Chromatic dispersion tolerance in optimized NRZ-, RZ- and CSRZ-DPSK demodulation

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Abstract: We present the results of a comprehensive analysis optimizing the performance of DPSK systems with increased FSR and narrow optical filtering, establishing improved chromatic dispersion tolerance of NRZ-DPSK by 20%, RZ-DPSK by 71% and CSRZ-DPSK by 74% approximately. Transmitting a 40Gb/s signals on a spectrally efficient 50GHz DWDM grid still exhibit improvements of 7% for NRZ-DPSK, 37% for RZ-DPSK and 22% for CSRZ-DPSK, relative to a typical DPSK receiver. The optimized delay and optical filtering scale with the amount of chromatic dispersion. We also demonstrate the impact of limited transmitter bandwidth on optimal optical filtering and bit delay parameters.

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1. Introduction

Differential phase shift keying (DPSK) in its variants, such as non-return-to-zero (NRZ-), return-to-zero (RZ-) and carrier-suppressed- return-to-zero (CSRZ-) DPSK, is becoming one of the formats of choice in next generation optical communication systems [1, 2]. DPSK is usually demodulated in a delay-line interferometer with a one-bit delay such that the phases of two adjacent bits are compared during the entire bit time [3-5]. It was recently shown that free-spectral-range (FSR) optimization can increase optical filtering (OF) or CD tolerance for RZ- and NRZ-DPSK [6-9]. Although quite convincing, those results fail to identify the optimal value of FSR value versus CD. It was also mentioned in [6-8] that transmitter bandwidth has an impact of optimal FSR parameter but only for NRZ-DPSK and the specific impact and requirements are yet to be fully explored. Most importantly there has been little discussion on the combined effect of FSR optimization and tight OF on the increase of CD tolerances.

In this paper we report a comprehensive analysis of the parameter space of OF bandwidth and FSR for the NRZ-, RZ- and CSRZ-DPSK formats, establishing that simultaneous FSR and OF optimization significantly improves CD tolerances. The results can be used as guidelines in designing DPSK receivers according to the maximum amount of chromatic dispersion allowed in the system. The specific impact of transmitter bandwidth on the optimized FSR and OF parameters is also presented. Finally, we show the impact OF and FSR optimization on DWDM DPSK systems with high channel density.

2. Principle of operation

The optimisation obtained through increasing the FSR of the Delay Interferometer (DI) can be explained using the equivalent baseband model detailed in [10], representing the DPSK link as two parallel paths with Transfer Functions (TF) given in our modified notation by the product \( H_L(f) = H_T(f)H_F(f)H_{\alpha}(f)H_{\pi}(f) \) of the TF \( H_T(f) \) of the Transmitter (TX).

![Fig. 1. DPSK spectrum with overlayed transfer functions for optical filtering and delay-line interferometer. Free-spectral-range larger than the bitrate and tighter optical filtering puts a greater emphasis on the optical duobinary (ODB) port (constructive) rather than the alternate-mark-inversion port (destructive).]
pulse-carver, the fiber dispersion $H_F(f)$, the OF $H_0(f)$ and the TFs describing the DI propagation to the constructive (ODB) / destructive (AMI) DI ports:

$$H_\pm(f) = \left[\exp(-j2\pi f / FSR) \pm 1\right]/2$$  \hspace{1cm} (1)

$$|H_+(f)|^2 = \cos^2 \left(\pi f / FSR\right)/4$$  \hspace{1cm} (2)

$$|H_-(f)|^2 = \sin^2 \left(\pi f / FSR\right)/4$$  \hspace{1cm} (3)

The benefit of taking $FSR > R$, (with $R = T_b^{-1}$ the bitrate) is then interpreted as an equalization measure; by reducing the OF bandwidth (BW) we improve the CD tolerance and reduce ASE noise, however this in itself would introduce ISI, which is subsequently equalized by increasing the FSR of the filters in (1) as shown in Fig.1. The enhanced BW filters (1) then act as equalizers for the other TFs in the chain $H_+(f)$. While the ASE noise reduction due to tighter optical filtering is undone to some extent by the noise enhancement through the enhanced BW equalizers (1), an improvement in CD tolerance is achieved: Up to $f = \pm FSR/2$, the ODB port TF (2) is low-pass, while the AMI port TF (3) is high-pass, accentuating the frequencies farther away from the optical carrier, resulting in emphasis of CD. Increasing the FSR, both TFs are horizontally stretched, on one hand reducing the rolloff of (2) which becomes less of a low-pass, making up for (partially equalizing) the increased rolloff of the tight OF, hence mitigating the ISI induced by the tight OF. On the other hand, stretching the high-pass TF (3) reduces its “rollup” making it less of a highpass, hence diminishing the emphasis of CD at the AMI port. This has similarities with biasing the photocurrent imbalance to favor the ODB port, as was demonstrated in [7].

3. Numerical model

Simulations were performed for a C-band Pseudo random binary signal (PRBS) DPSK signals at bitrate $R$, modulated with a Mach-Zehnder modulator (MZM) with 20dB of extinction ratio. The RZ- and CSRZ-DPSK signals were generated using a second MZM driven by a $R/2$ clock with a $V_\pi$ drive voltage for CSRZ-DPSK and $R$ clock with $V_\pi$ drive voltage for RZ-DPSK. At the receiver, the signal was filtered through a 2nd order Gaussian OF and demodulated in an MZ delayline interferometer (DLI). Balanced detection was followed by $\frac{3}{4}R$ 4th-order Bessel electrical filter. The bit error rate (BER) was estimated by means of a Karhunen-Loeve expansion for non-Gaussian noise statistics, with 1024 simulated bits at 64 samples per bit in a simulation BW of $25R$. The OSNR in 0.1 nm was set using $OSNR = 10\log(R)$ dB corresponding to 10, 16 and 20 dB of OSNR at 10, 40 and 100 Gb/s respectively. The CD was varied from 0 to 272 in normalized units of $10^{-3}$ (Gb/s)$^2$ ps/nm using $CD_{index}=R^2LD$ [10] where L is the fiber length and D the CD in ps/nm/km. The Q parameter was calculated from the BER value as in [3, 7] using $Q = 20\log \sqrt{2}erfc^{-1}(2BER)$, with $erfc^{-1}$ the inverse complementary error function.

4. Results

Similarly to what has been reported elsewhere, we find that the optimal OF for NRZ-, RZ- and CSRZ-DPSK for a one-bit back-to-back demodulation to be around $1.25R$ for NRZ-, 1.75$R$ for RZ- and 1.8 $R$ for CSRZ-DPSK. The optimal FSR varies over the OF BWs but is also very dependent on CD. The results indicate that either tighter optical filtering or larger FSR tends to increase CD tolerance but their combination leads to optimal CD performance.
For RZ-DPSK with optimal OF, the optimal FSR/R value is 1 as was noted in [4]. With tighter filtering, larger FSR yields better performance. Figure 2 illustrates the dramatic impact of optimizing the FSR and OF in the presence of CD. For 0 CD, by drawing a line on the contour plot at OF 1.75R, 0.88R and 0.75R, we obtain results similar to [7]. On the 0 CD plot, the orientation of the contour line for tight optical filtering clearly demonstrate the effect of increasing the FSR. The advantage of having complete results shown as contour plot is that it provides the penalty curve for a wide range of OF bandwidth which is practical if optimal OF bandwidth is not possible.

As CD is increased to 54, 110 and 218 x 10^3 (Gb/s)^2 ps/nm, the optimal OF bandwidth drops dramatically while the optimal FSR value increases almost linearly. With optimal parameters, CD tolerance increases by 71% at 9.8 dBQ as shown in Fig. 3. Using the normalized values for a 40Gb/s RZ-DPSK signal, the results translate into an OSNR of 16dB and residual CD tolerance increase from 74 ps/nm to 127.5 ps/nm.

Fig. 2. RZ-DPSK Q-factor versus free spectral range and optical filtering bandwidth for CD index of a) 0, b) 54, c) 110 and d) 218 x 10^3 (Gb/s)^2 ps/nm.
Although the improvement may be considered small on an absolute scale, it may be of great importance for short distance office to office 40 Gb/s systems which cannot afford chromatic dispersion compensation.

Fig. 3. Chromatic dispersion tolerance improvement using FSR and optical filtering optimized for best back-to-back performance versus using optimized parameters. Using channel spacing of 1.25R (50GHz for 40G signal) with optimized parameters yields better results than a single non-optimized channel.

Fig. 4. NRZ-DPSK Q-factor versus free spectral range and optical filtering bandwidth for CD index of a) 0, b) 54, c) 110 and d) $218 \times 10^3 \text{(Gb/s)}^2 \text{ps/nm}$. 
Such systems are currently being deployed using the ODB modulation format because of its high chromatic dispersion tolerances [12]. For dispersion compensated systems, the method provides an increase in tolerances to varying residual CD or improper dispersion slope compensation. Another interesting observation from the contour plot is that at $110 \times 10^3$ (Gb/s)$^2$ ps/nm, if the OF is not reduced, increasing the FSR does not improve CD tolerances.

The impact of optimising the FSR and OF in the presence of CD is also apparent for NRZ-DPSK as shown in Fig. 4. With optimal parameters, CD tolerance increases by 20% as illustrated in Fig. 3. For a 40Gb/s signal it translates into residual CD tolerance increase from 118 ps/nm to 142 ps/nm. For CSRZ-DPSK, the same phenomenon is observed as illustrated in Fig. 5. With optimal parameters, CD tolerance increases by 74% as illustrated in Fig. 3. Similarly to RZ-, the contour plots for NRZ- and CSRZ- at $110 \times 10^3$ (Gb/s)$^2$ ps/nm show that if OF bandwidth is not reduced, CD tolerances and not improved significantly by increasing the FSR.

Fig. 5. CSRZ-DPSK Q-factor versus free spectral range and optical filtering bandwidth for CD index of a) 0, b) 54, c) 110 and d) $218 \times 10^3$(Gb/s)$^2$ ps/nm.
The optimal values of FSR and OF can be selected depending on the amount of CD in the system. As shown in Fig. 6, OF BW values for RZ- and CSRZ- drop drastically for 0 to 100 x 10^3 (Gb/s)^2 ps/nm CD index. For the three formats, the OF BW then decreases linearly with CD index. The optimal FSR increases with CD as shown in Fig. 6. Interestingly, the optimal FSR/R value for NRZ-DPSK is not unity even in the absence of CD as was also shown in [8].

Tunable bandwidth optical filter and tunable FSR interferometer are not readily available or easily integrated in a DPSK receiver. Fortunately the results of Figs. 2-6 do not indicate that a tunable solution is required to properly demodulate a DPSK signal. By choosing the FSR and OF parameters for a specific amount of CD, the penalty without CD is not significant. For example in Fig. 2 for RZ-DPSK at 218 x 10^3(Gb/s)^2 ps/nm of CD, the optimal parameters are OF/R=0.9 and FSR/R=1.25 as shown in Fig. 5. Using those values for zero CD gives a Q of 11.8dB for an insignificant penalty 1.2dBQ. Alternatively, using a standard 1.75 OF/R and 1 FSR/R which would be optimized for back-to-back demodulation, would incur a penalty greater than 5dBQ and a Q smaller than 5dBQ for 218 x 10^3(Gb/s)^2 ps/nm of CD. Choosing OF bandwidth and FSR optimized for the maximum CD tolerances, effectively flattens the penalty curve versus CD which can be very beneficial in a DPSK system.

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5. Channel spacing and transmitter bandwidth

It was remarked in [8] that FSR optimization enables minimizing channel spacing in DWDM systems. To quantify this benefit, we ran simulations observing the center channel in five independent DWDM channels separated in frequency by 1.25R and pre-filtered before multiplexing with FSR and OF values re-optimized to maximize the Q-factor at the receiver.
The results shown in Fig. 3 indicate that all three DPSK formats with optimized FSR and OF using 1.25\(R\) channel spacing, outperform a single non-optimized channel. The CD tolerance using a 40Gb/s DWDM system with 50GHz channel spacing with 16dB of OSNR is increased by 37% for RZ-DPSK, 7% for NRZ-DPSK and 22% for CSRZ-DPSK, relative to a single channel with non-optimized demodulation.

Finally, as was noted by [7, 8], transmitter bandwidth impacts the optimal FSR for NRZ-DPSK. We thoroughly studied this effect for three DPSK formats with 0.75\(R\) and 0.5\(R\) modulator and modulator driver BW and found that this effect is also true for RZ-DPSK. The results presented in Fig. 7 indicate that when comparing with the 0-CD contour plots of Fig. 2, 4 and 5, reducing the optical filtering and increasing the FSR improves performance of a lower BW transmitter. The results open the potential of using lower bandwidth electronic components, for example using 10Gb/s modulators and drivers, for 20Gb/s DPSK systems.
transmission [13]. The smaller transmitter bandwidth provides a narrower spectrum and the penalty is somewhat compensated by using an optimized FSR and OF bandwidth. The penalty is only 1dBQ for RZ-DPSK and 0.8 dBQ for NRZ-DPSK. Interestingly, CSRZ-DPSK is not improved when using a larger FSR or narrower OF filtering bandwidth. Nevertheless, the method could enable lower-cost transponders with substantial improvements in CD tolerance by combining larger FSR, narrow optical filter and smaller transmitter bandwidths.

5. Conclusion

We reported a comprehensive analysis of the parameter space of OF bandwidth and FSR for the NRZ-, RZ- and CSRZ-DPSK formats, establishing that simultaneous FSR and OF optimization significantly improves CD tolerances. The results can be used as guidelines in designing DPSK receivers according to the maximum amount of chromatic dispersion allowed in the system. The specific impact of transmitter bandwidth on the optimized FSR and OF parameters is also presented. Finally, we show the impact OF and FSR optimization on DWDM DPSK systems with high channel density.