An RZ DPSK receiver design with significantly improved dispersion tolerance

D. S. Govan and N. J. Doran

Institute of Advanced Telecommunications, University of Wales Swansea, Singleton Park, Swansea SA2 8PP
d.govan@swansea.ac.uk

http://www.swansea.ac.uk/iat

Abstract: We show an improved DPSK receiver design which can increase useful dispersion tolerance by up to a factor of two. The increased dispersion tolerance is achieved through optimization of the optical filter at the receiver and the delay of the Mach-Zehnder interferometer. In this paper we fully explain the concept, quantify the gain and provide an explanation for the operation of the receiver.

OCIS codes: (060.5060) Phase modulation.

References and links

1. A H. Gnauck, P. J Winzer, "Optical phase-shift-keyed transmission," J. Lightwave Technol **23**, 115-130 (2005). http://ieeexplore.ieee.org/iel5/50/30066/01377439.pdf
2. B. Mikkelsen, P. Rasmussen, P. Mamyshev, F. Liu, "Partial DPSK with excellent filter tolerance and OSNR sensitivity," Electron Lett. **42**, 1363-1364 (2006). http://ieeexplore.ieee.org/iel5/2220/4027802/04027831.pdf?tp=&isnumber=&arnumber=4027831
3. Y. K. Lizé, L. Christen, X. Wu, J.-Y. Yang, S. Nuccio, T. Wu, A. E. Willner and R. Kashyap, "Free spectral range optimization of return-to-zero differential phase shift keyed demodulation in the presence of chromatic dispersion," Opt. Express **15**, 6817 (2007). http://www.opticsexpress.org/abstract.cfm?id=134975
4. C. Hsieh, V. Ai, x. Chien, A. Liu, H. Gnauck, X. Wei, "Athermal demodulator for 42.7-Gb/s NRZ-DPSK signal," in Proc. ECOC 2005 Glasgow, UK, Paper Th1.5.6, 2005. http://www.optoplex.com/PDF/Athermal_DPSK_Demodulator.pdf
5. D. Penninckx, H. Bissessur, P. Brindel, E. Gohin, F. Bakhti, "Optical differential phase shift keying (DPSK) direct detection considered as a duobinary signal," in Proceedings of ECOC 2001, Amsterdam, 456-457, http://ieeexplore.ieee.org/iel5/7749/21330/00989713.pdf
6. A. J. Price, N. Le Mercier, "Reduced bandwidth optical digital intensity modulation with improved chromatic dispersion tolerance," Electron. Lett. **31**, 58-59 (1995), http://ieeexplore.ieee.org/iel1/2220/8346/00364286.pdf?arnumber=364286
7. X. Wei, X. Liu, S. Chandrasekhar, A. H. Gnauck, G. Raybon, J. Leuthold, P. J. Winzer, "40 Gb/s Duobinary and Modified Duobinary Transmitter Based on an Optical Delay Interferometer," in Proc. ECOC 2005, Glasgow, U.K., 2005, Paper Th1.5.6.

1. Introduction

Differential phase shift keying (DPSK) is an important modulation format because of its suitability for high data rate systems. This is largely due to its improved optical signal to noise ratio (OSNR) performance compared to on-off keying (OOK) [1]. Many of the other limitations associated with OOK such as tolerance to chromatic dispersion and polarisation mode dispersion (PMD) are equally limiting to DPSK. It is therefore of interest to discover ways in which the DPSK format may be made more resistant to these impairments, especially when strong filtering is used for improved spectral efficiency.

In a recent paper it was shown that partial demodulation of NRZ-DPSK can increase the performance of the receiver when strong filtering is being used, particularly in the presence of dispersion [2]. The effects noted for NRZ-DPSK in [2], particularly with no dispersion, have a

#87336 - $15.00 USD Received 10 Sep 2007; revised 21 Nov 2007; accepted 25 Nov 2007; published 4 Dec 2007

different origin to those reported here and were in fact caused primarily by the NRZ signal being partially converted to RZ. In another paper, [3], the effects of dispersion and PMD on RZ-DPSK were investigated with partial delay demodulation of the signal. In [3] a limited (12.5%) increase in dispersion tolerance was shown, in this paper we show that further optimization can lead to up to a 100% increase in dispersion tolerance. In particular we find that to gain the full benefit from partial DPSK it is essential to use the correct filter bandwidth, and that this bandwidth is narrower than the typical values used elsewhere.

Partial DPSK (PDPSK) refers to DPSK where the relative delay between the arms of the demodulation Mach-Zehnder interferometer (MZI) at the receiver is less than one bit period [4]. In this case rather than completely interfering with the adjacent bit, each bit partially interferes with the adjacent bit and partially with itself. Although this would normally be expected to cause a penalty [1] when there is dispersion present it is possible to optimize the receiver to give improved performance. In this paper we examine, numerically, the cause of these improvements and show that this can be extended to all RZ DPSK formats including carrier suppressed return to zero (CSRZ) pulse shapes. We also optimize the key parameters in this receiver, the relative delay in the MZI and the filter bandwidth, to maximise the dispersion tolerance that can be achieved. The key point is that matching the filter bandwidth to the partial delay leads to a greatly improved dispersion tolerance without loss of OSNR.

2. System under investigation

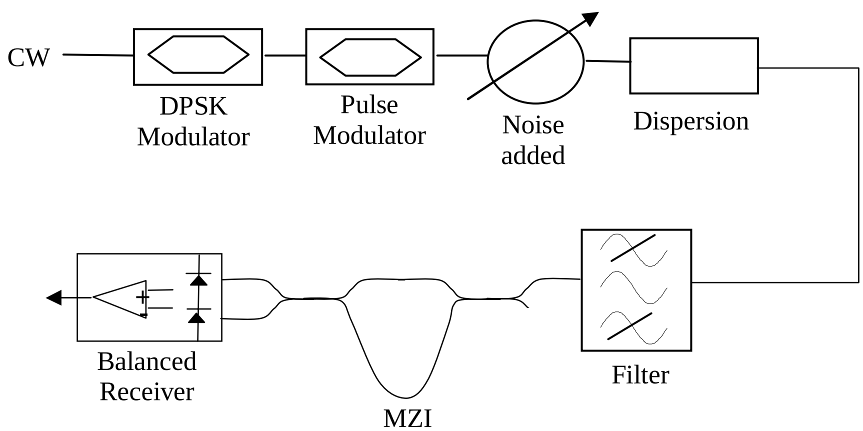

Fig. 1. The system modelled in these simulations. The filter shape and bandwidth were varied as well as the delay in the MZI

The system used for the simulations, Fig. 1, is as follows; a 2^7 PRBS is used to drive a Mach-Zehnder modulator to produce a 42.7GBit/s DPSK optical signal this is followed by a pulse carving MZ-modulator. Noise is then added to the signal and it passes through a short length of fiber to give the required dispersion. The signal is then filtered, goes through the MZI and is finally received using a balanced detector. The bandwidth and shape of the filter and the delay of the MZI were varied to find the optimum value for each dispersion. The default receiver used for comparison contained a 50GHz Gaussian filter with a 1 bit delay in the MZI. Q Values were calculated assuming Gaussian statistics, the OSNR at the input to the receiver was ~20 dB for all calculations.

3. Results

The system described above was investigated with 50% RZ and 67% (carrier suppressed) RZ with dispersions between 0 and 200ps/nm. The delay of the MZI and the filter bandwidth were optimized to give the best performance. A second order Gaussian filter shape was found to be the optimum shape for all dispersions although first order and third order Gaussian

#87336 - $15.00 USD Received 10 Sep 2007; revised 21 Nov 2007; accepted 25 Nov 2007; published 4 Dec 2007

filters were also investigated. We show in Fig. 2 that in all cases the dispersion tolerance was substantially improved by reducing the delay of the MZI and appropriately tuning the filter bandwidth.

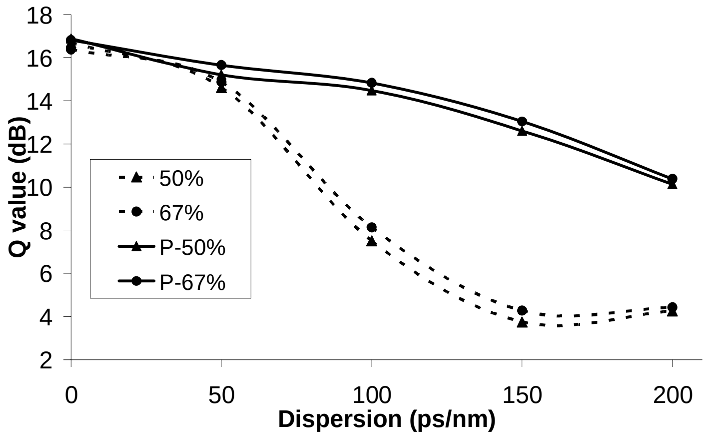

Fig. 2. Q-value as a function of dispersion for the receiver in Fig. 1 and 42.7GB/s transmission. The dotted lines are for a 1 bit delay and a 50GHz filter bandwidth and the solid lines for optimized delay and filter bandwidth the % refer to the RZ mark-to-space ratio.

Figure 2 shows clearly that the dispersion tolerance can be more than doubled by optimizing the delay of the MZI and the filter bandwidth. Taking zero penalty to be our default system with 1 bit delay and 50GHz Gaussian filter the 1dB penalty goes from 30 (40) ps/nm to about 80 (65) ps/nm and the 2dB penalty goes from 55 (55) ps/nm/km to 120 (115) ps/nm/km for RZ (CSRZ). It is also apparent that without this optimization, dispersions greater than ~50ps/nm cannot be tolerated without significant penalty, in the absence of additional compensation e.g. electronic compensation. With dispersion of 50ps/nm an 11.7ps pulse has broadened to 19ps. With the delay and filter optimized more than 100ps/nm can be tolerated with the same penalty, this is equivalent to the 11.7ps pulse broadening to 32ps which is substantially greater than the bit period of 23.4ps at a 42.7Gbit/s data rate. It is also worth noting that the roll off of ‘Q’ with increasing dispersion is quite slow and smooth which would therefore permit very large dispersion tolerance with limited impact on the ‘Q’. For example a very large improvement in ‘Q’ (7dB) can be observed in Fig. 2 for 100ps/nm dispersion.

The effect of optimizing the filter bandwidth and delay of the MZI can be seen most clearly in the contour plots in Fig. 3. The graph on the left shows the Q-value plotted against filter bandwidth and normalized delay in the MZI for a 50% RZ signal with no dispersion in the system. The optimum receiver has delay of approximately 1 bit in the MZI and a filter bandwidth of ~80GHz. The plot on the right shows the same 50% RZ signal after passing through a dispersion of 100ps/nm. The optimum delay has been reduced to 70% of a bit period and the filter bandwidth is reduced to ~36GHz. Similar plots to those in Fig. 3 were produced for other pulse shapes such as NRZ and 67% carrier suppressed RZ and for other values of dispersion. It can be seen from these graphs that there is a general trend that as the delay in the MZI is reduced it is also important to reduce the filter bandwidth. It can be seen from Fig. 3 that when the receiver is optimized for 100ps/nm dispersion the performance degrades more quickly with variation in the filter bandwidth and MZI delay away from the optimum values than it does with no dispersion

#87336 - $15.00 USD Received 10 Sep 2007; revised 21 Nov 2007; accepted 25 Nov 2007; published 4 Dec 2007

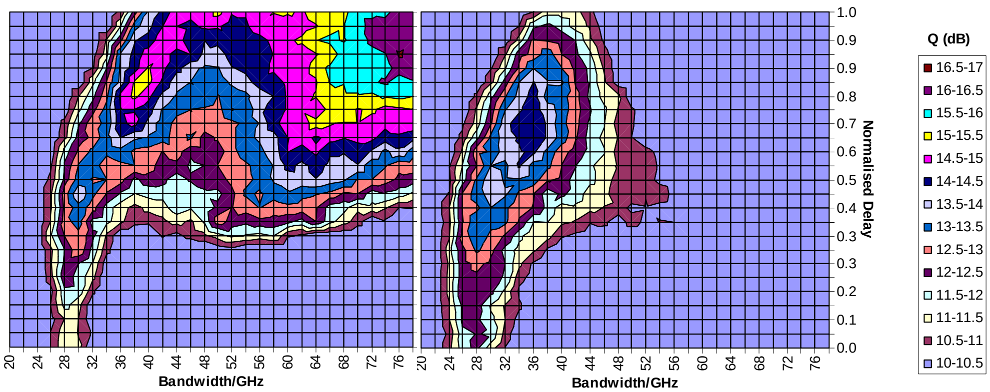

Fig. 3. Q-value plotted against filter bandwidth and normalized delay in the MZI for a 50%-RZ signal with 0ps/nm dispersion (left) and 100ps/nm dispersion (right).

.Full details of the filter bandwidth and delay optimized for a range of dispersions can be found in Fig. 4. Both the filter bandwidth and the delay are significantly reduced to optimize the dispersion tolerance of the receiver. The delay is reduced almost linearly with dispersion to approximately 50% of the bit period. The graph for 67% RZ shows some deviation from the linear reduction as the contour plot for this format is not as well resolved as for 50% RZ leading to some uncertainty in the values to take. The filter bandwidth drops rapidly to approximately 35GHz with 50ps/nm of dispersion and is then almost constant. From this graph it is clear that both a narrow filter and a delay of less than 1 bit period in the MZI are required to get the full benefit from partial DPSK. These results show that to get the maximum dispersion tolerance from reducing the delay it is necessary to have a filter bandwidth of ~35GHz (or 80% of the symbol rate) rather than a more usual filtering of ~50GHz.

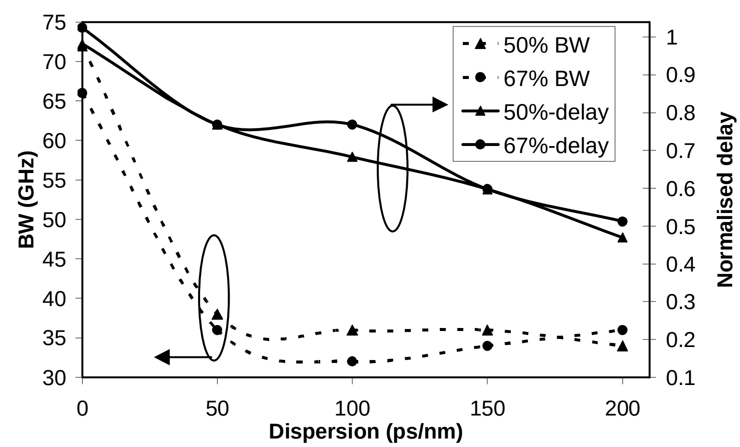

Fig. 4. Filter bandwidth and MZI delay as function dispersion. MZI delay is given with the solid lines and is related to the axis on the right; filter bandwidth is the dashed line and is related to the axis on the left. Both 50% RZ and 67% RZ results are given.

4. Discussion

The reason for the improved dispersion tolerance in the arrangement in Fig. 1 can be understood by looking at the limit of the optimization process. When a DPSK signal is received without a delay interferometer, or equivalently an MZI with no relative delay

#87336 - $15.00 USD Received 10 Sep 2007; revised 21 Nov 2007; accepted 25 Nov 2007; published 4 Dec 2007

between the two arms, and with strong filtering it can be directly detected as a duobinary signal [5]. When this is done balanced detection cannot be used and so the 3dB benefit from using DPSK is no longer present. In fact the contour plots in Fig. 3 can be considered to show a DPSK signal with balanced detection, and the related 3dB benefit in OSNR performance, being received in the top right and a duobinary signal with no benefit from balanced detection but high dispersion tolerance being received in the region nearer the bottom left.

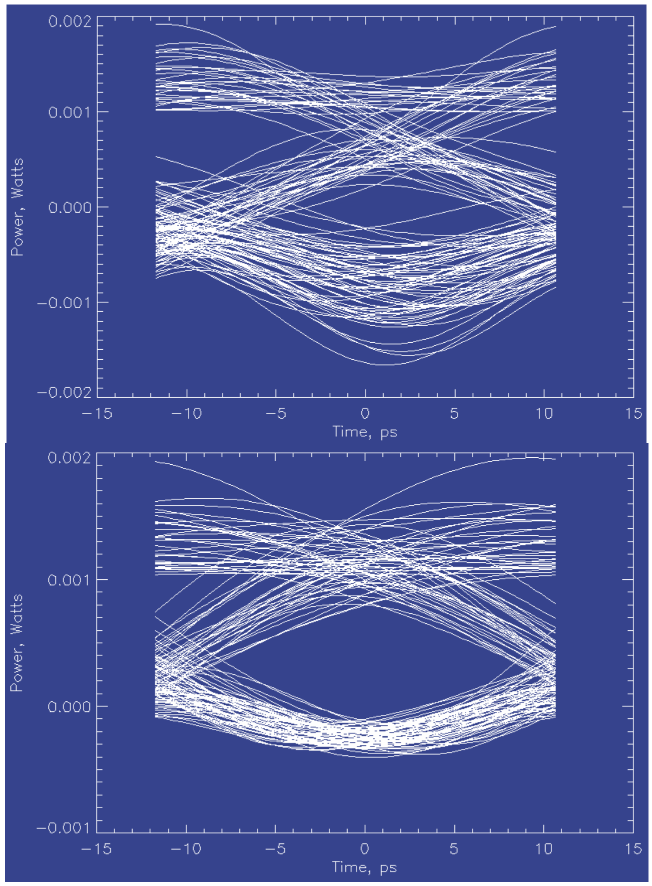

Fig. 5. Eye diagrams for the 50%- RZ DPSK signal after 100ps/nm of dispersion. The top one is for a 1 bit delay and 50GHz filter, the one on the bottom has a 0.67 bit delay and a 36GHz filter.

From this it is clear that as the delay in the MZI is reduced and the filter bandwidth is narrowed the signal is partially being converted to a duobinary signal which are well known for having high dispersion tolerance [6]. In fact when a DPSK signal is received the constructive port of the MZI has a duobinary signal and the destructive one has a modified duobinary signal [7]. The modified duobinary signal has a wider bandwidth and by filtering strongly this signal is largely removed.

As the signal converts to duobinary there is a reduction in the OSNR performance as there is no longer perfectly balanced detection. Eye diagrams illustrating the effect of the optimization can be seen in Fig. 5. The eye-diagrams show the improvement in eye opening when the optimized receiver is used for a 42.7Gbit/s signal with 100ps/nm of residual dispersion. In the upper eye-diagram a normal DPSK receiver is used with a 1 bit delay in the MZI and a filter with a 50GHz bandwidth. The lower eye-diagram shows the same signal received with a 0.67 bit delay in the MZI and a 36GHz filter. It can be seen from the eye-

#87336 - $15.00 USD Received 10 Sep 2007; revised 21 Nov 2007; accepted 25 Nov 2007; published 4 Dec 2007

diagram that with the optimization the appropriate decision level increases from zero. This is an indication that perfect balanced detection is no longer being used. It follows that although with dispersion there is a benefit from using partial-DPSK when no dispersion is present there is a penalty. This can also be seen in the contour plots given in Fig. 3.

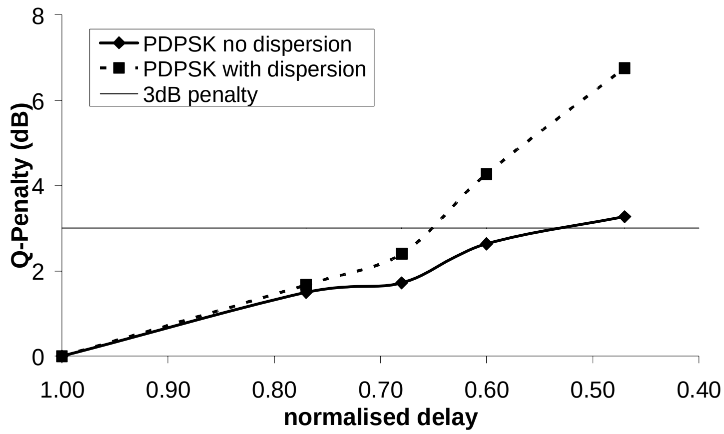

Fig 6. Q penalty at the receiver as a function of MZI delay. The solid line represents the P-DPSK with no dispersion the short dashed line is the same with dispersion and the horizontal line represents a 3dB penalty.

Figure 6 shows the Q-penalty relative to optimized value for 1 bit delay plotted against the MZI delay, the filter bandwidth is optimized to the values given in Fig. 4. The Q-penalties with and without dispersion are shown along with the 3dB penalty. Without dispersion the PDPSK penalty reaches a maximum of 3dB with a delay of 0.55 of a bit period and a filter bandwidth of 34GHz, which is what is expected as the balanced detection is removed. With a delay in the MZI of ~0.8 of a bit period (dispersion 50ps/nm) the dispersion penalty and the OSNR penalty (when using PDPSK) are approximately equal. For shorter delays (used for greater dispersions) there is a clear benefit from using PDPSK with the dispersion penalty increasing more than the OSNR penalty.

5. Conclusions

We have shown that by varying the delay of an MZI and the filter bandwidth at the receiver of a DPSK system it is possible to improve the tolerance to chromatic dispersion. In this paper we have fully optimized both the filter characteristics and the amount of delay used in the MZI to maximize the dispersion tolerance. In particular we found that a filter bandwidth of ~80% of the symbol rate is optimal with the delay varying depending on the amount of dispersion. Using the optimized values we found it is possible to double the dispersion tolerance (i.e. 100% improvement) of a DPSK receiver. We have also shown that the improved dispersion tolerance is obtained by converting partially the DPSK signal into a duobinary signal prior to detection and that this inevitably reduces the OSNR performance however this is more than compensated for through the improved dispersion tolerance in systems with sufficiently large residual dispersion. It is interesting to speculate as to whether there could be advantage in transmitting as DPSK but to receive as pure duobinary using this receiver configuration since DPSK may give the best transmission impairment resilience and duobinary the optimized dispersion tolerance at the receiver. This option has not been directly addressed in this work.

Acknowledgements

This work is part-funded by the European Union through the Welsh Assembly Government

#87336 - $15.00 USD Received 10 Sep 2007; revised 21 Nov 2007; accepted 25 Nov 2007; published 4 Dec 2007