Impact of the Channel Count on the Nonlinear Tolerance in Coherently-detected POLMUX-QPSK modulation

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Abstract: GPU-based transmission simulations with different channel counts (1~81) are used to determine the minimum required channel number for correctly simulating fiber nonlinearities that impact 40G/100G CP-QPSK signals in dispersion un-compensated transmission systems.
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1. Introduction

Coherently-detected polarization-multiplexed (CP) quadrature phase shift keying (QPSK) modulation combined with digital signal processing (DSP) is now nearly generally adopted as the most suitable transmission format for next generation high speed (e.g. 40G and 100G) optical wavelength division multiplexed (WDM) transmission [1-6]. linear distortions such as chromatic dispersion (CD) and polarization mode dispersion (PMD) can be nearly fully compensated thanks to the FIR filter based digital signal processing (DSP) algorithms in the receiver. However, the DSP algorithms only compensate linear impairments and CP-QPSK modulated signals can still suffer strongly from nonlinear transmission impairments. In particular, inter-channel nonlinearities such as cross-phase modulation (XPM) and cross-polarization modulation (XPolM) limit the maximum feasible transmission distance in WDM systems using CP-QPSK modulation [2-6].

Computer based numerical transmission simulations by solving the nonlinear Schrödinger equations (NLSE) are convenient, flexible and useful tool to investigate or predict the system performance. However, limited by the extraordinarily high simulation time required even for the most modern CPUs generally only a few channels [3, 6] (e.g. around 10 channels) are used to simulate nonlinear impact in a WDM system. This approach is sufficient when we assume that inter-channel nonlinearities in a WDM system are mainly introduced by a few nearest neighbors. This assumption is generally valid for a WDM transmission over standard single mode fiber (SSMF) and with large channel spacings (e.g. 100 GHz or 200 GHz). However, simulations based on a limited number of channels may be insufficient for transmission over fibers with a low dispersion coefficient or narrow channel spacing (e.g. 50GHz-grid) . Moreover CP-QPSK suffers not only XPM but also from XPolM which is known to cause degradations over a large bandwidth [2-5]. To our knowledge, only a few papers [4, 5] have investigated the channel number impact for CP-QPSK and these papers only focused on dispersion managed WDM transmissions mixed with 10G OOK channels. In this paper we investigate and clarify the channel number requirement to correctly simulate fiber nonlinear effect in both 40G and 100G CP-QPSK uncompensated WDM systems while considering different fiber types. The extensive simulations required to investigate the impact of large channel numbers is enabled by a Graphics Processing Unit (GPU) based parallel implementation of the NLSE, which has been demonstrated to be able to speed up simulations with more than a factor 100 compared to CPU based simulations [7].

2. Simulation assumptions

We assume a WDM transmission system with 50-GHz channel spacing, employing CP-QPSK as the modulation format of choice. For the transmitter, two independent QPSK signals are generated by using two Mach-zehnder modulators (MZM) and then polarization multiplexed using a polarization beam combiner (PBC). An additional MZM is used to generate the RZ pulse carving that is assumed only for 100G CP-QPSK. For the receiver, the received optical field is split into two polarization signals by using a polarization beam splitter (PBS). Then the two polarization signals are combined with a local oscillator and fed into balanced detectors through a 90^{o} optical hybrid. The four tributary signals are processed further by a sequence of standard DSP algorithms [1-2]. The DSP block contains a frequency domain equalizer compensating for the major part of the CD, a clock recovery, a time domain equalizer compensating adaptively residual CD as well as PMD, a carrier recovery, a slicer followed by a decoder.

We focus here on dispersion un-compensated transmission as it has been demonstrated to show better performance when compared o dispersion managed transmission [1-3]. We examine in total four different fiber types: standard single mode fiber (SSMF), large effective area fiber (LEAF), TrueWave classic (TWC) and dispersion shifted fiber (DSF). The four fiber groups are considered to be representative for much of the worldwide deployed fiber in terms of both dispersion coefficients as well as nonlinear coefficients. Their parameters are listed in Table 1. Note that the dispersion coefficient for DSF has for simplicity been assumed to be -0.7 ps/nm/km (at 1540nm), instead of 0 ps/nm/km (at 1550nm) as transmission simulations with a dispersion coefficient of exactly 0 ps/nm/km are not practical. The simulated transmission link consists of a total of 20 spans with 80 km in length. The PMD is emulated by using 80 random waveplates per span and the PMD coefficient is assumed to be 0.01ps/km$^{0.5}$. Note that PMD has been shown to be insensitive in uncompensated CP-QPSK WDM links [6]. Therefore, PMD coefficient has negligible impact on investigating of penalty versus channel number.

Inline EDFAs are assumed noiseless and noise is only loaded before the receiver. The center channel is analyzed by calculating optical-signal-to-noise-ratio (OSNR) penalty at a BER of 10^{-3} based Monte-Carlo simulations run on several GPUs. In total 30 iterations are simulated for each case (i.e. each fiber type, each channel number and each channel input power) by assuming random initial states of polarization (SOPs), random bit sequences, as well as random timing and phases for the different WDM channels.

Table 1: Fiber parameters

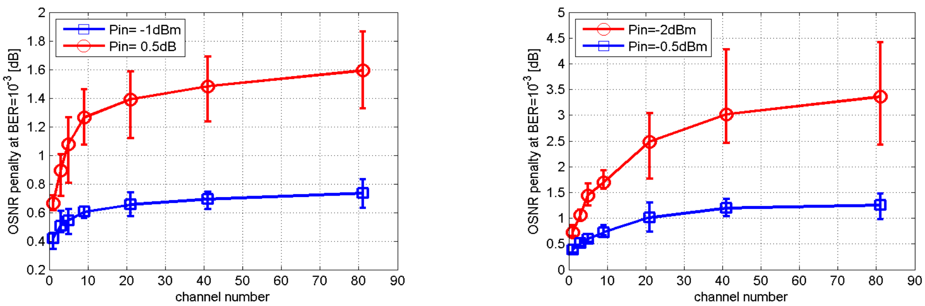
	SSMF	LEAF	TWC	DSF
Dispersion (ps/nm/km)	16.8 (1550nm)	4.2 (1550nm)	2.8 (1550nm)	-0.7 (1540nm)
Slope (ps/nm2/km)	0.058	0.086	0.068	0.070
Nonlinearity (1/W/km)	1.14	1.3	2	2
Attenuation (dB/km)	0.21	0.225	0.225	0.2

3. Results for 40G CP-QPSK

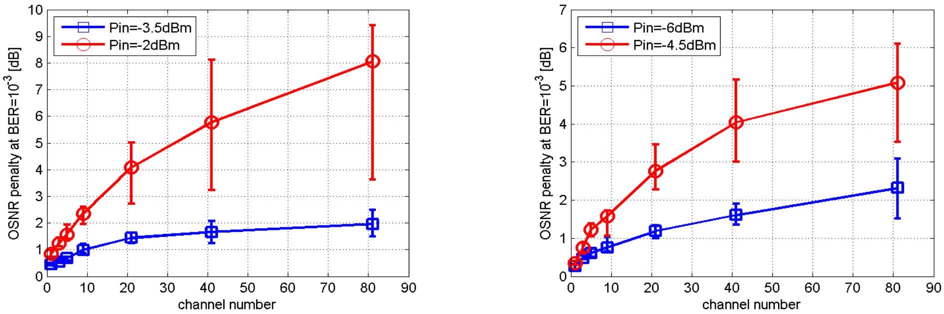
The mean OSNR penalty as well as the OSNR penalty variance as a function of the channel number (varied from 1 to 81) are shown in Figure 1 for a 45.8-Gb/s CP-QPSK with a 50-GHz channel spacing. We assumed two different input powers (Pin) for each fiber type. The blue curves marked with square are with low input powers (Pin_low) while the red curves marked with circles are with high input powers (i.e. Pin_high=Pin_low+1.5dB). Different Pin_lows are assigned to different fiber types based on the nonlinearity tolerance of the fibers in order to make a relative fair comparison of the channel number impact. As shown in Figure 1, about 0.5dB penalty is observed for single channel transmissions (i.e. channel number=1) with Pin_low.

For all fiber types, the OSNR penalty and its variance is increased with increasing channel number as well as with increasing channel input power. The increased impact of a higher channel input power is due to the fact that more channels as well as higher input powers lead to higher inter-channel nonlinearities. However, the increasing slope is different from one fiber to another. For example, only a minor increase of the penalty is observed for SSMF and LEAF when increasing channel number from 21 to 81, whereas a larger increase of the penalty is observed for TWC and DSF. The increasing slope is directly related to the nonlinear transmission penalty, which is mainly determined by the dispersion and nonlinearity coefficients. SSMF has the highest dispersion coefficient and lowest nonlinearity coefficients, while DSF has the lowest dispersion and largest nonlinearity coefficient among the four fiber types. It is necessary to point out that relative high power has been assumed for TWC (i.e. Pin=-2dBm) and hence a large penalty is observed in comparison to DSF.

By comparing the dependency of the transmission penalty on the channel number for the different fiber types, we can conclude that the minimum channel number required to correctly simulate the intechannel nonlinearity effects is approximately 20, 40, 80 and 80 for SSMF, LEAF, TWC and DSF, respectively. The required channel number may be reduced to 10, 20 and 20 for SSMF, LEAF and TWC with only a limited reduction in accuracy. However, 80 channels are still mandatory for DSF due to its very low dispersion coefficient. In addition, only the 1550 nm wavelength is examined here for SSMF, LEAF and TWC. The dispersion coefficients for all fiber types are smaller at shorter wavelength such as 1530nm and hence the inter-channel nonlinear impairments will be larger. In order to correctly simulate transmission performance at 1530 nm the required channel number should therefore be increased accordingly.



(a) SSMF (b) LEAF



(c) TWC (d) DSF

Figure 1: The OSNR penalty dependency on the channel number for 45.8-Gb/s CP-QPSK and different fiber types, (a) SSMF at 1550nm, (b) LEAF at 1550nm, (c) TWC at 1550nm and (d) DSF at 1540nm.

4. Results for 100G CP-QPSK

Similar simulations have been also carried out for 128-Gb/s RZ-CP-QPSK modulation, with the results depicted in Figure 2. Once again, different channel input power have been roughly scaled by the fiber parameters. We can draw from Figure 2 a similar conclusion as for 40G CP-QPSK discussed in part 3.

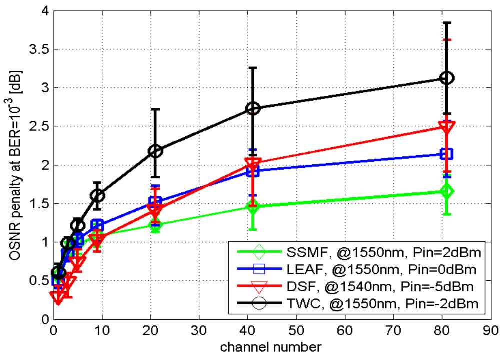


Figure 2: OSNR penalty dependency on the channel number for 128-Gb/s CP-QPSK and different fiber types.

5. Summary and conclusion

Thanks to the new possibilities allowed by the split-step Fourier method using GPU-based parallel implementations, we have determined the required channel number to correctly simulate nonlinear transmission penalties in dispersion un-compensated WDM systems using either 40G or 100G CP-QPSK modulation. This study has indicated that the general assumption of few channels (e.g. 10) for the WDM channel simulations is only valid for SSMF, but significantly underestimates the penalty for other fiber types such as LEAF, TWC and DSF.

6. References

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