaced channels the new frequencies coincide with the existing frequencies.

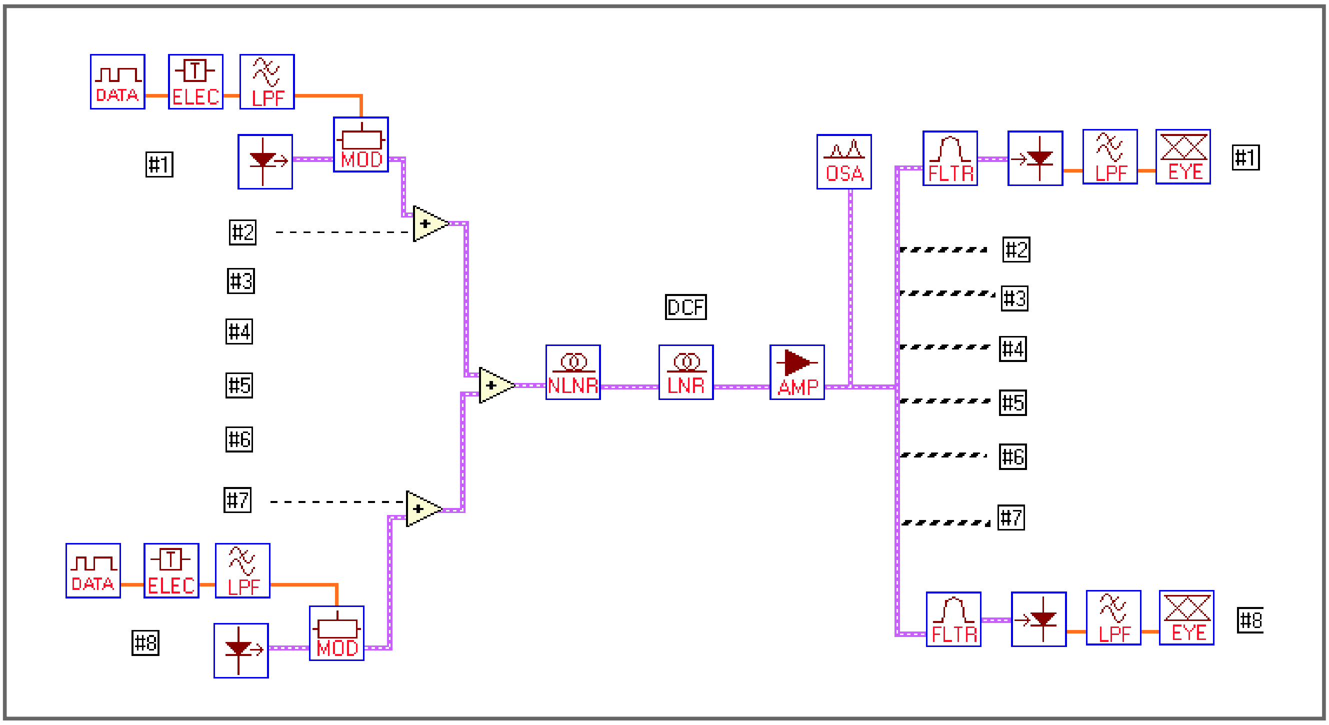

Fig. 1. Architecture of the 8-channel WDM system analysed

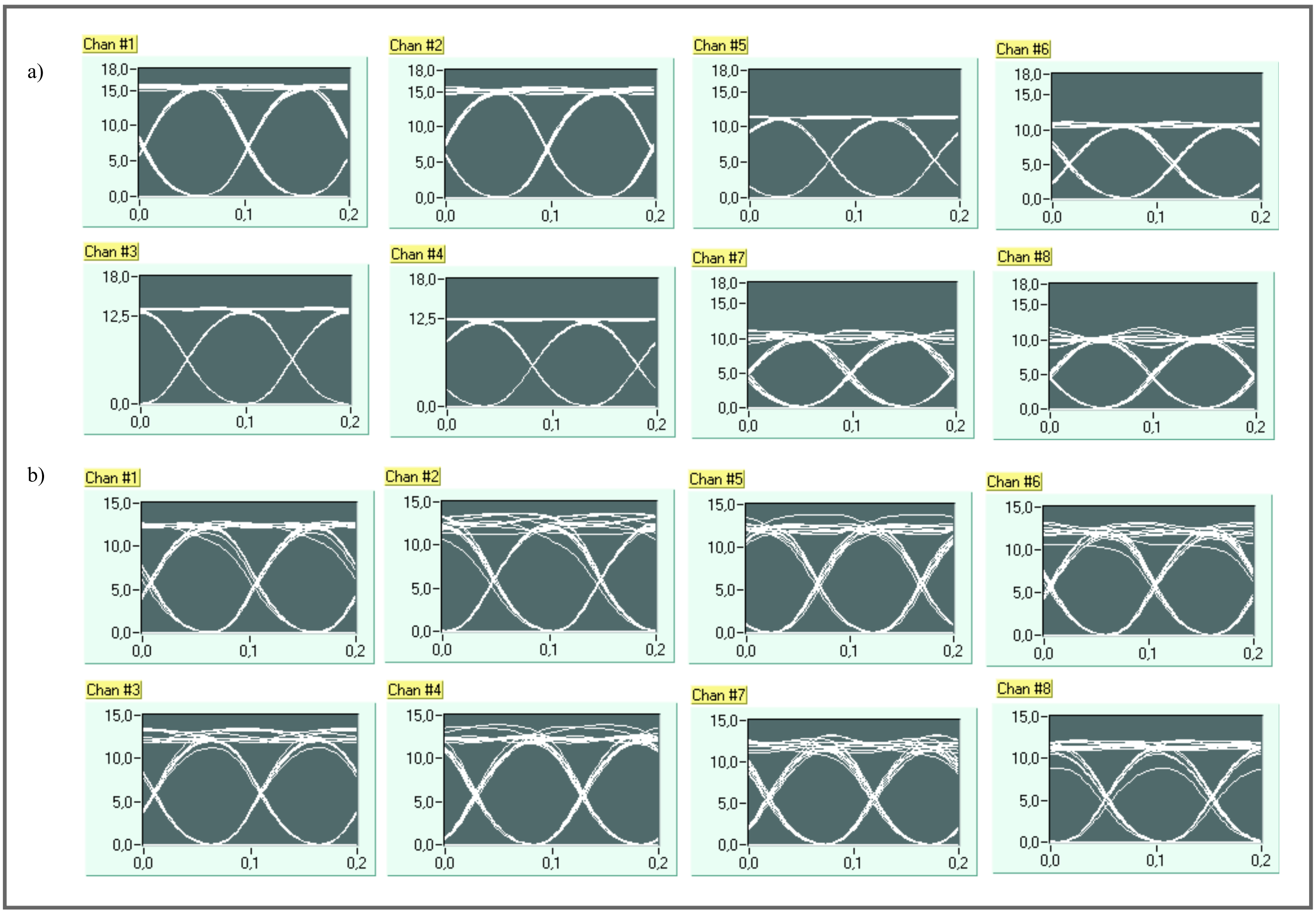

Fig. 2. The eye diagrams of the detected signal for equidistant channel spacing (a) and non-equidistant channel spacing (b)

Table 1
Non-equidistant frequency allocation schemes used in the calculations

Scheme	Channel index							
	0	1	2	3	4	5	6	7
A	196.1	196.0	195.7	195.2	194.6	193.9	192.9	192.7
B	196.1	195.9	195.5	194.5	194.2	193.4	192.7	192.2
C	196.1	195.8	195.1	193.9	193.7	193.1	192.6	192.2
D	196.1	195.5	194.8	194.0	193.1	192.1	190.9	189.8
E	196.1	196.0	195.9	195.8	195.7	195.6	195.5	195,4

Description of the analysed system

Propagation of the field in the X-polarization state in a nonlinear fibre is modelled using the following nonlinear partial differential equation [8]

$$\frac{\partial A_x}{\partial z} - \frac{i}{2}\beta_2\frac{\partial^2 A_x}{\partial T^2} - \frac{1}{6}\beta_3\frac{\partial^2 A_x}{\partial T^2} + \frac{\alpha}{2}A_x = -i\gamma\left[|A_x|^2 A_x - T_R A_x\frac{\partial^2 |A_x|^2}{\partial T^2}\right], \qquad (1)$$

where $A_x(z,T)$ is the slowly varying field envelope and β_2, β_3, α and γ are related to the dispersion, dispersion slope, loss and nonlinearity of the fibre. Equation (1) is solved using the split step Fourier method [8]. The algorithm uses an adaptive step-size [11].

The nonlinear coefficient γ for the fibre is defined as [8]

$$\gamma = \frac{n_2 \omega}{c A_{eff}} \, .$$

Here, n_2 is the Kerr nonlinear index coefficient, ω is the angular optical frequency, A_{eff} is the effective core area, and c is the light velocity in vacuum. The coefficient γ accounts for the effects of SPM [9], XPM [10] and FWM [11] effects. The simulations have been carried out for an 8-channel STM-64 transmission system, with 10 Gbit/s single channel data flow, what means an 80 Gbit/s aggregate transmission speed. The system is shown in Fig. 1 and corresponds to Synchronous Digital Hierarchy (SDH) standards. The inter-channel data synchronization has been obtained as identical 32-bit pseudo-random sequence in each of WDM channels. A de-correlation of the data has been achieved by imposing time delays for varying from channel to channel. At the detector side of the system optical band-pass filters with FWHM 40 GHz bandwidth and different transmission characteristics have been used in order to de-multiplex optical channels. The dispersion-shifted fibre is compatible with ITU-T G.653 standard. The transmission span is 120 km. A dispersion-compensating fibre with negative dispersion value is introduced at the end of the transmission span. The optical gain in Erbium-Doped Fibre Amplifiers has been chosen in a way to compensate for total attenuation of the link. The optical frequency distribution has been based on the 100 GHz (~0.8 nm) ITU-T G.692 Recommendation grid. The reference frequency for the first WDM channel is 196.1 THz (1552.52 nm). The calculations have been performed for a non-equidistant frequency allocation schemes A, B, C defined in Table 1 that allow for elimination of FWM generated frequencies, according to G.692 Recommendation. A scheme E has been added which corresponds to 8-channel WDM system with a 100 GHz equidistant grid. A total 8-channel optical power at the transmitter side is 17 dBm, this corresponds to laser peak-power of 12.5 mW and 6.25 mW mean-power for an NRZ code [12].

Results

Table 2 shows optical powers in transmitted channels.

The scheme A experiences minimum power losses caused by nonlinear interaction and this scheme has been analysed in detail. The results are shown in Table 3. The results indicate that Stimulated Raman Scattering causes the largest amount of inter-channel power transfer. Figure 2 shows the eye diagrams of the detected signal for equidistant channel spacing (Fig. 2a) and non-equidistant channel spacing (Fig. 2b). The eye opening is determined by inter-channel frequency gap and it is wider for non-equidistant channel spacing. However, the cross-talk level is as low as -28 dB. Figure 3 shows 8-channel optical spectrum for all channels transmitting (Fig. 3a) and with channel number 7 turned off (Fig. 3b). The absence of optical power in channel 7 results in an increase of optical power in neighbouring channels 6 and 8 what is a result of XPM, and a decrease of FWM

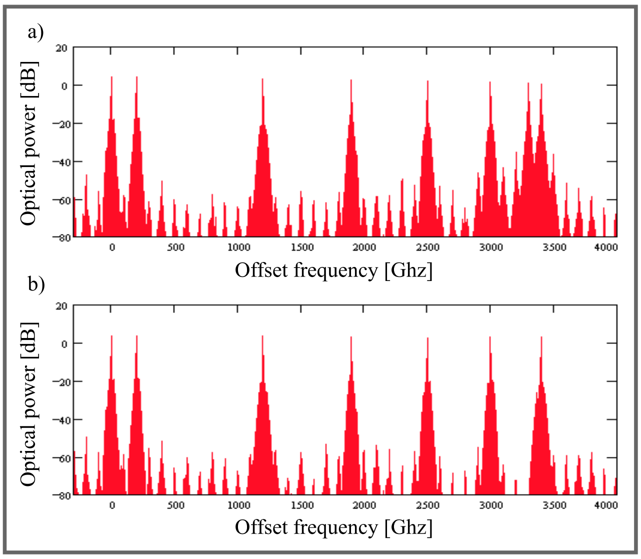

Fig. 3. 8-channel optical spectrum for all channels transmitting (a) and with channel number 7 turned off (b)

Table 2
Optical power in transmitted channels for different frequency allocation schemes

Scheme	Total optical bandwidth [mm]	Mean optical power per channel [mV]								Total optical losses in 8-th channel [dB]
		1	2	3	4	5	6	7	8	
A	28.2	7.56	7.38	6.54	5.99	5.56	5.22	5.01	4.96	1.00
B	31.2	7.71	7.26	6.67	6.03	5.81	5.13	4.88	4.77	1.17
C	31.2	7.48	7.12	6.71	6.21	6.07	5.24	4.79	4.63	1.31

Table 3
Optical power in transmitted channels for allocation scheme A

Nonlinear phenomena taken into account	Mean optical power per channel [mV]								Maximum power losses in 8-th channel [dB]
	1	2	3	4	5	6	7	8	
SRS, FWM, SPM, XPM	7.56	7.38	6.54	5.99	5.56	5.22	5.01	4.96	1.00
Without SRS	6.03	6.03	6.04	6.03	6.03	6.02	6.00	6.01	0.17
SRS only									0.83
Without losses	6.25								

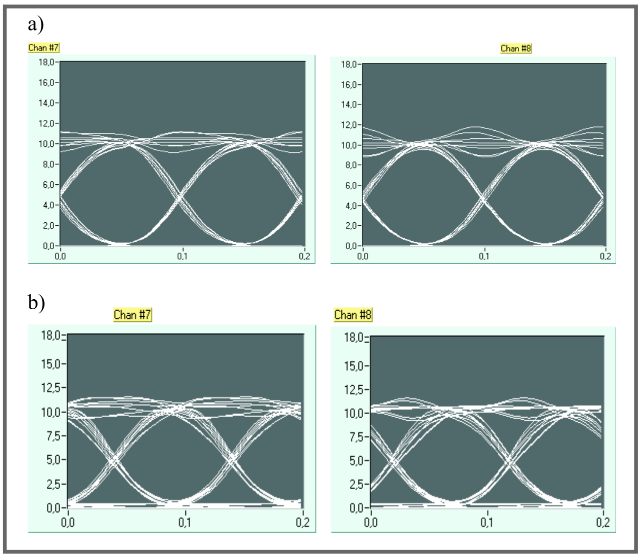

Fig. 4. The eye diagrams of the received signal A distortion of the signal depends on data correlation between channels

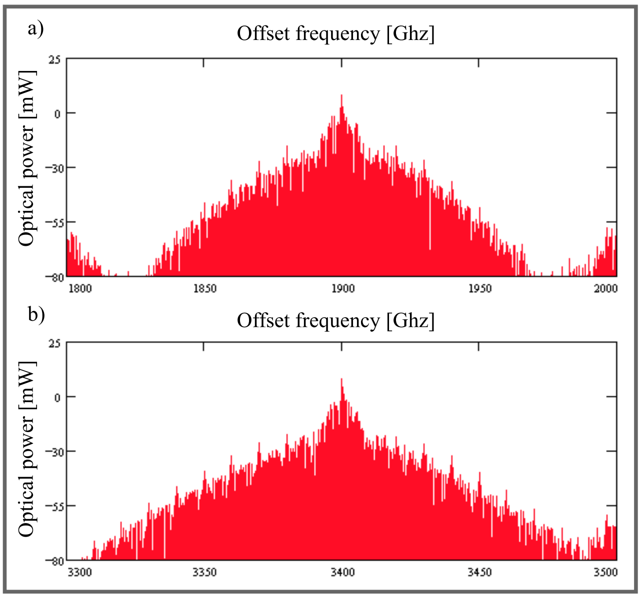

Fig. 5. The XPM optical spectrum degradation for two channels: with minimal (a) and maximal (b) distortion

components. Figure 4 shows eye diagrams of the received signal. A distortion of the signal depends on data correlation between channels, resulting mainly from XPM. Figure 5 shows the XPM optical spectrum degradation for two channels: with minimal and maximal distortion. Figure 6 shows optical spectra for Gaussian optical filter (Fig. 6a) and Lorentzian optical filter (Fig. 6b).

Conclusion

An 8-channel WDM 120 km dispersion shifted fibre transmission system based on ITU G.692 Recommendation frequency grid has been investigated for different frequency allocation schemes in view of inter-channel nonlinear interactions. The results indicate that:

- The largest amount of optical cross-talk is caused by XPM.The cross-talk can be decreased when using an optical fibre with larger dispersion value (standard fibre or non-zero dispersion shifted fibre).
- Non-equidistant frequency allocation in the system results in large value of transmitted bandwidth, exceeding EDFA gain bandwidth.
- Systems with standard fibre and dispersion compensation are the most promising for WDM applications.

References

[1] G. P. Agrawal, *Fiber-optic communication systems*. New York: Wiley-Interscience Publication, 1992.

[2] Y. Namihira, „Relationship between nonlinear effective area and modefield diameter for dispersion shifted fibres”, *Electron. Lett.*, vol. 30, no. 3, pp. 262–264, 1994.

[3] ITU-T Rec. G.653, „Characteristics of a dispersion-shifted single-mode optical fibre cable”, 1993.

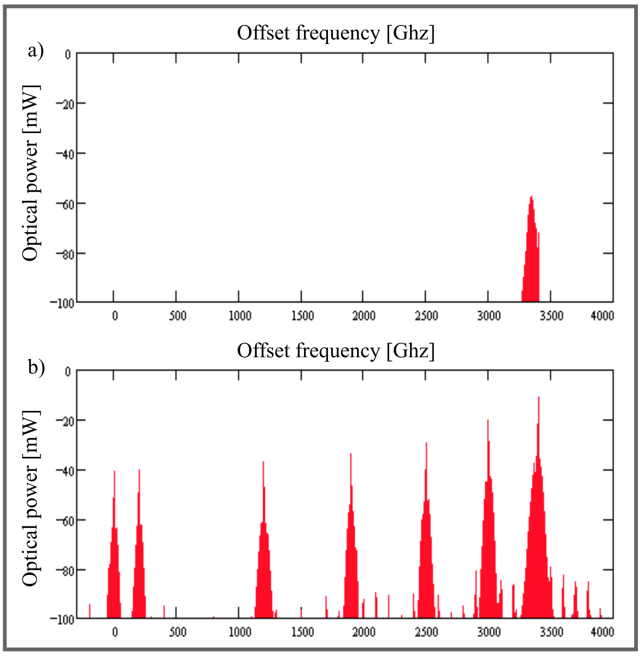

Fig. 6. The optical spectra for Gaussian optical filter (a) and Lorentzian optical filter (b)

[4] ITU-T Rec. G.957, „Optical interfaces for equipment and systems relating to the synchronous digital hierarchy”, 1995.

[5] ITU-T Rec. G.692, „Optical interfaces for multichannel systems with optical amplifiers”, 1997.

[6] ITU-T Rec. G.709, „Synchronous Multiplexing Structure”, 1993.

[7] ITU-T Study Group 15, Delayed Contribution D.170, Geneva, Feb. 9–20, 1998.

[8] G. P. Agrawal, *Nonlinear fiber optic*. Academic Press, 1989.

[9] D. Marcuse *et al.*, „Effect of fiber nonlinearity on long-distance transmission”, *J. Lightw. Technol.*, vol. 9, 1991.

[10] D. Marcuse *et al.*, „Dependence of cross-phase modulation on channel number in fiber WDM system”, *J. Lightw. Technol.*, vol. 12, 1994.

[11] R. W. Tkach *et al.*, „Four-photon mixing and high speed WDM system”, *J. Lightw. Technol.*, vol. 13, 1995.

[12] S. Pietrzyk *et al.*, „Power penalty caused by Stimulated Raman Scattering in WDM systems”, in *COST P2 Workshop on „Applications of Nonlinear Optical Phenomena*”, Limerick, Ireland, June 12–13, 1998.

Marian Marciniak,
National Institute of Telecommunications,
1 Szachowa Str., 04-894 Warsaw, Poland,
e-mail: M.Marciniak@itl.waw.pl

Waldemar Szczęsny,
National Institute of Telecommunications,
1 Szachowa Str., 04-894 Warsaw, Poland,
e-mail: W.Szczesny@itl.waw.pl