DPSK Receiver Design – Optical Filtering Considerations

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Abstract: We study via simulation the influence of the DPSK decoder free spectral range (FSR) when strong optical filtering is considered for the NRZ and RZ modulation formats and show that larger FSR can improve performance.

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1. Introduction

The differential phase-shift keying (DPSK) modulation format has attracted considerable attention in recent years due to its superior OSNR sensitivity and fiber nonlinearity tolerance compared to on-off keying formats. It has especially attracted attention for higher data rate applications, notably 40 Gbps and beyond. The practical direct detection DPSK receiver architectures considered in this study require two key components, namely a balanced photodetector and a delay-interferometer (DI). These components are quickly reaching a maturity level enabling mass production of DPSK based OC-768/OTU-3 line cards. One critical aspect in any DPSK receiver design is the choice of DI. This choice depends on many factors, including cost, size, control complexity, as well as DWDM system-level considerations such as channel spacing, single or mixed data rates (e.g. 10G + 40G on same platform), impact of terminal equipment filters and ROADMs, channel plan, as well as sparing and manufacturing considerations.

Although DPSK DI performance has been studied extensively for the return-to-zero (RZ) [1-3] and non-return-to-zero (NRZ) [4-6] formats, the effect of strong optical filtering in the DWDM link on DI performance has not been considered. This subject is of high importance for DWDM systems where the DPSK signals must pass through filters whose effective concatenated optical bandwidths approach, or are below, the data rate. Practical examples include deployment of OC-768/OTU-3 DPSK signals over OC-192/OTU-2 systems employing 50 GHz optical filters with ROADMs, and deployment over systems employing a large number of ROADMs, where the concatenated optical bandwidth can quickly go below 50 GHz. In this paper, we study via simulation the impact of the free spectral range (FSR) of the DI as a function of additional optical filtering for both the NRZ and RZ DPSK formats at 43 Gbps. Numerical results are experimentally verified for the NRZ format.

2. Experimental setup

The schematic of the experimental setup is shown in Figure 1.

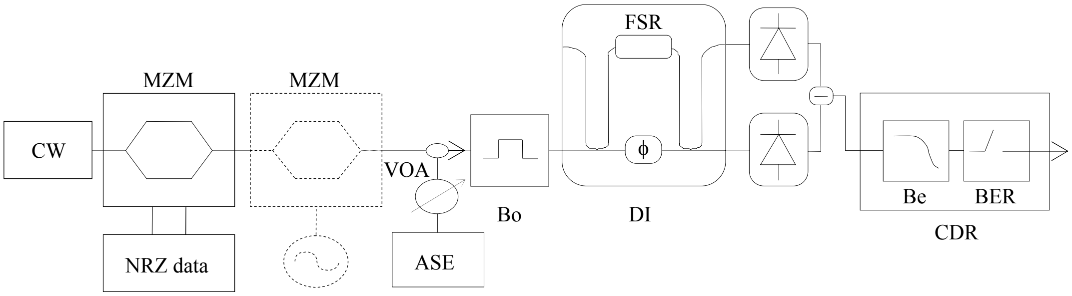

Figure 1. Experimental and simulation configuration. Solid lines indicate the experimental setup. Dashed lines indicate blocks included in the simulation model for RZ-DPSK.

Light from a continuous-wave (CW) laser was modulated using a Mach-Zehnder modulator (MZM) in a “push-pull” configuration (biased a null of transmission and with $\pm V\pi$ drive swing for both arms). The MZM was driven by a 43 Gbps NRZ electrical data sequence from a pseudo-random bit stream (PRBS) of length 2^{31}-1. In simulation, RZ signals were generated using a second MZM in a “push-pull” configuration to carve the NRZ signal with a 50% duty cycle. The carver was biased at middle of transmission and driven with a full clock rate R and $\pm\frac{1}{2}V\pi$ drive swing for both arms. The optical signal-to-noise ratio (OSNR) was set by adding optical amplified spontaneous emission (ASE) noise from a broadband ASE source. The ASE power was adjusted by a variable optical attenuator (VOA). At the receiver, the ASE is filtered by an optical filter. Three filter configurations are considered. The first is a 75 GHz flat top filter. The second is a combination of two 50 GHz interleavers concatenated with the previous 75 GHz filter. In simulation, the first and second filters were assumed second-order Gaussian with 3dB bandwidth of Bo=1.75R (75 GHz) and 0.88R (38 GHz) respectively. In simulation, another filter with the same shape and a 3dB bandwidth of Bo=0.75R (32 GHz) was considered. Two DI configurations are considered here. The first has a normalized FSR over the bit rate R very close or equal to FSR/R=1. The second has a normalized FSR of FSR/R=1.17, or in absolute units FSR=50 GHz. The second device has the advantage of potentially passing all ITU 50-GHz-grid channels over the C+L band. The two outputs of the DI were detected by a balanced photodetector. The photodetector output was coupled to a clock-and-data recovery (CDR) module. The bit-error ratio (BER) was reported through a BER analyzer. In simulation, the electrical transfer function of the receiver was considered to be a fourth-order Bessel-Thompson with 3 dBe bandwidth of Be=0.6R (25 GHz), which is consistent with modeling parameters used in other studies [1,2,4].

3. Numerical model

A Monte-Carlo numerical model using error counting was developed for this study. A PRBS length of 2^{10} (repeated 10 times before mixing with ASE noise) was used and errors were accumulated over 170 different noise seeds. The optimum time sampling point was found and the BER versus decision threshold level was swept. To account for phase noise from the CDR, a receiver box time window of ±10% of the bit duration has been assumed. The OSNR was set to 16 dB (reported in 0.1 nm resolution bandwidth). Electrical Q (in dB) was calculated from the BER value using the relationship: $Q = 20\log\left[\sqrt{2}\,erfc^{-1}(2BER)\right]$ where $erfc^{-1}$ is the inverse complementary error function. The model was verified against results found in the literature [1] as well as experimental observations.

4. Impact of DI FSR in the presence of strong optical filtering

The transfer function $D(f)$ (in electric field amplitude) of the DI is given by Eq. 1 for both the constructive and destructive ports,

$$D_{\substack{Constructive\\Destructive}}(f) = \frac{1}{2}\left[1 \pm \varepsilon \exp\left(\frac{j2\pi f}{FSR}\right)\exp\left(-j\phi\right)\right] \qquad (1)$$

where ε is related to the DI extinction ratio and ϕ is the optical phase difference between the two arms. When the FSR=R (delay of the upper arm is exactly one bit), there is perfect constructive/destructive interference on both ports. It is reported for the RZ format that when FSR=R, the performance is optimized and any deviation from that condition leads to a penalty [1]. However, one experimental paper [6] comparing DIs having FSR/R=1 and 1.17 for a NRZ-DPSK format at 42.7 Gbps reports similar performance without explaining in detail why this is to be expected. To understand the effect of the FSR on the performance, the DI can be seen as a filter. In Figure 2, *D(f)* of the constructive port is plotted for FSR/R=1 and 1.17 at R=42.84 Gbps. The spectrum of the NRZ and 50%RZ DPSK signals are also plotted for illustrative purposes. It can be seen that the equivalent filter bandwidth scales with the FSR. In other words, the larger is the FSR, the larger is the width of the DI. Obviously, not only the filter width of the DI has an impact on the performance but also the penalty due to the non perfect one bit delay case (FSR≠R) and the amount of ASE passing through the DI.

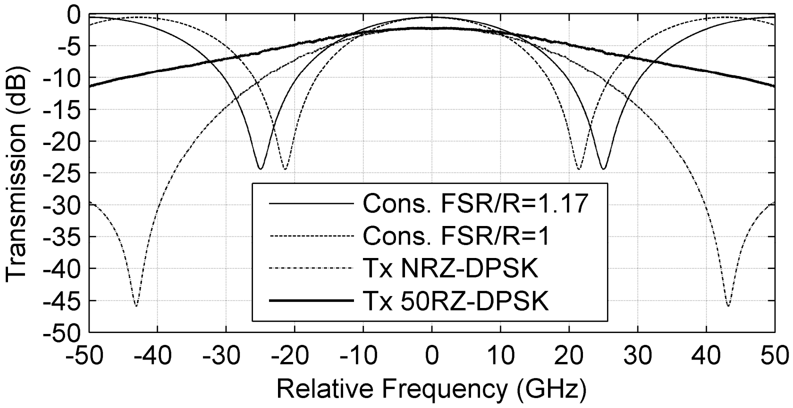

Figure 2. Transmission *D(f)* for the constructive port for FSR/R=1 and 1.17 at 42.8 Gbps.

To assess the impact of the FSR on performance, we have calculated the BER versus FSR/R for different optical filters Bo (1.75R, 0.88R and 0.75R). For every FSR considered, the phase ϕ in Eq. 1 has been adjusted such that the DI is always centered on the carrier wavelength. The BER is converted in Q and relative penalty is calculated by normalizing every filter case by its own optimum Q. The relative penalty is therefore not a measure of absolute performance but helps visualizing the location of the optimum FSR for all the filter cases studied. Figure 3a shows the relative Q penalty as a function of FSR/R for the 50RZ-DPSK format. As expected, for large Bo of 1.75R, the curve is centered around FSR/R=1 and a 10% mismatch leads to less than 0.5 dBQ penalty [1]. For a moderate filtering of Bo=0.88R, the curve clearly shifts toward higher FSR. For a narrow Bo of 0.75R, the curve has shifted even more toward higher FSR and the relative penalty of having a perfect one-bit delay DI is higher than 1 dBQ.

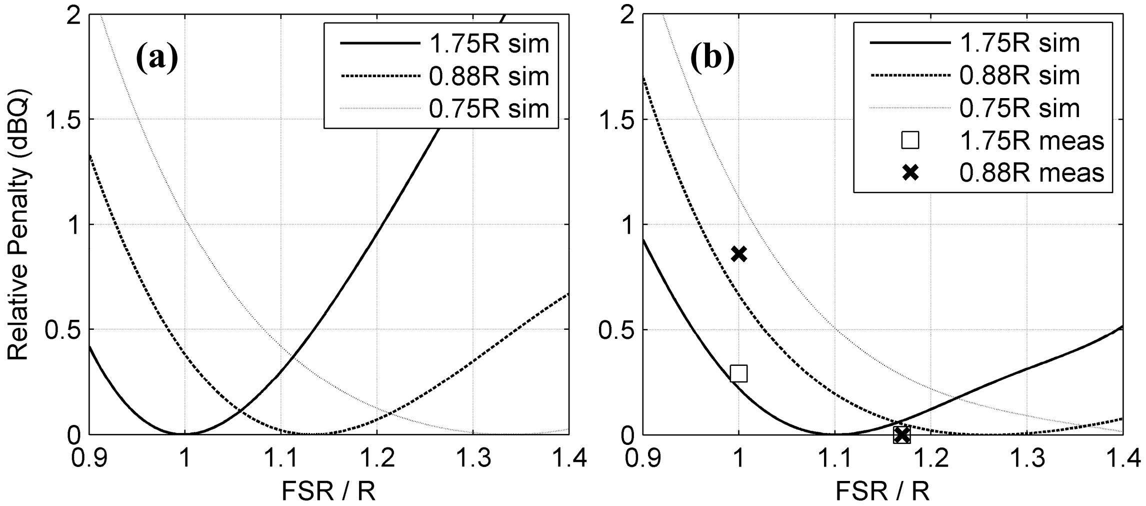

Figure 3. Relative Q penalty vs FSR/R for (a) 50RZ-DPSK. (b) NRZ-DPSK. The OSNR is set to 16 dB.

Figure 3b shows the relative Q penalty as a function of FSR/R for the NRZ-DPSK format. For this format, if one wants to accurately predict the DI penalty versus FSR, the risetime/falltime (or bandwidth) of the Tx has to be taken into account. For the simulation results shown, a Bessel-Thompson of fourth-order with a 3 dBe bandwidth of 19 GHz has been assumed for the Tx effective bandwidth. For large Bo of 1.75R, the optimum is not centered on FSR/R=1 but at FSR/R=1.1. In this case, a larger FSR will perform better than the perfect one-bit delay DI. This result is confirmed experimentally, as shown in figure 3 (squares) at 42.8 Gbps for a 42.8 GHz (FSR/R=1) and a 50 GHz (FSR/R=1.17) DIs. This illustrates that opening up the filter *D(f)* helps reduce intersymbol interference (ISI) of the NRZ signal. For moderate and large filtering effects (Bo of 0.88R and 0.75R respectively), the curves shift toward higher FSR like in the RZ case. For Bo=0.88R, the result was again confirmed experimentally (crosses) and good agreement between measurement and simulation is clearly seen.

5. Conclusion

Optimal DPSK receiver design depends not only on modulation format (RZ vs. NRZ), but also on the optical filtering properties of the DWDM system the channel is to be deployed over. When large effective optical filter bandwidths are present (Bo≥1.75R), a perfect one-bit delay DI yields optimal results for the RZ-DPSK case. For the NRZ-DPSK format, the optimal DI FSR depends on the particular risetime/falltime of the Tx implementation and typically ranges from FSR/R=1 to 1.2. When moderate to strong optical filtering is involved, an FSR/R greater than 1 and smaller than 1.4 helps reducing the optical filtering penalty for both NRZ-DPSK and RZ-DPSK.

6. References

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