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Maximum Likelihood Sequence Estimation for Chromatic-Dispersion Compensation in 4-ASK Modulation Format

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Abstract

Maximum likelihood sequence estimation is found to greatly relax the difficulty of level-spacing optimization in CD-varying 4-ASK optical networks and significantly enhance the CD tolerance by at least a factor of two.

1 Introduction

4 amplitude shift keying (4-ASK) is a promising cost-effective spectral-efficient modulation format to extend the transmission capacity. By operating at only half of the bit rate, 4-ASK not only improves the tolerance to chromatic dispersion (CD) compared to on off keying format [1-3], but also alleviates the speed limitation of electrical and optical components.

The CD in optical networks may change frequently due to the time-varying effects of the installed fibers and different routing paths. In the CD-varying optical systems, the level-spacing optimization of the 4-ASK signal is difficult. It is because the optimal level spacing changes with CD values, and improper level-spacing design will lead to significant CD tolerance reduction.

In this paper, we propose to use maximum likelihood sequence estimation (MLSE) for 4-ASK signal detection. It is shown that MLSE can effectively alleviate the sensitivity of CD tolerance to level spacing, therefore, relax the difficulty of level-spacing optimization. By using MLSE, the CD tolerance of the 4-ASK signal is significantly enhanced by at least a factor of two.

2 System Model

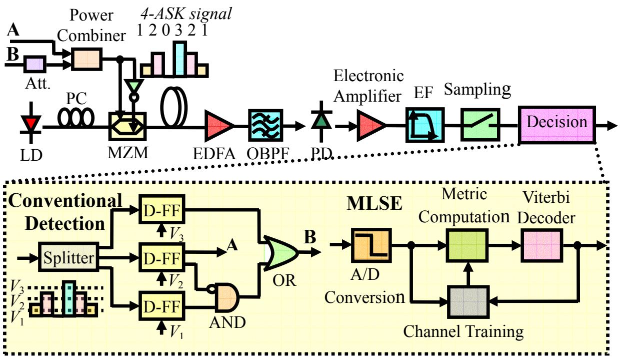

Figure 1: System Model

Fig. 1 shows the system model. 10-Gs/s 4-ary electrical signal is generated by combining two binary sources, *A* and *B*, using a power combiner. Attenuator is used before the source *B* to adjust the level spacing of the 4-ASK signal. A continuous wave light is modulated by the 4-ASK electrical signal using a Mach-Zehnder modulator (MZM). The generated optical 4-ASK signal is fed into a piece of fiber where CD is introduced. At the receiver, the signal is optically pre-amplified, filtered by a Gaussian-shaped optical bandpass filter (OBPF) and detected. After O-E conversion, the electrical 4-ASK signal is amplified, filtered by a 4th-order Bessel electrical filter (EF), sampled, and decoded conventionally or by MLSE. The optical and electrical filter bandwidths are optimized and are found to be 20 GHz and 8 GHz, respectively. Analog to digital (A/D) converter in MLSE has 5-bit resolution. MLSE is a 16-state machine and its metric, $PM(b_k)$, is:

$$PM(b_k) = PM(b_{k-1}) - \sum_{t_j} \log(p(I(t_j) \mid b_{k-m},\ldots,b_k)) \qquad (1)$$

For one sample per bit, $t_j=(k-m/2)T$. For two samples per bit, $t_j=(k-m/2)T$, or $(k-(m+1)/2)T$. b_k and $p(I(t_j) \mid b_{k-m},\ldots, b_k)$ are 4-ASK logical data and the probability of the received signal value at $t=t_j$ given the logical data $b_{k-m},\ldots, b_k$. m is the memory length. The initial metric of MLSE is obtained using nonparametric histogram method. The performance is evaluated in terms of the required E_b/N_0 (received photon number per bit) to achieve BER of 10^{-9} for analytical investigation and 10^{-4} for simulation. E_b and N_0 are the optical average power in one bit slot and the preamplifier's noise power spectral density.

3 Dependency of CD Tolerance on Level Spacing without MLSE

Karhunen Loeve expansion and saddlepoint approximation are used for the analysis at a BER of 10^{-9} in this section. Fig. 2 shows the $\log_{10}$(BER) versus E_b/N_0 for both matched filter (circles) and practical filter in the adopted system (triangles). From the figure, it is shown that the 4-ASK signal by using practical filter has around 2-dB penalty compared to that by using matched filter. The required back-to-back E_b/N_0 for the adopted system at

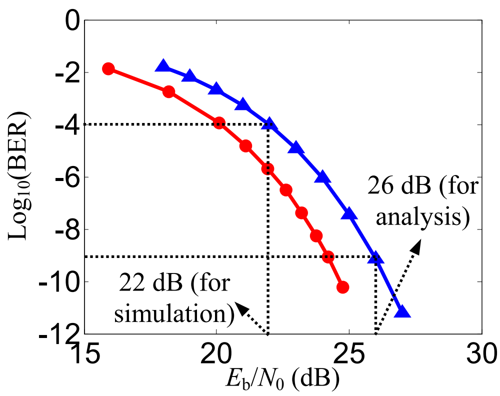

Fig. 2: BER versus E_b/N_0 for 4-ASK signals under matched filter (circles) and practical filter in the adopted system (triangles).

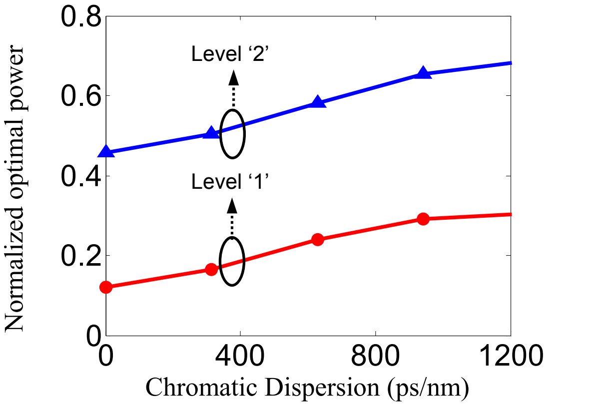

Fig. 3: Normalized optimal power for level ‘1’ and level ‘2’ versus CD at BER=10^{-9}. Magnitudes of level ‘0’ and ‘3’ are 0 and 1, respectively.

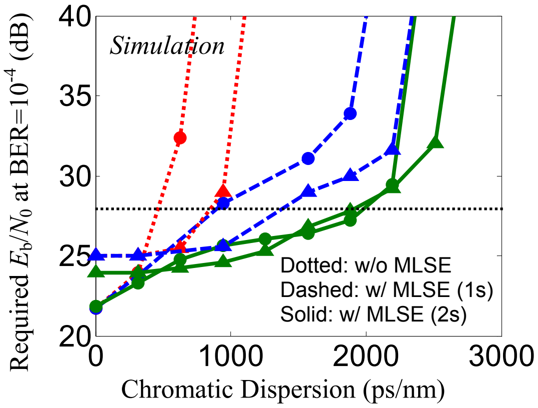

Fig. 5: Required E_b/N_0 versus CD for 4-ASK signal with level spacing optimized at 0 ps/nm (circles) and 700 ps/nm (triangles).

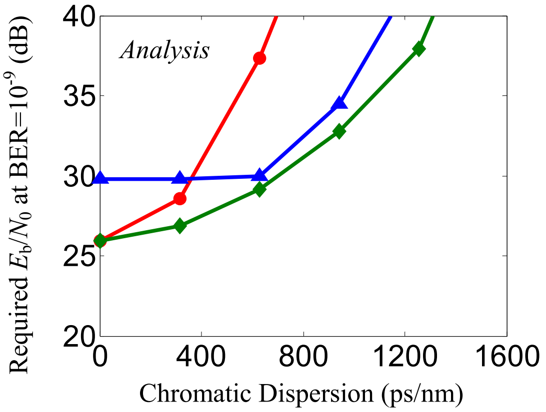

Fig. 4: Required E_b/N_0 versus CD for 10-Gs/s 4-ASK signal with level spacing optimized at 0 ps/nm (circles), at 700 ps/nm (triangles), and at every CD value (diamonds).

BER of 10^{-4} and 10^{-9} are around 22 dB and 26 dB, which will agree with the results in Fig. 4 & 5.

Fig. 3 shows the optimal power for level ‘1’ and level ‘2’ versus CD, where the optical power is normalized by that of level ‘3’. From the figure, it is shown that optimal level spacing changes with CD values. Because the lower eyes of the 4-ASK signal is vulnerable to CD-induced ISI, higher powers are required for level ‘1’ and level ‘2’ as CD value increases. However, in practice, after the initial system design, the level spacing is usually fixed regardless of CD variations. Therefore, it is desirable to find out the CD tolerance under a fixed level spacing. Fig. 4 depicts the CD tolerance of 10-Gs/s 4-ASK signal with level spacing optimized at (i) 0 ps/nm (circles), (ii) 700 ps/nm (triangles), and (iii) every CD value (diamonds) (the ideal case). It is shown that case (i) is worse than case (ii) and (iii) for CD values larger than 400 ps/nm. For case (ii), the required E_b/N_0 for large CD value approaches to that with case (iii). However, compared to case (i), case (ii) has several dB’s penalty for small CD values. Without MLSE, the performance trade-off for small and large CD values complicates the level-spacing optimization in CD-varying 4-ASK optical networks.

4 MLSE for CD Compensation in 4-ASK Format

In this section, Monte Carlo simulations are performed to investigate the performance of MLSE for CD compensation in 4-ASK format at BER of 10^{-4}. Fig. 5 shows the required E_b/N_0 versus CD for different level spacings without MLSE (dotted), with one-sample per bit MLSE (dashed), and with two-sample per bit MLSE (solid). Circles and triangles represent the level spacing optimized at 0 ps/nm and 700 ps/nm, respectively. From the figure, it is found that MLSE using one- or two-sample per bit can significantly enhances the CD tolerance of 4-ASK signal. For two-sample per bit MLSE, CD tolerance is improved by at least a factor of two for both level-spacing designs. Furthermore, with two-sample per bit MLSE, the back-to-back sensitivity of 4-ASK signal with level spacing optimized at 700 ps/nm is improved by 1 dB. At E_b/N_0 of 28 dB, the CD tolerances for the two different level-spacing designs are both around 2000 ps/nm, more than two times of that without MLSE. Therefore, by using two-sample per bit MLSE, the sensitivity of CD tolerance to level spacing is alleviated.

5 Conclusions

We have showed that optimal level spacing of 4-ASK signal changes with CD values and improper level-spacing design leads to significant CD tolerance reduction. As a result, level-spacing optimization is difficult in CD-varying 4-ASK optical systems. We propose MLSE for 4-ASK signal detection. It is found that MLSE can effectively alleviate the sensitivity of CD tolerance to the level spacing, thus relax the difficulty of level-spacing optimization. By using MLSE, the CD tolerance of 4-ASK format is significantly enhanced. At E_b/N_0 of 28 dB, MLSE can enhance the CD tolerance of the 4-ASK signal to 2000 ps/nm, more than two times of that without MLSE. Thus MLSE makes the cost-effective 4-ASK a promising format to extend the transmission capacity of optical networks. This work is supported in part by HK CERG Grant CUHK411005.

6 References

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