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SIGNAL IMPAIRMENTS SOURCES WITHIN HIGH SPEED OPTICAL TRANSMISSION

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Lucrarea prezintă rezultate produse de simulări şi experimente referitoare la distorsiuni nelineare într-un canal optic. Deoarece intensitatea optică în canal atinge valori de megawatt/cm², efectul Kerr distorsionează semnalul. Rotaţiile fazei, dispersia cromatică, dispersia modului de polarizare şi nelinearităţile fibrei deformează unda optică odată cu creşterea puterii. Procesele cuantice de interacţie electroni legaţi- undă optică condiţionează îmbunătăţirea factorului optic de zgomot de creşterea puterii optice, ceea ce poate conduce la distorsiuni nelineare ale semnalului. În consecinţă, performanţa unui sistem optic de transmisie este maximă la un anumit nivel al puterii, rezultat din compromisul între zgomotul optic şi nelinearităţile Kerr.

The paper presents computational and experimental results of nonlinear impairments within an optical channel. Due to high megawatt/cm² intensity, Kerr effect is causing signal distorsions. Phase rotations, cromatic dispersion, polarization mode dispersion and fiber nonlinearities result in different waveform distorsions that increase with signal power. Quantum processes ruling the interactions between bond electrons and optical field demand increasing optical power to improve the optical signal-to- noise ratio, therefore nonlinear impairments of the signal occur. Eventually, peak performances of the optical transmission take place at a certain signal power level, which represents a trade-off between optical amplifier noise and fiber Kerr nonlinearities.

Keywords: Kerr effect, optical signal-to-noise ratio, nonlinear distorsions, optical dispersion

Acronyms and Abreviations

(I)FWM	(Intrachannel) Four Wave Mixing
(I)XPM	(Intrachannel) Cross Phase Modulation
ASE	Amplified Spontaneous Emission
BER	Bit Error Ratio
CSRZ	Carrier-Suppressed Return to Zero
DB	Duo Binary
DPSK	Differential Phase Shift Keying
DQPSK	Differential Quadrature Phase Shift Keying

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FEC	Forward Error Correction
MLSE	Maximum Likelihood Sequence Estimation
mux/dmux	multiplexer/demultiplexer
NF	Noise Figure
NPN	Nonlinear Phase Noise
NRZ	Non Return to Zero
OADM	Optical Add/Drop Multiplexer
OOK	On/Off Keying
OSNR	Optical Signal to Noise Ratio
RZ	Return to Zero
SE	Spectral Efficiency
SPM	Self Phase Modulation
VSB	Vestigial SideBand
WDM	Wavelength Division Multiplexing

1. Introduction

Fiber optic transmission could suffer from both separate or cumulative effects of chromatic dispersion, polarization mode dispersion, optic filtering and fiber nonlinearities. Poor quality optical transmission might be described by the optical signal-to-noise ratio *OSNR* penalty which is defined as the difference between the *OSNR* delivered into the network and the required *OSNR* in the absence of impairments.

OSNR is defined as the ratio of the optical power to the amplified spontanous emission in the fiber:

$$OSNR = \frac{P}{2B_{ref}N_{ASE}} \tag{1}$$

where P is the average signal power, B_{ref} is an optical reference bandwidth (typically chosen 0.1nm at 1550nm) and N_{ASE} is the power spectral density of the amplified spontanous emission in each polarization.

The required *OSNR* is the minimum OSNR value claimed to achieve a certain transmission BER target.

Table 1 lists the required *OSNR* for a 10^{-3} BER target and a variety of modulation formats at 42.7 Gb/s transmission rate.

Table 1

Requested OSNR for modulation formats

	Requested *OSNR* (dB) at BER = 10^{-3}				
Modulation Format	Back-to-back	10 x OADM (0.4 b/s/Hz)	5 x OADM (0.8 b/s/Hz)	Chromatic Dispersion (ps/nm)	Differential Group Delay (ps/nm)
NRZ-OOK	15.9	18.2	-	54	8
50% RZ-OOK	14.4	15.8	-	48	10
67% CSRZ-OOK	14.9	14.2	-	42	11
DB	16.6	14.2	18.4	211(152)	6
VSB-NRZ-OOK	16.4	15.6	17.3	63(155)	6
VSB-CSRZ	14.8	14.7	16.7	51(154)	11
NRZ-DPSK	11.7	12.1	17.6	74(161)	10
50% RZ-DPSK	11.1	11.5	17.0	50(161)	10
NRZ-DQPSK	13.2	12.6	12.9	168(176)	20
50% RZ-DQPSK	12.2	12.0	12.0	161(186)	21

Multi-Gb/s optical communication FEC schemes generously improve the BER factor from 10^{-3} to less than 10^{-16}. The actual *OSNR* values could disagree to some extent from numbers within Table 1 due to optical and electronic hardware aspects involving different bit rates, drive waveforms, filters characteristics, modulator extinction ratios.

The delivered *OSNR* is the *OSNR* at the end of the transmission line. The delivered *OSNR* depends on the transmission line parameters and on the launched signal power. Its relation is:

$$OSNR_{delivered}(dB) = 10\lg\frac{1000}{h\nu B_{ref}} + P_{in} - NF - L_{sp} - 10\lg N \tag{2}$$

where N is the number of identical amplification sections, P_{in} (dBm) is the input power into the fiber, NF (dB) is the effective noise figure of a span, L_{sp} (dB) is the span loss.

In most cases, the *OSNR* penalty rapidly exceeds any increase in the impairment. Once the signal is corrupted by one transmission impairment, its immunity to other transmission impairments decreases. Therefore one should attempt to operate transmission at low individual impairment, typically less than 2dB per impairment.

The *OSNR* margin is the delivered *OSNR* – to - the required *OSNR* ratio and accomodates transmission system penalties. The total system margin is calculated by adding penalties from individual impairments, though penalties are not strictly additive, to qualify the worst case of simultaneous, yet unlikely occurance of impairments. In a statistical approach, the total penalty is the probability that the

OSNR margin drops down below a predetermined value and guarantees a maximum system failure probability.

2. Filter Concatenation

The third and fourth columns in Table 1 display required *OSNR* helpful values to chain 10 x OADMs, respectively 5 x OADMs in an interleaving polarization (featured by a small coherent crosstalk) single WDM channel. Depending on the modulation format, coherent WDM crosstalk could threaten the system, especially at 0.8 b/s/Hz spectral efficiency. Also, the numbers in Table 1 ignore the bandwidth narrowing resulting from a high SE (0.4 to 1.0 b/s/Hz) modulation format driven through multiple OADMs and long length nonlinear fiber.

3. Chromatic Dispersion

The fifth column in Table 1 shows out the accumulated chromatic dispersion resulted from a 2dB *OSNR* penalty at 42.7Gb/s, with no OADMs and mux/demux bandwidths of 85GHz. 40Gb/s modulation formats employ dispersion tolerances of around 50ps/nm, excepting a few spectrally narrow formats which furnish better dispersion tolerances. Dispersion tolerance depends on the waveforms and filters in the system. Numbers in brackets from the fifth column in Table 1 represent dispersion tolerances for a 5 OADMs at 0.8b/s/Hz SE. Filtering narrows the signal spectrum, hence the dispersion tolerance increases. However, a high dispersion tolerance tailored DB format sees a reduction in dispersion tolerance when tightly filtered. The dispersion tolerance decreases if fiber nonlinearities exist.

Digital signal processing on the reception side could increase the dispersion tolerance. The 10.7Gb/s MLSE algorithm enhances dispersion tolerance by a factor of up to 2.6 for NRZ-OOK. The amount the dispersion tolerance is increasing with depends on equalization techniques and modulation formats. For example, MLSE reception of a DB format improves dispersion tolerance 1.3 times. The use of coherent demodulation followed by digital signal processing should increase the dispersion tolerance though the complex electronic hardware raises up the costs. Chromatic dispersion follows a square law with bit rate, therefore a four-fold increase in bit rate results in a sixteen-fold reduction in dispersion tolerance. For example, if a signal tolerates 50ps/nm at 47.2Gb/s, it can travel longer than 50 km through a standard single mode fiber optics at 10.7Gb/s with the same *OSNR* penalty.

4. Polarization Mode Dispersion

The sixth column in Table 1 gives first order polarization mode dispersion tolerance of different modulation formats, assuming 1 dB *OSNR* penalty. Most of the modulation formats employ a 1 dB *OSNR* penalty if the differential group delay equals 30% to 40% from the symbol length with the RZ format more resilient to polarization mode dispersion than the NRZ format. The resilience to polarization mode dispersion depends on the waveform, filters and residual distorsions. The polarization mode dispersion tolerance varies linearly with symbol duration. Accordingly, DQPSK format has twice the tolerance of the DB format at the same bit rate. The first order polarization mode dispersion tolerance linearly decrease with the bit rate.

The stochastic nature of the polarization mode dispersion makes the principal polarization state and the differential group delay to change on timescale between milliseconds (acoustic vibrations) and months (temperature variations of burried fiber). Applying a certain *OSNR* margin to cover the worst case scenario of polarization mode dispersion induced impairments could run the system down due to hazardous occurance of high differential group delay. If the system did not meet outage demands, polarization mode dispersion compensation techniques would have to be delivered to each channel at the reception side, alternatively the modulation format tolerance would have to be increased by optical/electronic equalization techniques.

5. Fiber Nonlinearities

The fiber optics parameters contributing to signal distorsions from fundamental Kerr nonlinear interactions are fiber dispersion, nonlinear index, dispersion slope, and polarization mode dispersion.

The Table 2 exhibits nonlinear interactions within an optical transmission system.

The amount of each nonlinearity class depends on per-channel symbol rate. As a rule, WDM systems with conventional periodic compensation of the optical dispersion suffer from interchannel nonlinearities, such as dispersion-managed solitons, at rates below 10Gbaud, while intrachannel nonlinearities, such as pseudo-linear transmission, threaten the system at rates higher of 10Gbaud. The impact of fiber nonlinearities depends on local fiber dispersion: low dispersion fiber has stronger interchannel effects than fiber with high local dispersion.

Table 2

Fiber nonlinearities effects

Nonlinearities							
Intrachannel interactions					Interchannel interactions		
Signal- Noise		Signal-Signal			Signal-Noise	Signal-Signal	
Nonlinear Phase Noise (NPN)	Parametric Amplification	Self Phase Modulation (SPM)			Nonlinear Phase Noise (NPN)	WDM Nonlinearities	
SPM-induced NPN	Modulation Instability	Isolated Pulse SPM	Cross Phase Modulation (IXPM)	Four Wave Mixing (IFWM)	XPM-induced NPN	XPM	FWM

The nonlinear processes-dominated signal distorsions in the fiber depends on bit rate, modulation format and fiber dispersion (see fig.1).

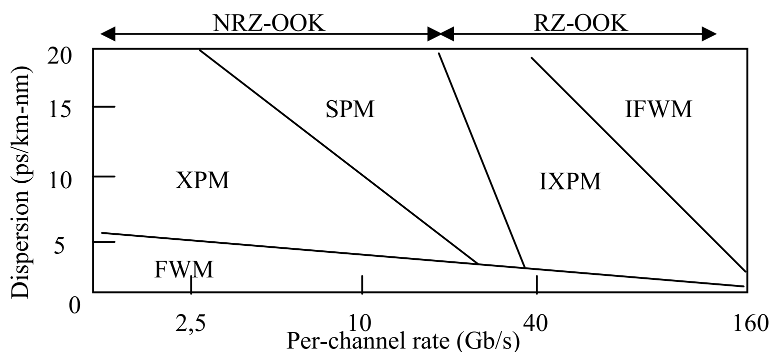

Fig. 1. Intrachannel and interchannel nonlinearities in WDM systems

Fig. 1 shows out dominant interchannel processes in a zero dispersion WDM channel that disturb the signal at rate below 10Gb/s.

Together with signal-to-signal interactions, optical transmissions suffer from signal-to-noise nonlinear interactions. These interactions significantly depend on the noise level, the poorer the *OSNR* the stronger the interactions during propagation and that is commonly with strong FEC. The most important signal-to-noise interaction is the SPM-induced nonlinear phase noise and XPM-induced nonlinear phase noise. These NPN processes control modulation formats that use optical phase to carry information (DPSK, DQPSK). The NPN processes are less important for formats that use optical phase for line coding (CSRZ, DB). The NPN effect is strong at low symbol rate, when the signal envelope slowly changes in time, or when low dispersion fiber is used. Formats with many phase levels are

NPN sensitive as well. Figure 2 presents the NPN effect in a 42.7Gb/s DPSK transmission.

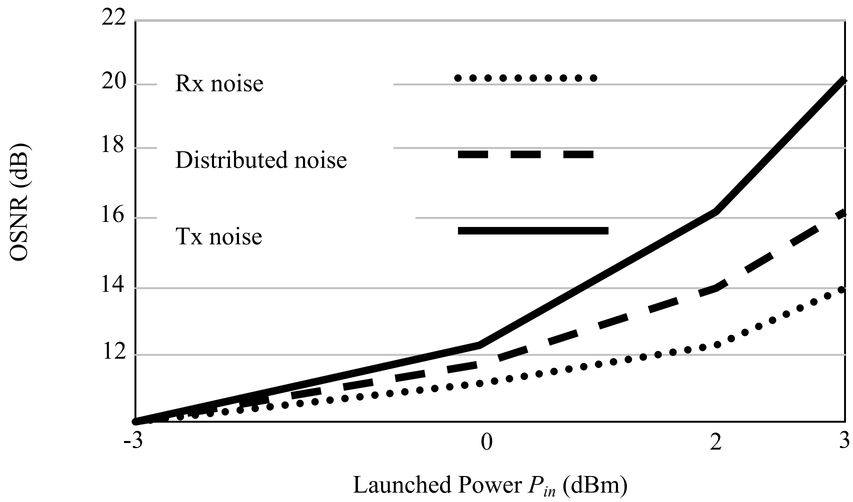

Fig. 2 Optical signal-to-noise ratio for RZ-DPSK with balanced detection, BER=10^{-3}

Each of the three plots draws *OSNR* related to the launched power into a nonzero dispersion shifted fiber. The middle plot presents the distributed noise, the physically case of an amplified spontanous emission (ASE) generated by an optical amplifier placed at the end-side of the section. The side curves draws hypothetical cases where the same ASE amount is added to emission (the lower graph) or to reception (the upper graph). The difference between the lower curve and the middle graph is the SPM-induced nonlinear phase noise penalty.

5. Conclusions

BER after FEC decoding at the reception side is the main measure of an optical transmission system performance. To relate BER measurements to system design, in which the random signal impairments result from in-line optical amplifier (ASE), the optical signal-to-noise ratio *OSNR* has been introduced. Optical transmission performances and modulation formats impacts on the system design have been related to signal impairing processes.

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