Multilevel ASK Amplitude Level Optimization in the Presence of Chromatic Dispersion and PMD

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Abstract

Offering reduced bandwidth occupancy and increased symbol duration, multilevel modulation formats promise a higher robustness towards chromatic dispersion (CD) and polarization mode dispersion (PMD) than binary formats. Especially for multi-level amplitude shift keying formats, which are promising candidates for cost efficient future metro networks at 100 Gb/s, this robustness substantially depends on the choice of the amplitude levels for the format. For example, optimum levels for maximum back-to-back receiver sensitivity do not necessarily lead to the highest CD or PMD tolerance. Within this paper, we show the influence of CD and PMD on the transmitted multi-level signal. We introduce four different methods of choosing the amplitude levels and determine the resulting impairment tolerance of the modulation formats. The results show that the requirements of every format are different depending on the impairment. The considered modulation formats are 2-,4- and 8-ASK in unipolar and bipolar forms. Bipolar ASK formats are generated as a mixture of ASK and differential binary phase shift keying (DBPSK).

1 Introduction

Future optical metro networks require low complexity and cost efficient modulation formats, which enable transmission at 100 Gb/s on existing fiber installations. To meet these demands, multilevel amplitude shift keying (ASK) formats in unipolar and bipolar constellations are promising candidates [1-5]. Since their symbol rate is lower than the data rate they offer high spectral efficiency and therefore increased tolerance towards chromatic dispersion (CD). This is important, since at high data rates, even a small amount of uncompensated chromatic dispersion might lead to strongly decreased system performance. Moreover, increased symbol duration leads to improved polarization mode dispersion (PMD) tolerance. These positive effects are accompanied by a reduced robustness towards inter symbol interference (ISI) due to the higher number of signal levels. ISI in combination with the nonlinearities of the optical transmission system leads to non-uniform closure of the multilevel eyes. Apart from the Kerr nonlinearity of the fiber itself, important nonlinearities are the Mach-Zehnder modulator (MZM) and the photo diode. Within this paper we show that the benefit due to reduced signal bandwidth is only attainable if the amplitude levels of the multilevel signals are optimized. We consider chromatic dispersion and PMD of first order, given by a constant value for the differential group delay (DGD). The requirements concerning the amplitude levels are different for both impairments.

2 Simulation Setups

The simulation setup for unipolar ASK is shown in **Fig. 1**. One data stream is split into $m=\log_2(M)$ parallel data streams $d_0\ldots d_{m-1}$ which are Gray-encoded into an M-level electrical signal. This signal drives a Mach-Zehnder modulator (MZM) using its full characteristics. After the MZM an optical bandpass filter is applied, emulating the multiplexer in a wavelength division multiplexing (WDM) system.

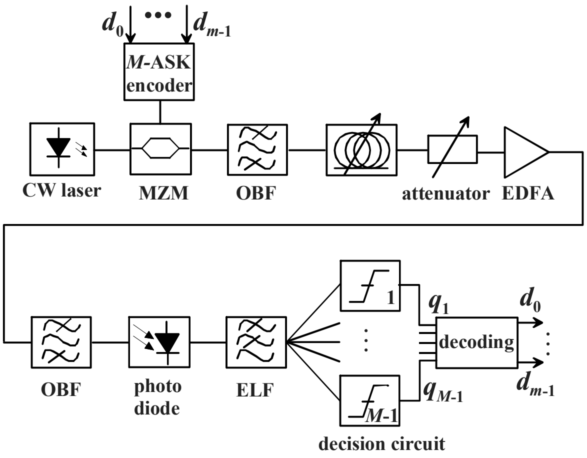

Fig. 1 Simulation setup for unipolar direct detection NRZ-*M*-ASK. Optical bandpass filters (OBF) and electrical lowpass filters (ELF) are optimized for individual modulation formats. CD or DGD is varied.

The variable impairment is either chromatic dispersion (in a lossless fiber) or differential group delay. In the second case, only PMD of first order is considered. The signal is split into two polarizations. It is assumed that the same amount of signal power travels along the slow and the fast axis, respectively, resulting in a splitting factor of $\gamma = 0.5$, which is the worst case. The variable impairment is followed by an erbium doped fiber amplifier (EDFA) with attenuator for noise loading and optical signal-to-noise-ratio (OSNR) variation. At the receiver side, another optical bandpass filter forms the WDM demultiplexer. Both bandpass filters are Gaussian filters of third order with a bandwidth of 1.5 x data rate R for 2-ASK, $0.95R$ for 4-ASK and $0.63R$ 8-ASK. After the photo diode, an electrical Bessel filter of fifth order reduces the noise and limits the bandwidth of the receiver electronics. Its 3dB-bandwidth is $0.74R$, $0.68R$ and $0.37R$ for 2-, 4-, and 8-ASK, respectively. After the electrical filter an M-1 decision and decoding logic according to [2] recovers the transmitted data. As a measure for signal quality the OSNR for a bit error ratio of $5 \cdot 10^{-4}$ is determined.

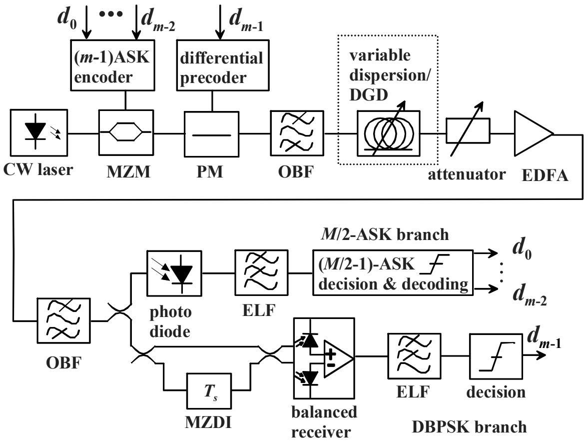

Fig. 2 Simulation setup for bipolar direct detection NRZ-M-ASK, a mixture of (M/2)-ASK and DBPSK Optical bandpass filters (OBF) and electrical lowpass filters (ELF) are optimized for individual modulation formats. CD or DGD is varied.

The system setup for bipolar modulation formats is shown in **Fig. 2**. It consists of an M/2-ASK transmission branch which resembles the unipolar ASK-transmitter with m-1 data streams. However, the MZM is followed by an additional phase modulator which adds a phase shift of π to the signal, according to the mth data stream which is differentially precoded. At the receiver side the M/2-ASK branch is detected by an (M/2-1)-level decision and decoder logic and the phase modulation is detected by a Mach-Zehnder delay interferometer followed by a balanced receiver. The bandwidth for optical and electrical filters are given by $1.5R$, $0.95R$ and $1.43R$ (2-, 4- and 8-ASK bipolar) for the optical filters and by $0.74R$, $0.37R$ and $0.25R$ (2-, 4- and 8-ASK bipolar) for the electrical filters, which are assumed to be equal in the M/2-ASK and the DBPSK branch. For all modulation formats non-return-to-zero (NRZ) pulse shape is considered.

3 Amplitude Level Optimization

Chromatic dispersion leads to a complex impulse response of the optical fiber. Although the input signal is real, CD will lead to a complex output. Actually, the fiber impulse response adds an imaginary part to the envelope of the electrical field, which real in case of M-ASK. For signal levels higher than zero this will result in a phase shift. In contrast, for the zero the complex envelope at the output of the fiber will nearly only be imaginary. The detection of the signal can be modeled as absolute square operation. The phase shift of the higher modulation levels will therefore not lead to severe degradation. The absolute value of the complex envelope determines the level spacing after detection. For the zero level, the dispersion induced imaginary part leads to an absolute value different from zero and therefore an enlargement of the detected zero level. By this effect the lowest eye opening of an m-ASK signal is distorted most. An optimization of amplitudes levels therefore should aim at increasing the eye openings which suffer most from distortion.

For PMD, the signal is split into a slow and a fast travelling polarization. Due to the different speeds, the signal pulse spreads and the polarization of total signal changes. Since again the absolute value (now in two polarizations) determines the eye openings, the same assumption concerning the optimization is made.

All components of the transmission system have an impact on the distorting effects of CD and PMD. The MZM and the photo diode add nonlinearities. Together with the filters this leads to a complex system which cannot be easily described analytically. Therefore numerical optimization methods are chosen.

Four methods of choosing the amplitude levels are considered:

(1) Equal level spacing in the optical domain regarding the complex envelope. This method leads to the highest back-to-back receiver sensitivity [2, 3]. It results from the fact that the optical channel considering only noise is a Gaussian channel. In the electrical domain this choice of levels would lead to quadratic spacing.

(2) Equal spacing in the electrical domain after the photo detector. This leads to a square root characteristic regarding the complex envelope of the optical signal. This method shows good dispersion tolerance for unipolar ASK formats as shown in [2].

(3) Numerical adjustment of the levels to achieve a quadratic spacing in the electrical domain at the receiver side. For back-to-back this would lead to method 1. However, to be able to tolerate a certain amount of CD or PMD a high value of the individual impairment is chosen. The eye diagram at the receiver is evaluated and the levels are optimized until a quadratic relation between the different eye openings is achieved. This would refer to an equidistant spacing if the absolute value is considered. In this optimization process the optical and electrical filters are neglected.

(4) Method 4 uses the same optimization process as method 3, but considers optical and electrical filters.

4 Results and Discussion

Fig. 3-6 show the results for the chromatic dispersion tolerance optimization. To keep the results independent of the data rate, the dispersion values are normalized. Since the effect of dispersion is proportional to the square of the data rate, the abscissa displays the amount of chromatic dispersion in ps/nm multiplied by the data rate. The ordinate is normalized to the required OSNR for a BER of $5 \cdot 10^{-4}$ for each binary ASK back-2-back transmission. Since the chromatic dispersion tolerance of unipolar formats is much better as for bipolar formats, the abscissas use different scales.

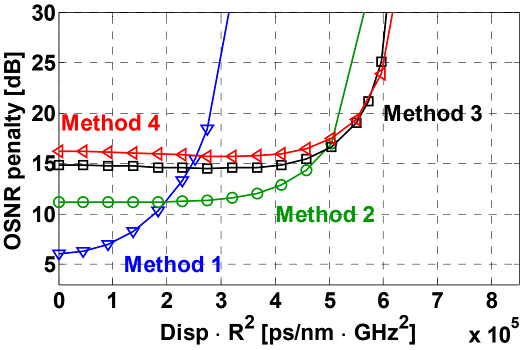

Fig. 3 Dispersion tolerance of NRZ-4-ASK unipolar for different level spacing. ONSR penalty compared to NRZ-2-ASK unipolar vs. normalized dispersion.

For unipolar modulation formats using method 2 a significant dispersion tolerance improvement can be achieved. Applying method 3 and 4 further improvements are possible, however on the expense of a highly decreased back-to-back sensitivity. Especially for 8-ASK and method 4 this can be seen. Therefore, for these formats, method 2 can be considered as a good trade-off between sensitivity and dispersion tolerance.

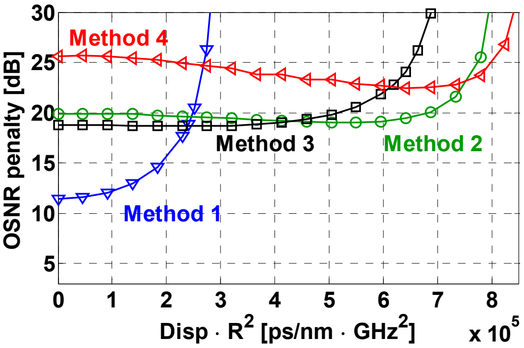

Fig. 4 Dispersion tolerance of NRZ-8-ASK unipolar for different level spacing. ONSR penalty compared to NRZ-2-ASK unipolar vs. normalized dispersion.

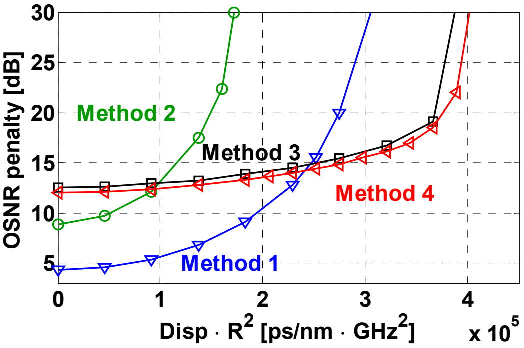

Fig. 5 Dispersion tolerance of NRZ-4-ASK bipolar for different level spacing. ONSR penalty compared to NRZ-2-ASK bipolar vs. normalized dispersion.

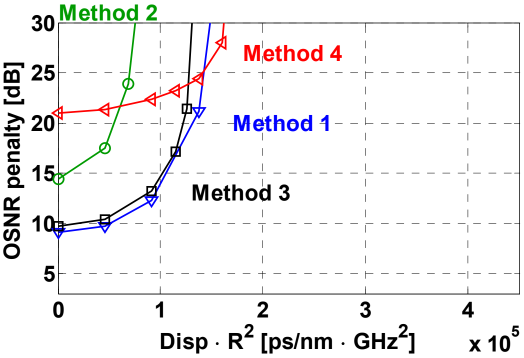

Fig. 6 Dispersion tolerance of NRZ-8-ASK bipolar for different level spacing. ONSR penalty compared to NRZ-2-ASK bipolar vs. normalized dispersion.

For bipolar formats method 2 decreases the sensitivity and the dispersion tolerance. This results from the fact, that this method enlarges the eye opening around zero which is detected by the DBPSK branch of the receiver and which suffers least from the effect of chromatic dispersion. However, the dispersion tolerance can be increased significantly for 4-ASK bipolar if method 3 or 4 are used. For 8-ASK bipolar, method

4 delivers a small increase of dispersion tolerance, but at the expense of more than 10 dB penalty in back-to-back sensitivity.

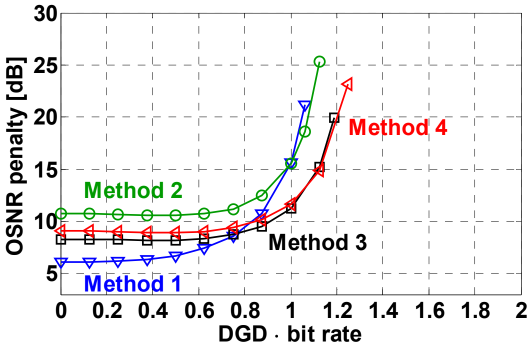

Fig. 7 PMD tolerance of NRZ-4-ASK unipolar for different level spacing. ONSR penalty compared to NRZ-2-ASK unipolar vs. normalized DGD.

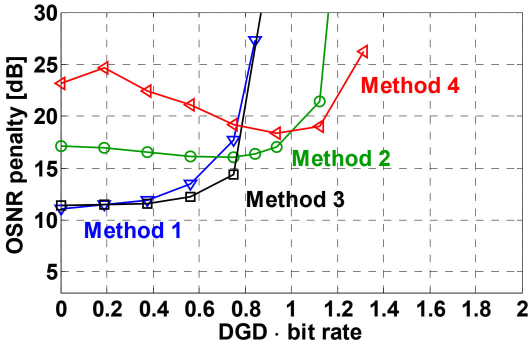

Fig. 8 PMD tolerance of NRZ-8-ASK unipolar for different level spacing. ONSR penalty compared to NRZ-2-ASK unipolar vs. normalized DGD.

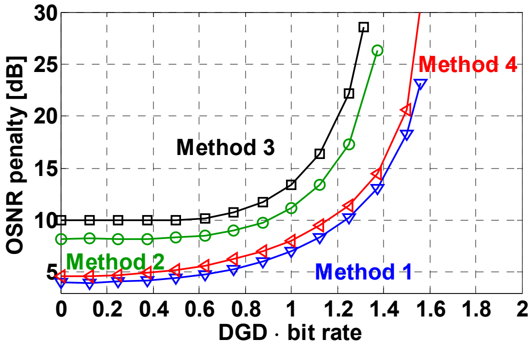

Fig. 9 PMD tolerance of NRZ-4-ASK bipolar for different level spacing. ONSR penalty compared to NRZ-2-ASK bipolar vs. normalized DGD.

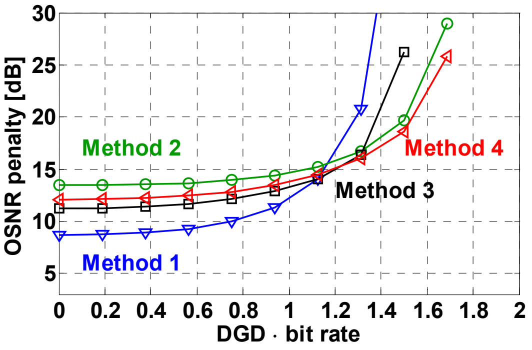

Fig. 10 PMD tolerance of NRZ-8-ASK bipolar for different level spacing. ONSR penalty compared to NRZ-2-ASK bipolar vs. normalized DGD.

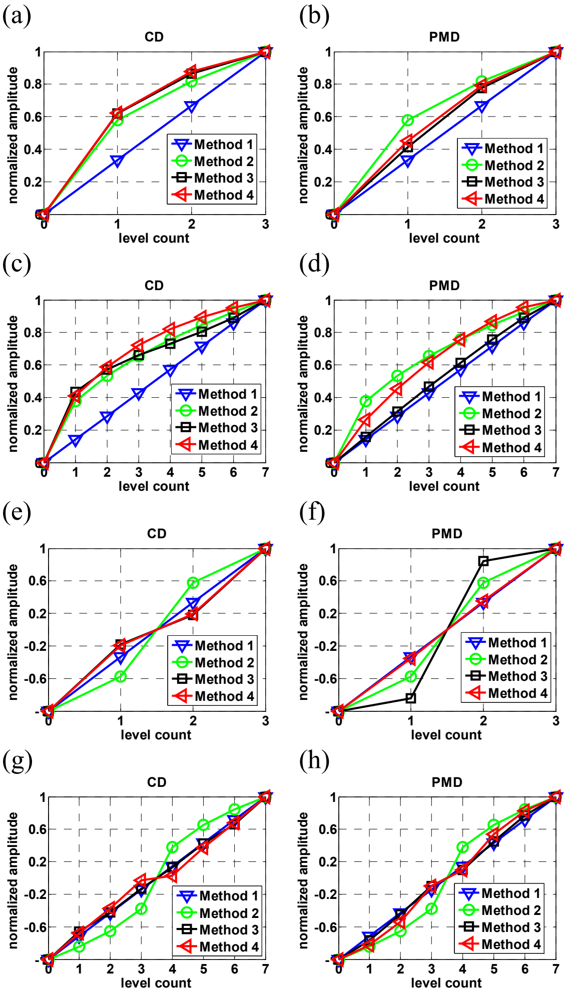

Fig. 11 Normalized amplitude levels v. level count for all modulation formats and methods: a) 4-ASK unipolar CD, b) 4-ASK unipolar PMD, c) 8-ASK unipolar CD, d) 8-ASK unipolar PMD, e) 4-ASK bipolar CD, f) 4-ASK bipolar PMD, g) 8-ASK bipolar CD, h) 8-ASK bipolar PMD.

Fig. 7-10 show the results for the optimization in the presence of PMD. For the abscissa, a normalization to the bit rate is introduced. Again the ordinate shows the OSNR penalty compared to the back-to-back sensitivity of 2-ASK unipolar and bipolar, respectively. The amplitude levels for method 1 and 2 are the same as for chromatic dispersion, whereas the levels for method 3 and 4 are optimized for a certain amount of DGD and therefore differ from the optimized for CD.

It can be seen that the requirements of a signal distorted by PMD are different from those of a signal distorted by CD. First of all, the differences between the methods are not as significant as for CD. Method 2 leads to small improvement only for the 8-ary modulation formats. In the case of 8-ASK unipolar a strong interaction between the filters and PMD leads to better performance in the presence of some DGD, as can be seen for method 4. For 8-ASK bipolar a small improvement can be achieved using method 4.

Fig. 11 shows the amplitude levels which result from each optimization method for all modulation formats. Regarding them, the very similar behavior of different methods for some modulation formats can be explained, since in some cases, the differences between the methods are very small.

5 Conclusion

We investigated the influence of chromatic dispersion and polarization mode dispersion on unipolar and bipolar multi-level ASK modulation formats. Unipolar modulation formats show a better robustness to chromatic dispersion than bipolar formats. In contrast to that, bipolar formats perform better in the presence of PMD. Moreover, the system degradation strongly depends on the amplitude level spacing of the formats. If only chromatic dispersion is present, equally spaced levels in the electrical domain are a good choice for unipolar formats. For bipolar formats, among all considered methods, only our eye diagram based optimization methods can improve the tolerance. If PMD is considered, the choice of the best optimization method strongly depends on the individual modulation format. Moreover, the possible improvement is not as big as for chromatic dispersion. In all cases a trade-off between receiver sensitivity and increased robustness has to be made.

6 References

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