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Optical duobinary modulation schemes using a Mach-Zehnder transmitter for lightwave systems

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I. Introduction

Duobinary optical transmission has become significant because of improving the dispersion tolerance in high-speed systems and reduction of crosstalk in WDM systems.

Modulation of duobinary signals is realised by a Mach-Zehnder modulator. Using AM-PSK the three-level signal is modulated as two intensity levels "off" and "on", that has two possible optical phases 0 and π. The intensity profile of the duobinary signal is the same as the binary intensity modulated signal. Therefore a binary IM-DD receiver can be used.

There are two different ways to drive a Mach-Zehnder modulator (MZ modulator) to generate an AM-PSK duobinary signal. On the one hand the MZ modulator can be driven by a three-level duobinary signal with push-pull operation [1]. On the other hand the MZ modulator can be driven asymmetrically. This so called "novel duobinary transmitter" is driven with only two-level binary signals to generate a AM-PSK duobinary signal [2]. Two different modulation schemes can be realised by this transmitter, duobinary modulation as well as AMI encoded modulation.

In this letter we compare the different modulation schemes of generating an AM-PSK duobinary signal by a MZ modulator. We have simulated both schemes of duobinary transmitters to consider their influence to dispersion sensitivity. We have especially considered the difference between the two possible modulation schemes of the asymmetrically driven MZ modulator.

II. Optical Duobinary Signalling

A partial response encoded sequence $c(k)$ is related to the binary data sequence $d(k)$ by the following encoding rule

$$c(k) = \sum_{\nu=0}^{n-1} \alpha_\nu d(k-\nu) . \qquad (1)$$

The encoding rule for a special code is fully described by n coefficients $\{\alpha_\nu\}$.

The duobinary code [3] has got $n = 2$ coefficients $\{\alpha_\nu\} = \{1,1\}$. That means a binary signal is encoded to a three-level duobinary signal by adding the current bit to the previous bit:

$$c(k) = d(k) + d(k-1) . \qquad (2)$$

The output symbols are 0, 1 and 2. Using an offset of -1 the output symbols change to -1, 0 and 1 without changing the encoding scheme itself. Blocks of ones have the same sign. This code follows a power spectral density of the signal multiplied with $\frac{4}{T}\cos^2(\omega T/2)$ that is responsible for a zero at half of the data rate $1/T$, where T is the bit duration. So the spectral occupancy can be reduced. This results in less dispersion sensitivity.

Decoding the received bits without recursion is possible by using a differential encoder as precoder in front of the encoder. The precoding rule for duobinary coding is

$$b(k) = \overline{d(k)} \oplus b(k-1) , \qquad (3)$$

where $d(k)$ is the binary data sequence, $b(k)$ is the precoded binary sequence, and "$\oplus$" is the logic instruction "XOR". Due to using a precoder and an encoder the decoding rule is very simple. The data bit $d(k)$ is the absolute value of the encoded bit $c(k) \in \{-1,0,1\}$. Therefore the intensity profile of the duobinary signal is the same as the binary intensity modulated signal when AM-PSK is used.

The AMI code is characterised by the coefficients $\{a_\nu\} = \{1,-1\}$ resulting in the encoding rule

$$c(k) = d(k) - d(k-1) , \qquad (4)$$

the precoding rule

$$b(k) = d(k) \oplus b(k-1) , \qquad (5)$$

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and the same decoding rule as written above. Blocks of succeeding ones are encoded as alternating signs. This code follows a power density spectrum of the signal multiplied with $\frac{4}{T}\sin^2(\omega T/2)$ resulting in a zero at the origin. Namely it is dc free.

Duobinary encoding devices can be realised either by a delay-and-add filter using a delay-line or by a duobinary filter [4], i.e. a low-pass filter with a 3-dB cut-off frequency of about ¼ bit rate. The transfer function approximates the main lobe of the cosine transfer function of the duobinary filter. A MZ modulator is used to generate a optical duobinary signal. Assuming an ideal MZ modulator the output optical field can be expressed by

$$E_0(t) = E\cos\left(\frac{\pi}{2}\frac{U_1(t)-U_2(t)}{U_\pi}\right)\cdot \exp\left(j\frac{\pi}{2}\frac{U_1(t)+U_2(t)}{U_\pi}\right) \tag{6}$$

where U_π is the switching voltage, and U_1 and U_2 are the voltages applied to each arm of the device. Using a MZ modulator in push-pull configuration means $U_1 = -U_2$. The driving voltage is the three-level duobinary encoded signal. The peak value is set to U_π. The "off" state of the duobinary optical signal corresponds to the "0" of the duobinary encoded signal. The symbols "-1" and "1" of the duobinary encoded signal are represented by the "on" state of the optical signal with the phase 0 and π, respectively.

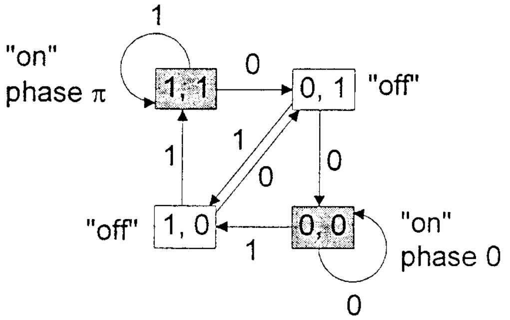

Figure 1: State diagram of duobinary encoding. In the rectangular boxes: $b(k)$ and $b(k-1)$. Possible state changes depend on the bits 0 and 1 as indicated at branches.

The asymmetrical driven MZ modulator is driven only by the two-level precoded signal. Therefore the realisation of this device is very simple. Using asymmetrically driven MZ modulator the driving voltage of one electrode is driven by precoded two-level signal and the other one is driven by the precoded signal, that is delayed one symbol length. The output signal of the MZ modulator depends on the combination of the current and the previous precoded bit. Therefore the MZ modulator has four different states generating three different optical duobinary output signals: two "off" states and two "one" states with the phase 0 and π. Figure 1 shows the state diagram. On the one hand there are two states on the diagonal line with the same current and previous bit, either both ones or both zeros, that allow to rest in the current state. On the other hand there are two states on the other diagonal line with different current and previous bits, that force state change. Optical duobinary encoding means in accordance with the state diagram, that the states representing the same current and previous bit are encoded by the optical signals "on" either with the phase 0 or π. The states representing different current and previous bits are encoded by the optical signal "off". As a consequence blocks of ones of the duobinary encoded signal have the same phase, either 0 or π.

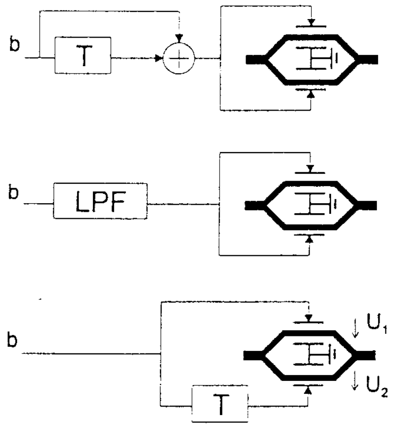

Figure 2: Principles of duobinary modulation schemes using a MZ modulator. From top to bottom: delay-and-add filter (MZ modulator in push-pull configuration), duobinary low-pass filter (MZ modulator in push-pull configuration), asymmetrically driven MZ modulator.

The MZ modulator is driven in the following way to realise the duobinary encoding directly. It is driven asymmetrically with the voltages $U_1 = -b(t)$ applied to arm 1 and $U_2 = b(t-T)$ applied to arm 2. $b(t)$ is the binary precoded signal. The peak value is set to U_π. Then the optical output field of the MZ modulator corresponds to a duobinary encoded AM-PSK modulated signal.

The alternative asymmetrical encoding scheme realises the AMI code. The state diagram represents identical current and previous bit in contrast to duobinary encoding as optical signal "off". Then the two states representing different current and previous bit are encoded as optical "on" with the phase 0 or π, respectively. In that

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case blocks of ones of the encoded signal have alternating phase. Note that this encoding scheme does not represent duobinary encoding but AMI encoding. The voltage $U_1 = b(t) - U_\pi$ is applied to the arm 1 and $U_2 = b(t-T)$ is applied to the arm 2. Then the optical output field of the MZ modulator represents the AMI code.

The main difference between symmetrical (push-pull configuration) and asymmetrical driving of the MZ modulator is the chirp of the modulated optical duobinary signal. Push-pull configuration means $U_1 = -U_2$. Considering equation (6) the exponential term is 1 in this case. Therefore the phase of the modulated signal is either 0 or π, related to the sign of the cosine term. In contrast to this an asymmetrically driven MZ modulator induces a chirp. A shaped pulse with rising and falling edges has an intensity modulation and a phase modulation with range of π.

III. Simulations

The simulation model consists of a data source generating a pseudorandom binary sequence at 10 Gb/s, a precoder, a duobinary encoder followed by a MZ modulator, the fibre and a simple receiver consisting of a PIN diode. The MZ modulator is described by equation (6). The chromatic dispersion of the fibre is modelled by a low-pass equivalent fibre transfer function $H(f) = \exp\left(j\pi L D \lambda_0^2 f^2 / c\right)$, with the fibre dispersion coefficient $D = 17$ ps/km/nm. L is the fibre length, λ_0 is the operation wavelength, and c is the speed of light in the free space.

First we have considered the MZ in push-pull configuration. The duobinary encoder is realised in two different ways. On the one hand as a delay-and-add filter followed by a pulse shaping low-pass filter realised as 2nd-order Butterworth filter with 5-GHz bandwidth. On the other hand as a duobinary filter realised as 2nd-order Butterworth filter with 2,5-GHz bandwidth. A binary signal with sinusoidally shaped edges is used for comparison. We have considered the eye diagram of the received signal depending on different fibre lengths. The eye of the binary transmission is fully closed after 130 km fibre length. The duobinary signals still can be detected and extends the transmission distance. At any rate the transmitter consisting of an duobinary filter has a better performance considering the signal-to-noise ratio, as one can see in figure 3.

Alternatively we have simulated the asymmetrically driven MZ modulator. One the one hand we have considered the duobinary encoded signal with blocks of ones with the same phase and we have simulated the AMI encoded signal with blocks of ones with alternating phase. In both cases we have driven the MZ modulator with different dynamic ranges. On the one hand modulation voltage has the peak value U_π for getting the maximum modulator transmission. Then the pulse has a phase modulation with a range of π. On the other hand the dynamic range of the modulation voltage is reduced to 50% . In that case the modulation transmission as well as range of the pulse's phase modulation is reduced.

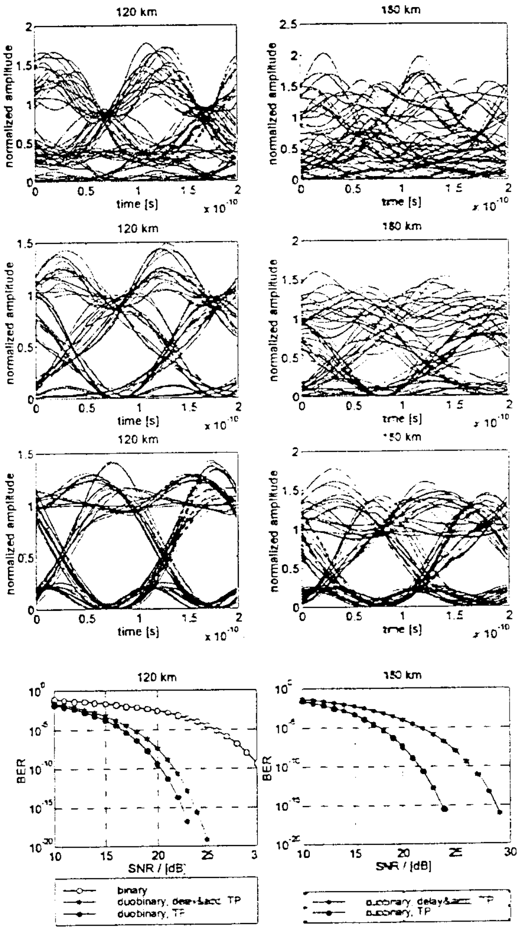

Figure 3: From top to bottom: eye diagrams of binary transmission, duobinary transmission realised by delay-and-add filter followed by a pulse shaping low-pass filter, duobinary transmission realised by a duobinary low-pass filter and BER over SNR, fibre length 120 km in left column, fibre length 180 km in right column, data rate 10 Gb/s.

The eye diagrams after a transmitting distance of 80 km are shown in figure 4. The eyes of the signals modulated by reduced driving voltage are less distorted. The best eye results for the AMI signal with reduced driving voltage. The longer the transmission distance the more distorted are the signals with full output range in contrast to

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those with reduced one, the duobinary modulated as well as the AMI modulated.

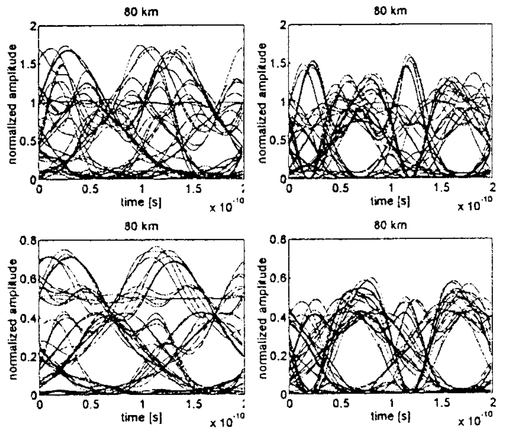

Figure 4: Eye diagrams of asymmetrically driven MZ modulator transmitter after a distance of 80 km, data rate 10 Gb/s. Figure left top: duobinary, full output range of MZ modulator. Figure right top: AMI, full output range of MZ modulator. Figure left bottom: duobinary, reduced output range of MZ modulator. Figure right bottom: AMI, reduced output range of MZ modulator.

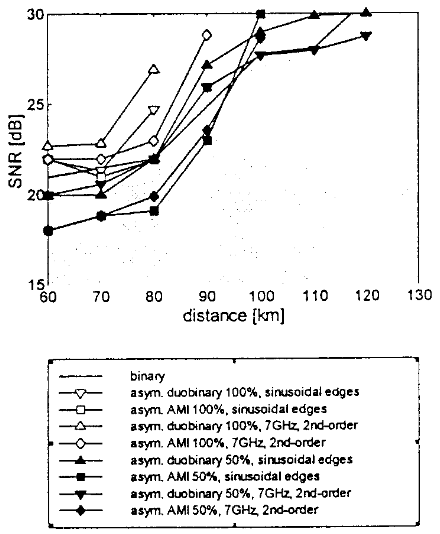

Figure 5: SNR related to the fibre length for asymmetrical modulation schemes, duobinary as well as AMI modulated, in contrast to binary transmission. (The light grey area characterises improvement compared to binary transmission.)

Considering the signals compared to binary transmission there is pour performance. Especially there is no longer transmission distance. Figure 5 shows the performance of asymmetrical modulation schemes, duobinary as well as AMI. The signal-to-noise ratio over fibre length is shown. The light grey area characterises improvement compared to binary transmission. The considered pulses either have sinusoidally shaped edges or they are low-pass filtered by 2nd-order Butterworth filter with 7-GHz bandwidth. Although the transmission distance is not extended, the AMI modulation scheme with reduced modulation voltage yields the best result with a gain of about 3 dB compared to binary transmission at 80 km fibre length. The modulation schemes using reduced modulation voltage result in a small gain compared to binary transmission. Nevertheless the asymmetrical modulation schemes have pour performance. The reason of this effect is the induced chirp of the asymmetrical modulation schemes that is responsible for the increased dispersion sensitivity. Therefore reduced chirp due to reduced driving voltage leads to better performance compared to fully driven MZ modulators.

V. Conclusion

Optical duobinary signals modulated by a MZ modulator in push-pull configuration lead to improved dispersion sensitivity and extended transmission distance in relation to binary transmission. Yet asymmetrical modulation schemes, duobinary and AMI, give no rise to extending transmission distance because of the induced chirp. Reducing the driving voltage the gain rises according to reduced chirp. Nevertheless the performance is not nearly as good as modulation using MZ modulators in push-pull configuration.

References

[1] Yonega, Kuwano. Dispersion-Tolerant Optical Transmission System Using Duobinary Transmitter and Binary Receiver. Journal of Lightwave Technology, vol. 15, no. 8, 1997.

[2] Franck, Hansen, Nielsen, Eskildsen. Novel Duobinary Transmitter. ECOC'97, Edinburgh.

[3] Lender. The Duobinary Technique for High-Speed Data Transmission. IEEE transactions on communication and electronics, 1963.

[4] Walklin, Conradi. On the Relationship Between Chromatic Dispersion and Transmitter Filter Response in Duobinary Optical Communication Systems. IEEE photonics technology letters, vol. 9, no.7, 1997.