Combination of optical and electronic logic gates for error correction in multipath differential demodulation

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Abstract: We present an optical multipath error correction technique for differentially encoded modulation formats such as differential-phase-shift-keying (DPSK) and differential polarization shift keying (DPolSK) for fiber-based and free-space communication. This multipath error correction method combines optical and electronic logic gates. The scheme can easily be implemented using commercially available interferometers and high speed logic gates and does not require any data overhead therefore does not affect the effective bandwidth of the transmitted data. It is not merely compatible but also complementary to error correction codes commonly used in optical transmission systems such as forward-error-correction (FEC). The technique consists of separating the demodulation at the receiver in multiple paths. Each path consists of a Mach-Zehnder interferometer with a different integer bit delay used in each path. Some basic logic operations follow and the three paths are compared using a simple majority vote algorithm. Experimental results show that the scheme improves receiver sensitivity by 1.5 dB at BER of 10^{-3},in back-to-back configuration. Numerical results indicate a 1.6 dB improvement in the presence of Chromatic Dispersion for a 25% increase in tolerance for a 3dB penalty from ±1220 ps/nm to ±1520 ps/nm. and a 0.35 dB improvement for back-to-back operation.

OCIS codes: (060.2330) Fiber optics communications, (060.5060) Phase modulation , (060.2360) Fiber optics links and subsystems.

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1. Introduction

Differentially encoded optical modulation formats such as differential phase shift keying (DPSK), Quadrature DPSK (DQPSK) and differential polarization shift keying (DPolSK) generated considerable attention in the past 5 years. DPSK is currently under serious consideration as a deployable data-modulation format for high-capacity optical communication systems due to its 3 dB OSNR advantage over intensity modulation and its non-linear tolerance [1-6]. However DPSK OSNR requirements are still 1.2 dB higher than for its coherent counterpart, PSK for a BER of 10^{-3}. Multi-symbol processing strategies have been proposed to reduce this penalty through soft detection, including decision feedback based techniques [7-15], providing ~1-3 dB sensitivity improvements for DPSK optical transmission, however the analog or high-speed digital soft detection feedback electronics remain challenging to implement. It would be advantageous to attain comparable processing gains over multiple demodulation paths with hard detection rather than soft detection, i.e. by applying digital logic processing on the balanced outputs of multiple Mach-Zehnder Delay Interferometers (DLI). Forward error correction (FEC) is now commonly used in most types of long-haul transmission systems. With only a 7% overhead, enhanced FEC (eFEC) can convert a $2\text{x}10^{-3}$ error to $1\ \text{x}10^{-15}$ while Super FEC with a 25% overhead, can correct errors from as low as $6\ \text{x}10^{-3}$ [16]. When error rates exceed those values, FEC becomes somewhat inefficient. It would be useful to have an error correction algorithm that could take a poor error rate and bring it to a FEC-capable error rate without affecting the effective bandwidth of the transmission.

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In this paper we propose and experimentally demonstrate an optical multi-path error correction technique for differentially encoded modulation formats. The scheme can be readily implemented using commercially available DLIs [6] and high-speed logic gates. After optical demodulation and hard detection, basic logic operations are applied on each path to recover the data signal. The partially correlated errors induced by ASE noise are then corrected using a simple majority-vote algorithm [17]. We find through numerical simulations that back-to-back DPSK receiver sensitivity is improved by 0.35 dB at BER of 10^{-3} with optimal filtering and 0.45dB in a 25GHz channel. In chromatic dispersion (CD) –limited channels such as in fiber optic transmission, we numerically obtain a 1.6 dB improvement and the tolerance to CD is increased by 25% from ±1220 ps/nm to ±1520 ps/nm. Experimentally we measured a 1.5 dB sensitivity improvement. The main advantage of the proposed method is that it does not require any data overhead and hence its performance improvement is attained without affecting the effective bandwidth of the transmitted data. This diversity demodulation scheme is compatible with and complementary to error correction techniques commonly used in optical transmission systems such as forward-error-correction (FEC). Since the error correction is obtained through hard detection, it is also compatible with soft electronic distortion compensation schemes such as feed forward equalization (FFE), decision feedback equalization (DFE), and maximum likelihood sequence estimation (MLSE) [18-21]. The scheme is differentiated from [7-14] in that it is a hard detection scheme and could therefore be combined with the other soft detection multipath-methods. Furthermore, we present here an experimental and numerical demonstration at 10 Gbps whereas [7-11, 14] were numerical demonstrations.

2. Theory

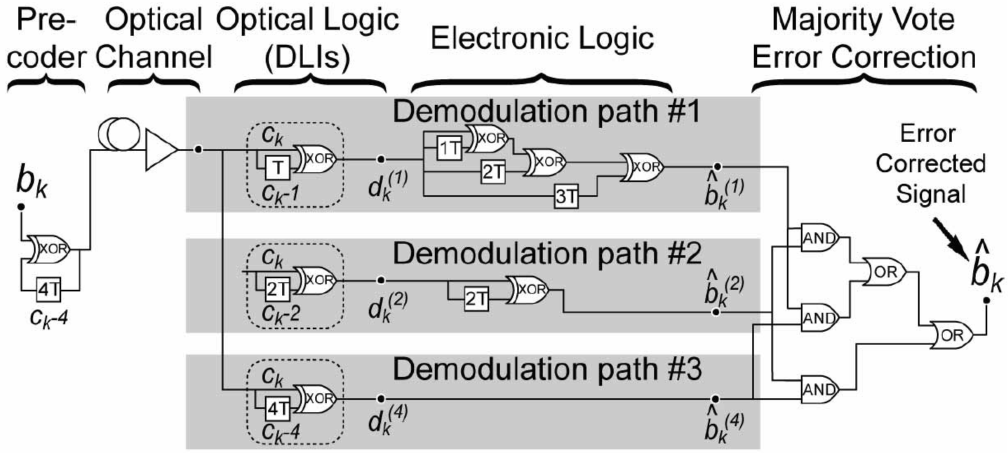

Fig. 1.Conceptual diagram of multipath demodulation with majority vote error correction. The DPSK precoder uses a 4-bit delay. The optical logic is performed by the passive DLI DPSK demodulator. The electronic logic recovers the original signal before majority vote is applied.

The scheme takes advantage of the combination of the optical logical XOR function of the DLI and electronic binary logic gates. A simple logic representation of the system is illustrated in Fig. 1. A modified 4-bit form of Differential Precoding (DP) is performed at the transmitter prior to optical modulation. The received signal is corrupted by amplified spontaneous emission (ASE) noise accumulated along the transmission fiber from amplifiers. Optical demodulation is performed using multiple demodulation paths each consisting of a DLI with a different integer bit-delay. The bits are then detected. The output of the 4-bit delay DLI recovers the proper transmitted bits, since a 4-bit differential precoder is used at the transmitter. Electronic logic blocks consisting of XOR gates and delays follow the outputs of the 2-bit and 1-bit delay DLIs, re-aligning the three paths together. Finally error-correction is performed through a simple majority vote algorithm. The digital processing can be described by Eqs. (1)-(4), where $\oplus, \&, |$ respectively denote the XOR (addition-modulo-2), AND, OR logic functions:

$$c_k = b_k \oplus c_{k-4} \tag{1}$$

represents the differential encoder using a 4 bit delay where b_k is the information message bit in time bin *k*, and c_k is the differentially encoded message transmitted in the channel, as shown in Fig. 1. Next,

$$\begin{gathered} d_k^{(1)} = c_k \oplus c_{k-1} \oplus \varepsilon_k^{(1)} \\ d_k^{(2)} = c_k \oplus c_{k-2} \oplus \varepsilon_k^{(2)} \\ d_k^{(4)} = c_k \oplus c_{k-4} \oplus \varepsilon_k^{(4)} \end{gathered} \tag{2}$$

represent the optical differential demodulations for the 1-bit, 2-bit and 4-bit delay DLIs, where d is the data after optical demodulation of c, and e is the noise in the transmitted time bins. Then

$$\begin{gathered} \hat{b}_k^{(1)} = d_k^{(1)} \oplus d_{k-1}^{(1)} \oplus d_{k-2}^{(1)} \oplus d_{k-3}^{(1)} \\ \hat{b}_k^{(2)} = d_k^{(2)} \oplus d_{k-2}^{(2)} \\ \hat{b}_k^{(4)} = d_k^{(4)} \end{gathered} \tag{3}$$

represent the electronic XOR gates necessary to realign all 4 paths to the initial signal where

$$\hat{b}_k = \hat{b}_k^{(1)} \,\&\, \hat{b}_k^{(2)} \mid \hat{b}_k^{(1)} \,\&\, \hat{b}_k^{(3)} \mid \hat{b}_k^{(2)} \,\&\, \hat{b}_k^{(3)} \tag{4}$$

represents the majority vote error correction algorithm using the bit stream from all three DLIs.

Referring to the bit intervals *T*=1/*R* (with *R* the bitrate) the DP performs a modulo-2 addition of the current transmitter output bit with the input data bit 4*T* seconds earlier, i.e. it implements an accumulator with 4-bit delay, whereas conventional DPSK uses a DP with 1-bit delay.

First, assume that there are no errors, i.e. $\varepsilon_k^{(1)} = \varepsilon_k^{(2)} = \varepsilon_k^{(4)} = 0$. Applying the identity $a \oplus a = 0$, it follows from (1)-(4) that the output of the 4-bit delay DLI (yielding the estimate $\hat{b}_k^{(4)}$) correctly recovers the transmitted stream, and so do $\hat{b}_k^{(2)}$ and $\hat{b}_k^{(1)}$:

$$\hat{b}_k^{(4)} = d_k^{(4)} = c_k \oplus c_{k-4} = b_k \oplus c_{k-4} \oplus c_{k-4} = b_k$$
$$\hat{b}_k^{(2)} = d_k^{(2)} \oplus d_{k-2}^{(2)} = \left(c_k \oplus c_{k-2}\right) \oplus \left(c_{k-2} \oplus c_{k-4}\right)$$
$$= c_k \oplus c_{k-2} \oplus c_{k-2} \oplus c_{k-4} = c_k \oplus c_{k-4} = d_k^{(4)} = b_k$$
$$\hat{b}_k^{(1)} = d_k^{(1)} \oplus d_{k-1}^{(1)} \oplus d_{k-2}^{(1)} \oplus d_{k-3}^{(1)}$$
$$= c_k \oplus c_{k-1} \oplus c_{k-1} \oplus c_{k-2} \oplus c_{k-2} \oplus c_{k-3} \oplus c_{k-3} \oplus c_{k-4} = c_k \oplus c_{k-4} = b_k \tag{5}$$

Extending the model to include the additively injected error indicators $\varepsilon_k^{(i)}, i = 1, 2, 4$ at the DLI outputs yields after some manipulation

$$\hat{b}_k^{(\Delta)} = b_k \oplus \eta_k^{(i)}, \;\; i \in \{1, 2, 4\} \tag{6}$$

where $\eta_k^{(i)}$ are effective binary noise streams at the majority-vote input, given by

$$\eta_k^{(1)} \equiv \varepsilon_k^{(1)} \oplus \varepsilon_{k-1}^{(1)} \oplus \varepsilon_{k-2}^{(1)} \oplus \varepsilon_{k-3}^{(1)}, \qquad \eta_k^{(2)} \equiv \varepsilon_k^{(2)} \oplus \varepsilon_{k-2}^{(2)}, \qquad \eta_k^{(4)} \equiv \varepsilon_k^{(4)} \tag{7}$$

Notice that the underlying noise bits of the form $\varepsilon_k^{(i)}$ are not statistically independent, hence nor are the effective noise bits $\{\eta_k^{(1)}, \eta_k^{(2)}, \eta_k^{(4)}\}$ independent.

It is apparent that (6) defines an effective binary channel wherein b_k repetition-coded with 3-fold diversity, i.e. the same bit is transmitted over three scalar binary channels corrupted by the partially correlated effective noises. The proposed decoding scheme applies a simple majority-vote strategy reducing the probability of errors, relative to a single use of either one of the three paths, and also provides improvement relative to conventional DPSK. When errors are uncorrelated in each demodulation path, the correction rate of majority vote is determined by the individual Error Rates (ER):

$$\left[ER^{(1)} \cdot ER^{(2)} \cdot \left(1 - ER^{(4)}\right)\right] + \left[ER^{(1)} \cdot \left(1 - ER^{(2)}\right) \cdot ER^{(4)}\right] + \left[\left(1 - ER^{(1)}\right) \cdot ER^{(2)} \cdot ER^{(4)}\right]$$

This is the upper limit of majority vote error detection. Since there is only partial correlation between the effective noise bits, there is a low probability that two or three of the paths assume the same value simultaneously. The majority vote correction method is analogous to what has been proposed in the RF domain at MHz speed [17]. Combining soft FEC or soft detection techniques with this method could be done immediately after the interferometers in Fig. 1 before a hard decision is made to obtain $d_k^{(1)}, d_k^{(2)}, d_k^{(4)}$.

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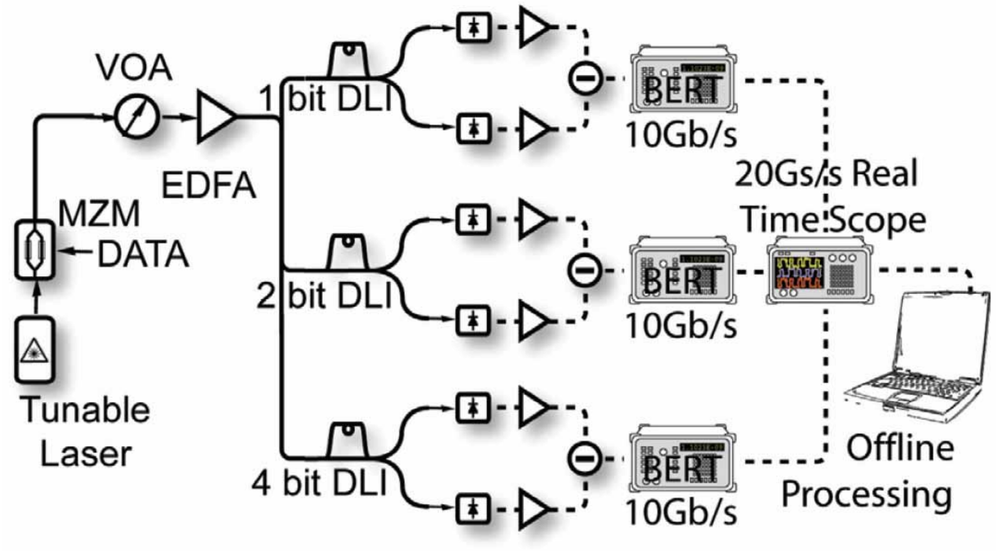

Fig. 2. Experimental setup for the demonstration of multipath DPSK demodulation majority vote error correction. Using 3 commercial DLIs, three 10Gbps bit error rate tester and a 20Gs/s real time scope. Logic operations were processed offline.

3. Results

Monte Carlo simulations were performed using a 2^{15}-1 pseudo random bit sequence (PRBS) at 10Gbps with 12.5 GHz optical filter and 8 GHz electrical filtering at the receiver. Using these parameters we find an improvement in receiver sensitivity of 0.35dB at BER of 10^{-3} as illustrated in Fig. 3. Our simulation of BER versus OSNR curve for standard back-to-back DPSK, which would overlap with the 4 bit delay demodulation in Fig. 3, agrees with previously published results [9] wielding confidence in our numerical results. Figure 3 also provides the theoretical limit of majority vote error correction (ideal majority vote) assuming the errors were completely uncorrelated, confirming that in multi-path demodulation, errors are partially correlated. The theoretical limit when the demodulation paths are completely independent allows a $1.2\text{x}10^{-2}$ error rate to become 2 $\text{x}10^{-3}$ suitable for eFEC or it allows a $2.1\text{x}10^{-2}$ error rate to reach $6\text{x}10^{-3}$ suitable for Super FEC. In a back-to-back transmission, errors are somewhat correlated in each demodulation path such that the coding reduces, correcting a $2.6\text{x}10^{-3}$ BER to a $2\text{x}10^{-3}$ BER and $6.92\text{x}10^{-3}$ BER to a $6\text{x}10^{-3}$ BER. Transmission impairments (i.e. chromatic dispersion (CD), polarization mode dispersion (PMD), non-linear phase noise, cross-phase-modulation), and receiver degradations (i.e. non-ideal filtering, DLI's frequency offset) result in decorrelated errors between demodulation paths. Figure 3, also illustrates that error propagation due to the 4-bit precoding doubles the errors of the 2-bit delay demodulation and quadruples the errors in the 1-bit delay. Nonlinear phase is an important degradation in DPSK transmission systems. The other multipaths schemes [7-14] also exhibited increased performance in the presence of nonlinear degradations, which can explain the decorrelation of errors between the paths. We would expect majority vote error correction to perform closer to its theoretical limit in the presence of non-linear phase.

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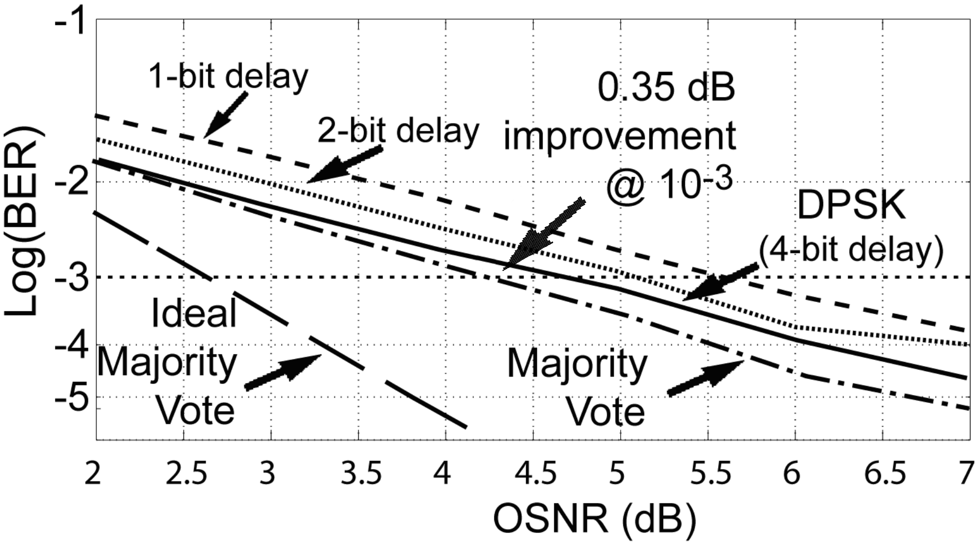

Fig. 3. Numerical results for the 1 bit-delay, the 2 bit delay and 4-bit delay paths and majority vote. Ideal majority vote performance if errors were uncorrelated is shown.

We performed experimental verification using the setup illustrated in Fig. 2. A 2^{15}-1 PRBS pattern was phased modulated at 10Gbps and then sent through a variable attenuator and erbium amplifier. The DPSK demodulators from ITF Laboratories had FSR's of 10GHz, 5GHz and 2.5GHz providing 1, 2 and 4 bit delay. A 70 Ghz optical filter was used and the 3 photodiodes had bandwidths of approximately 8GHz. The three paths were detected simultaneously using three receivers and three bit-error-rate testers. Only the destructive arm of the DLI was detected since we lacked access to three balanced receivers. The detected bits were then fed into a 20Gsample/s real time oscilloscope with sufficient memory for offline-process of 500 000 bits for each path.

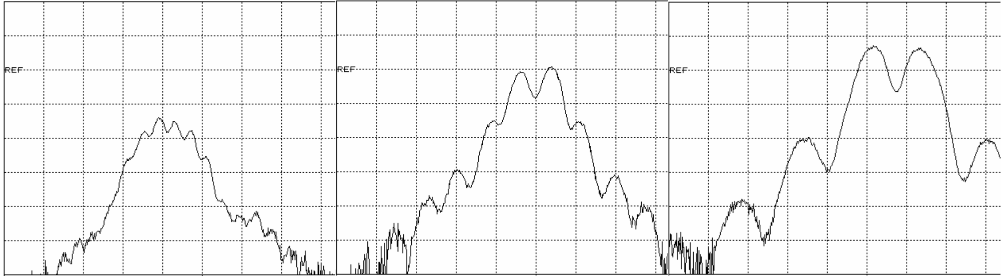

Fig. 4. Optical spectra for the destructive arm of the 4 bit delay (2.5 GHz) , 2bit delay (5 GHz) and 1 bit delay (10 GHz) demodulators on an optical spectrum analyzer (OSA). The longer delays were passive devices resulting in asymmetric spectra.

Figure 4 illustrates the optical spectra at the destructive arm of the 4 bit delay (2.5 GHz), 2bit delay (5 GHz) and 1 bit delay (10 GHz) demodulators, as measured on an optical spectrum analyzer (OSA). Figure 5 illustrates the experimental eye diagrams of the destructive port for 4 bit delay, 2bits delay and 1 bit delay demodulator. The longer delays were passive devices in our experiment making them more difficult align the frequency of the laser to the transmission frequency of the DLI. This can be seen by asymmetric spectra and noisy eye diagrams.

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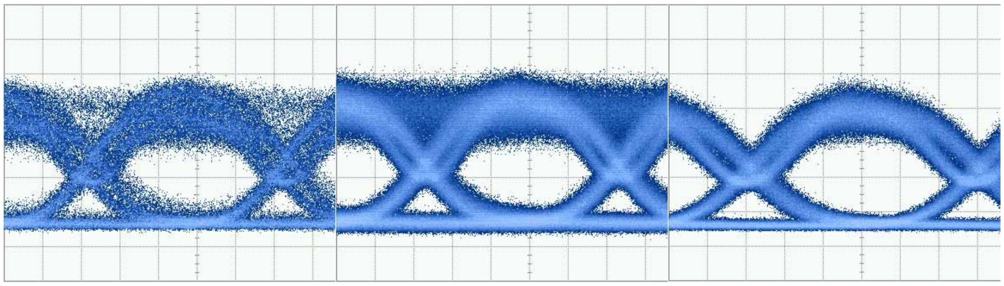

Fig. 5. Eye diagrams of the destructive port for 4 bit delay, 2bit delay and 1 bit delay demodulator. The longer delays demodulator were passive devices in our experiment making them more difficult to align the frequency of the laser to the transmission frequency of the DLI which resulted in a penalty.

The experimental BER improvement is illustrated on Fig. 6. At a BER of 10^{-3}, the back-to-back improvement is 1.5dB and the method was demonstrated capable of correcting a 5 x 10^{-2} to 2 x 10^{-3} for eFEC and of 1 x 10^{-2} to 6 x 10^{-3} for SuperFEC.

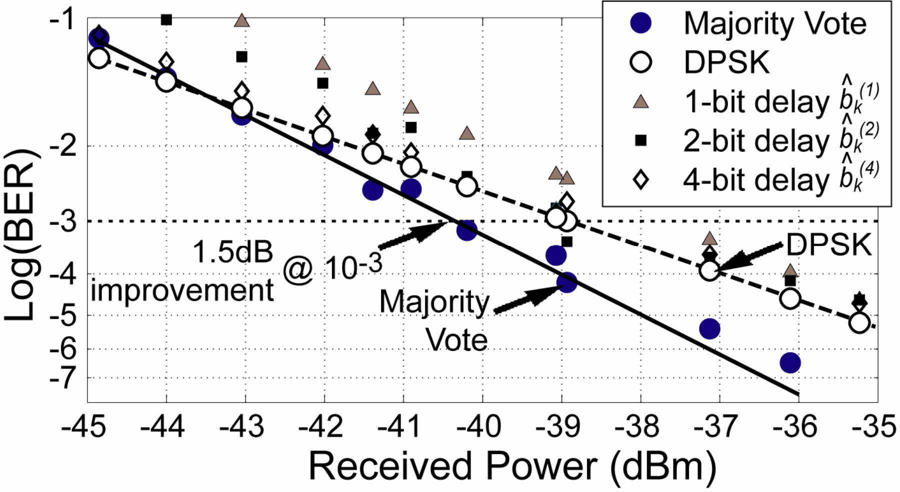

Fig. 6. Experimental results for the 3 paths and the majority vote combined output. A 1.5dB is observed at BER 10^{-3} in back-to-back configuration. The better experimental results are a results of errors being decorrelated between path due to non-optimal optical and electrical filtering and modulator driving voltage slightly less than $2V\pi$.

To explain the superior experimental performance we simulated the required OSNR for a BER of 10^{-3} at 10Gbps for different combinations of optical and electrical filtering bandwidth. Figures 7 & 8 illustrate the simulated contour plots. With majority vote error correction, the effect of optimizing the optical filtering is less significant which can be quite advantageous in multi-wavelength system where filtering is limited to the wavelength demultiplexer. The discrepancy can then be partly explained as due to non-ideal optical and electrical filtering in our experiment. The experimental discrepancy is further explained by frequency offsets on the longer delay DLIs which creates uncorrelated errors [22] in the three paths, thus bringing the performance of majority vote error correction closer to the ideal majority vote theoretical error correction limit illustrated in Fig. 3.

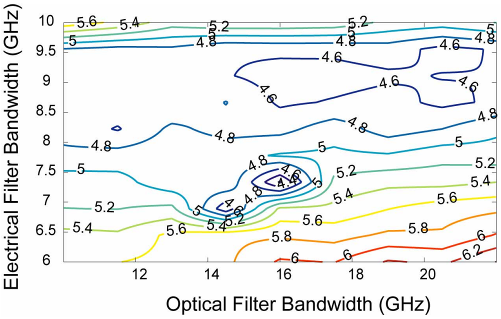

Fig. 7. DPSK contour plot of required OSNR at BER 10^{-3} for electrical and optical filter bandwidth combination.

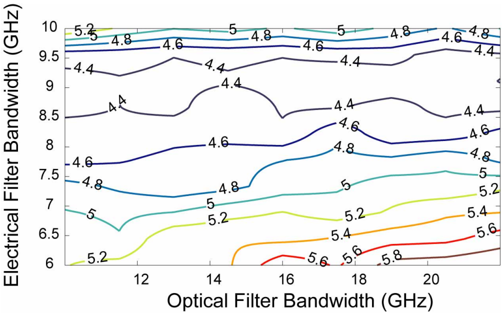

Fig. 8. Majority vote multipath demodulation contour plot showing very good tolerance to optical filtering.

4. Chromatic dispersion sensitivity

Chromatic dispersion in the demodulated signal may lead to beneficial decorrelation of the errors in each path. Such uncorrelated errors improve the performance of the method by bringing the correction efficiency closer to the theoretical limit illustrated in Fig. 3. Figure 5 illustrates numerical results for CD sensitivity. The baseline curve matches previously reported results for CD tolerance for NRZ-DPSK and as expected, majority vote provides a 1.6 dB improvement at a BER of 10^{-3}. Chromatic dispersion tolerance for a 3dB penalty is increased by 25% from ±1220 ps/nm to ±1520 ps/nm.

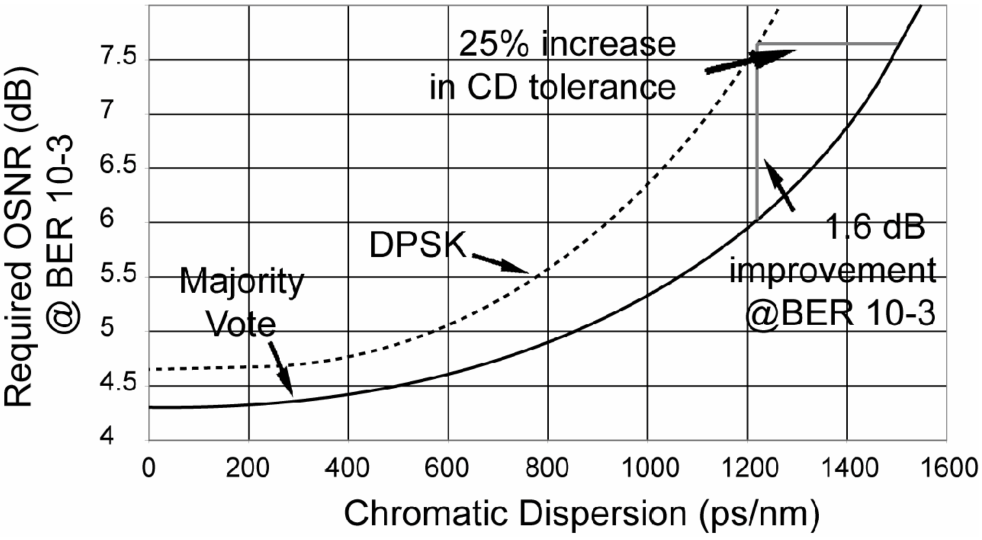

Fig. 9. OSNR penalty versus CD for DPSK and majority vote demodulation. A 25% increase in CD tolerance is found for a 1.6dB improvement at BER=10^{-3}.

5. Conclusion

We proposed and demonstrated experimentally and numerically an optical multi-path demodulation error correction technique for differentially encoded modulation formats. By combining optical and electronic logic gates we find that DPSK receiver sensitivity is improved by 0.35 dB numerically and 1.5 dB experimentally at BER 10^{-3}.The method increases chromatic dispersion tolerance by 25% while increasing optical and electrical filtering tolerances. The method does not require any error correction overhead and is complementary to other electronic distortion compensation schemes such as MLSE and DFE, and error correction algorithms such as forward-error-correction (FEC).

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