Free spectral range optimization of return-to-zero differential phase shift keyed demodulation in the presence of chromatic dispersion

Yannick Keith Lizé[1, 2, 3], **Louis Christen**[2], **Xiaoxia Wu**[2], **Jeng-Yuan Yang**[2], **Scott Nuccio**[2], **Teng Wu**[2], **Alan E. Willner**[2], **Raman Kashyap**[3]

[1]*ITF Laboratories, Montreal, Canada*
[2]*Viterbi School of Engineering, University of Southern California, Los Angeles, California, 90089, USA*
[3]*Advanced Photonic Concepts Laboratory, École Polytechnique de Montréal, Montreal, Canada*
yannick.lize@gmail.com

Abstract: Optical differential phase shift keying is normally demodulated in a delay-line interferometer with a 1-bit delay such that the free-spectral-range of the demodulator is equal to the transmitted bitrate. We show using Karkunen-Loeve expansion simulation that free-spectral-range optimization leads to increased chromatic dispersion tolerances. The optimized delay inversely scales with the amount of chromatic dispersion such that a delay slightly shorter than the bit period increases tolerances with no adverse effect on the polarization-mode-dispersion tolerance or frequency offset penalty at the receiver.

OCIS codes: (060.5060) Phase modulation.

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1. Introduction

Due to its increased receiver sensitivity and increased tolerance to various fiber-based impairments, differential-phase-shift-keying (DPSK) has been pursued aggressively as an alternative to on-off keying (OOK) [1-6]. After several years of laboratory experiments and field demonstrations [7-9], Return-to-zero (RZ-) DPSK is currently being deployed for next generation high capacity optical networks. In DPSK the information is encoded on the difference of phase between consecutive bit period rather than the absolute phase of the signal, a delay-line Mach-Zehnder interferometer (DLI) [6] is commonly used to convert phase difference into intensity modulation which can be detected by standard photo-diodes. The two arms of the DLI are delayed relative to each other by a single bit time such that the free spectral range (FSR) of the interferometer is equal to the transmitted bitrate. The phase of one bit in the data stream is then compared to the phase of the subsequent bit. The two output ports of the DLI, representing the constructive and destructive interference between the phases of adjacent bits, are connected to balanced receivers where it is the balanced detection that is responsible for most of the advantage of DPSK over OOK.

In back-to-back configuration, the most efficient DLI has a complete one-bit delay such that the phases of two adjacent bits are compared during the entire bit time for maximum eye opening. It has been shown that DLI degradations such as bit delay mismatch and frequency offset [10-13], transmission impairments such as chromatic dispersion (CD), polarization-mode-dispersion (PMD), and nonlinearities [14,16] or the combination of DLI degradations and transmission impairments [17] can distort the phase of the DPSK signal and reduce receiver sensitivity. It might be advantageous to optimize the FSR of the DLI to actually counteract the phase degradation of the transmission impairments in order to enhance the DPSK receiver sensitivity. It was recently demonstrated that FSR optimization can increase optical filtering and CD tolerances for NRZ-DPSK [18].

In this paper we demonstrate that in the presence of CD, offsetting the FSR of the DLI to obtain partial bit delay in the demodulation of a RZ-DPSK signal increases CD tolerance with no adverse effect on the PMD tolerance or frequency offset penalty. We find up to 1dB increase in receiver sensitivity at BER 10^{-3} or a 12.5% increase in CD tolerance. We show a 0.25 dB increase in receiver sensitivity for PMD impairment which although approaching the resolution of the simulation, at the very least indicates that the FSR optimization does not impact PMD tolerance. The optimal FSR scales with CD and PMD. Furthermore, we show that some of the increased degradation stemming from the combination of transmission impairments and frequency offset [17] is actually mitigated by using partial bit delay demodulation.

2. Concept and Theory

Normally in DPSK demodulation, an exact 1 bit delay is used to demodulate the signal. The effect of bit delay mismatch at the interferometer has been extensively studied [11, 13, 17]. As seen in Fig. 1, when less than 1-bit delay is used, part of the bit interferes onto itself which provides deterministic constructive interference for every bit time. This normally creates eye closure in back-to-back OSNR sensitivity measurement but the deterministic interference is

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not affected by transmission effects and provides a buffer between bits after demodulation which minimizes inter-symbol interference (ISI). CD and PMD are a main cause of ISI in fiber optic transmission. The ISI tolerance that is provided by the constant interference of partial bit delay demodulation is not as efficient in the presence of PMD since the deterministic interference will occur independently in the two orthogonal polarization states. PMD will cause a time delay between the two polarizations such that the time location of the deterministic interference will drift and ISI will still occur. This also explains why NRZ-DPSK provides a greater improvement than RZ-DPSK for FSR optimization [18] since the RZ formats provides an ISI resistant "buffer" that FSR optimization provides.

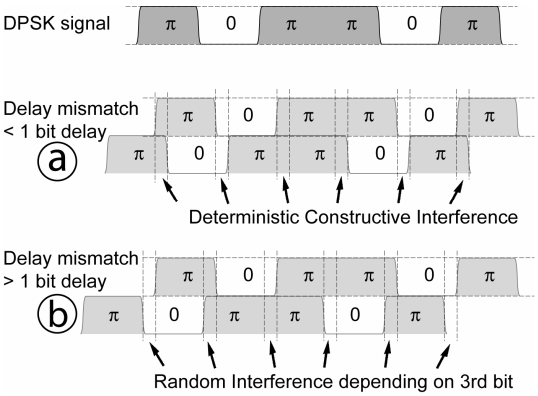

Fig. 1. Concept of bit delay mismatch. For mismatch smaller than one bit period a constant deterministic interference occurs for each bit period leading to greater tolerance to ISI.

It has been shown [11,13,17] that in back-to-back transmission, a DLI with a mismatch greater than 1-bit delay such that the FSR is smaller than the bit rate has larger negative impact than a mismatch of less than 1-bit delay.

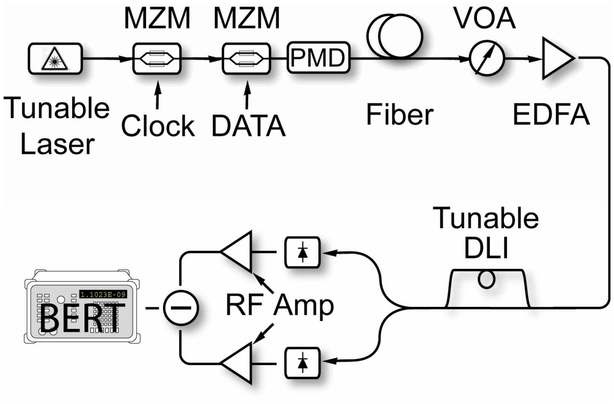

Fig. 2. Diagram of the setup for simulations using a 40Gbps RZ-DPSK signal with 50GHz 3rd order Gaussian optical filter and 32GHz Lorentzian electrical filter. Karkunen-Loeve expansion for non-Gaussian noise statistics was used with 512 bits simulated at 60 samples per bit in a simulation bandwidth of 0.48 THz.

3. Results

Simulations were performed for a 40Gbps RZ-DPSK signal with 50GHz 3rd order Gaussian optical filtering and 32GHz Lorentzian electrical filtering. Karkunen-Loeve expansion for non-Gaussian noise statistics was used with 512 bits simulated at 60 samples per bit in a simulation bandwidth of 0.48 THz. The setup for the simulations is illustrated in Fig. 2.

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Results show that the optimal bit delay in the presence of residual CD or PMD is no longer a 1 bit delay. Complete BER curves were simulated for each combination of parameters and OSNR penalty at BER=10^{-3} were inferred from a linear fit of the Log(Log(BER)) versus OSNR in dB.

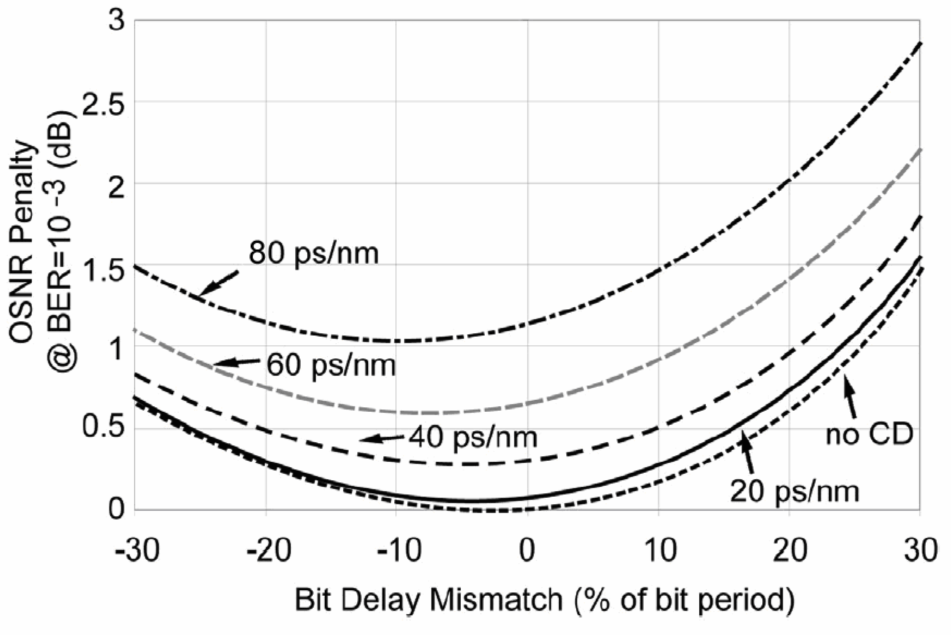

Fig. 3. Bit delay mismatch penalty for different values of chromatic dispersion. The optimal bit delay is no longer 1bit in the presence of CD.

3.1 Chromatic dispersion and bit delay mismatch

The OSNR penalty at BER=10^{-3} versus bit delay mismatch in percentage of the bit period at 40Gbps for an RZ-DPSK signal is illustrated in Fig.3 for different values of CD. The results shown in Fig.3 for no CD are similar but not exactly the same as previously reported results for bit delay mismatch penalty [11-13]. This is explained by the fact our results are for *RZ*-DPSK and we calculate the OSNR penalties at BER of 10^{-3}. Interestingly with increasing CD, the penalty curve shifts to the left of the zero-delay-mismatch point such that the optimal delay is no longer equal to the bit period. Again, a mismatch larger than the bit period causes a greater penalty than a mismatch smaller than the bit period.

Figure 4 illustrates the OSNR penalty versus CD for a perfect 1-bit delay and with the optimized delay mismatch. Results for 1-bit delay are in agreement with previously reported results for CD tolerance of RZ-DPSK [16]. For optimal bit delay mismatch, full BER versus OSNR curves were simulated for all the combinations CD and delay mismatch to find the optimal point.

We find that RZ-DPSK becomes 12.5% more tolerant to CD at 3dB penalty than standard 1-bit delay demodulation. The Fig. also shows that the optimal mismatch values increase with increasing CD and that the bit delay is about ¾ of the bit period at 3dB. The Fig. indicates indicate that at no CD, the optimal point is not zero mismatch but the difference in OSNR penalty at that point is less than 0.01dB which is much lower than the simulation accuracy.

Figure 5 illustrates the OSNR penalty versus PMD for a perfect 1-bit delay and with optimized delay mismatch. As expected the improvement is not as significant as for CD. The PMD tolerance is increased by 2% for a 3dB OSNR penalty which is on the order of the simulation accuracy. More importantly, it indicates that optimizing the DLI to increase tolerance to CD does not degrade the tolerance to PMD in the RZ-DPSK demodulation.

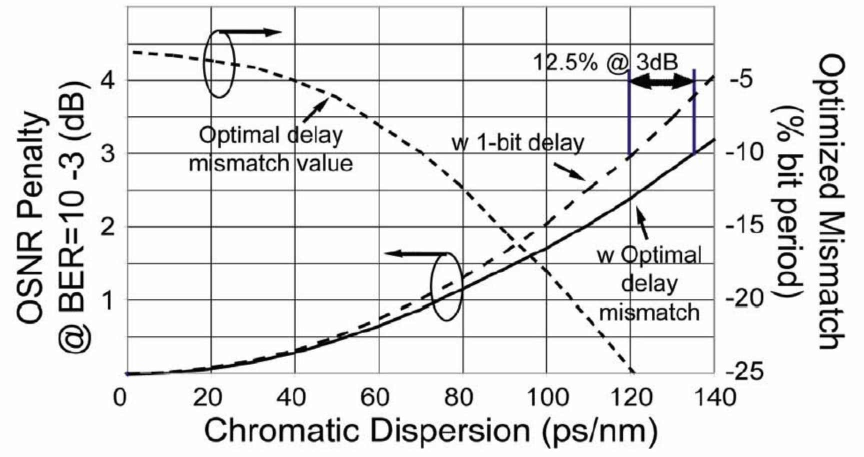

Fig. 4. Numerical results of optimal mismatch as percentage of bit period for CD. Difference in OSNR penalty for exact 1-bit and with optimal bit delay mismatch. An improvement of 12.5% of CD tolerance is observed at 3dB OSNR penalty.

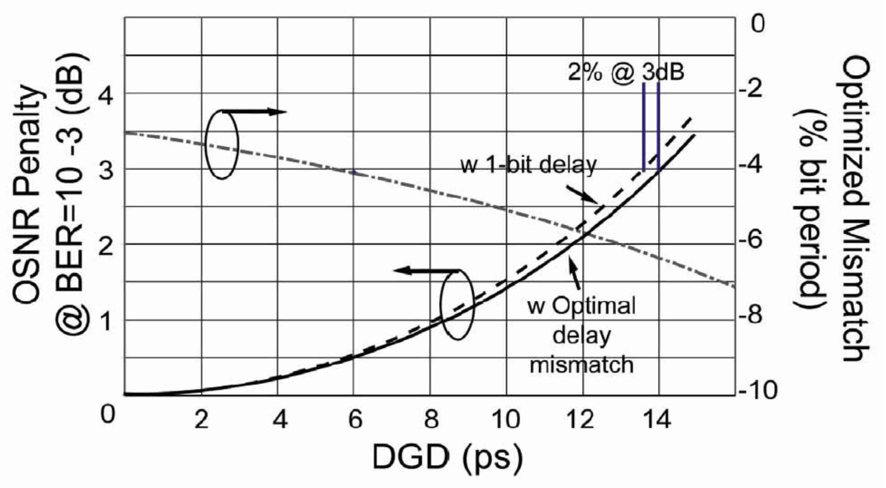

Fig. 5. Numerical results of optimal mismatch as percentage of bit period and OSNR penalty for PMD. The improvement of 2% in PMD tolerance is not significant and within the accuracy of the numerical simulation but it nevertheless indicates that optimized FSR for CD will not be degraded by PMD.

3.2 Frequency Offset, chromatic dispersion and bit delay mismatch

Frequency offset penalty in DPSK demodulation occurs when the transmission peak of the DLI is not aligned to the frequency of the transmitting laser. This is caused by the improper phase tuning of the demodulator [11-14]. It was recently reported that the combination of frequency offset to residual CD at the receiver incurs a greater penalty than the sum of the two degradations [17] because of the combination of phase degradations. Figure 6 illustrates the frequency offset penalty with 140ps/nm of CD for different values of bit-delay mismatch. The baseline curve with no CD is similar to previously reported results [11-14] but we used RZ-DPSK and calculated the OSNR penalty at BER 10^{-3}. A 0.5dB penalty is incurred when the frequency of the signal is offset from the transmission peak of the DLI by about 4% of the bitrate in back-to-back demodulation. The OSNR penalty coming from CD [16] has been

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subtracted from Fig. 6 such that only the frequency offset penalty is shown so as to more clearly visualize the OSNR penalty stemming from the *combination* of CD and frequency offset. With 140ps/nm of CD, the frequency offset penalty alone doubles. Again the total OSNR penalty would also incorporate the CD penalty.

If the bit delay mismatch is greater than 1-bit delay, Fig. 6 illustrates that the penalty of combining CD and frequency offset is further increased. For a mismatch of +10% the frequency offset penalty climbs from 0.5dB at 4% offset to a very significant 2dB penalty. The penalty for a 4% offset, is 1.5dB for a perfect one bit delay but reduced to about 1 dB for a -15% mismatch.

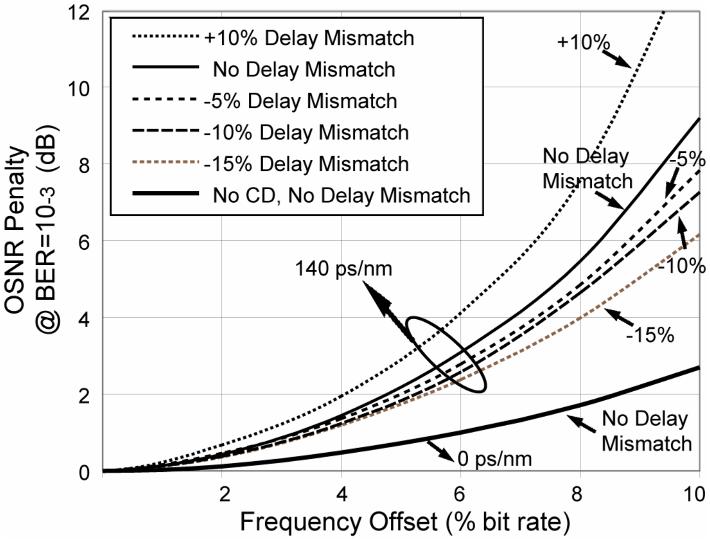

Fig. 6. Combination of frequency offset and CD with the CD penalty subtracted out. Optimized bit-delay mismatch compensates for some of the increased penalty incurred by the combination without reaching the no-CD level.

Unlike in the CD case, the combination of PMD with frequency offset does not yield an increased penalty when the signal is not centered on the transmission frequency of the DLI. Since partial bit delay demodulation has little effect on PMD tolerance, its effect on the combination of frequency offset and PMD also has little effect.

4. Conclusion

We presented the optimization of the bit delay mismatch in RZ-DPSK demodulation in the presence of chromatic dispersion. We showed that by offsetting the FSR of the DLI to obtain partial bit delay in the demodulator, CD tolerance is increased with no adverse effect on the PMD tolerance or frequency offset penalty. We find that up to 1dB increase in receiver sensitivity with a 12.5 % increase in CD tolerance is possible. We show a 0.25 dB increase in receiver sensitivity for PMD impairment demonstrating that the mismatch is not negatively affected by PMD. The optimal delay mismatch scales with CD and PMD.

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