Enhanced Electrical Duobinary Decoder with Low-BW Based Receivers for Short Reach Indoor Optical Links

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Abstract *We propose and experimentally validate a novel scheme combining both binary and electrical duobinary detection. At 50Gb/s, in a 1-bit memory channel, we obtain a Rx sensitivity of -25.7dBm with a 25G-class Rx and a low path penalty after 20km using a 1342nm EML Tx.*

Introduction

Passive optical networks (PON) have been widely employed to deliver fibre to the home (FTTH) services. PONs are also employed in other applications such as local area networks (LAN)[1]. Current and future PON generations may be used to provide high speed connectivity on a campus or inside a factory, for example, while keeping the network passive. The lack of high performance full BW APDs, and the need to compensate for transmission impairments, motivated the next generation of ITU PON to consider digital signal processing (DSP) and advanced FEC codes[2]. For indoor applications, the optical link is short, however, lower BW components and simplified DSP can help to reduce transceiver costs and power consumption. In addition, simple DSP and tailored FEC can potentially reduce processing time and network latency.

Electrical duobinary (EDB) detection with a low BW Rx was proposed previously at 25 Gb/s[3]. With a simple differential encoder in the transmitter (Tx) and an exclusive OR (XOR) in the Rx, a conventional non-return to zero (NRZ) signal can be properly detected. EDB has an inherent Rx penalty of 3 dB compared to NRZ. Alternatively advanced DSP schemes like maximum likelihood sequence estimation (MLSE) can effectively overcome the BW limitation and adapt to channel impairments using several received bits and determining the most probable Tx bits[4].

We propose here a novel enhanced electrical duobinary (EEDB) scheme that combines binary detection (BD) and conventional EDB to detect and correct errors in the received signal. The scheme takes advantage of the simplicity of EDB while improving its Rx sensitivity and reducing its intrinsic penalty. The scheme is tested by simulations and then experimentally at a bit-rate of 50 Gb/s with a Rx having a 17 GHz BW. We measure a Rx sensitivity of -25.7 dBm using EEDB (2 dB better than EDB) and an optical path penalty (OPP) of 0.4 dB after 20 km fibre at 1342 nm. These results are shown to be comparable to those with the same Rx and a 6-tap feed-forward equalizer (FFE).

EEDB scheme

The EEDB scheme takes advantage of the correlation that exists between neighbouring bits in the intersymbol interference (ISI) generated by the Rx BW limitation and dispersion in the fibre channel. To do this, first we detect the conventional binary signal with a conventional mid-level threshold (Thr_m). Half a bit time later, we employ two more thresholds (upper and lower) to detect a 3-level signal as for conventional EDB. Fig. 1 illustrates the two decision instants (DI) and the Thr for BD (DI_b, Thr_m) and EDB (DI_d, Thr_u, Thr_l). Initially, EEDB uses 2-DIs but also works with a single DI (1-DI).

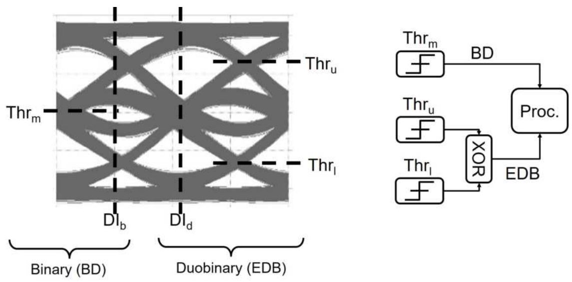

Fig. 1: DI and Thr for BD and EDB (left), and block diagram of the DB and EDB bit detection (right).

The BD and EDB bits are related by the following equation:

$$z[n] = y[n] + y[n-1] \quad (1)$$

where $y[n]$ and $z[n]$ are the current binary and duobinary decided bits respectively. From the detected bits, we compute $y[n] + y[n-1]$ (coded BD) and compare the result with $z[n]$. A wrong bit in $y[n]$ produces two errors in $z[n]$. As the duobinary eye is more open than the binary eye in a limited BW system, we assume that errors are more likely to appear in $y[n]$. Hence, when the outcome of the comparison gives two consecutive errors, we simply invert $y[n]$.

The above algorithm can correct isolated

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errors and identical consecutive errors in $y[n]$. To further improve the scheme, we use the two-bit delay relation between EDB and BD in Eq. (2):

$$z[n] - z[n-1] = y[n] - y[n-2] \qquad (2)$$

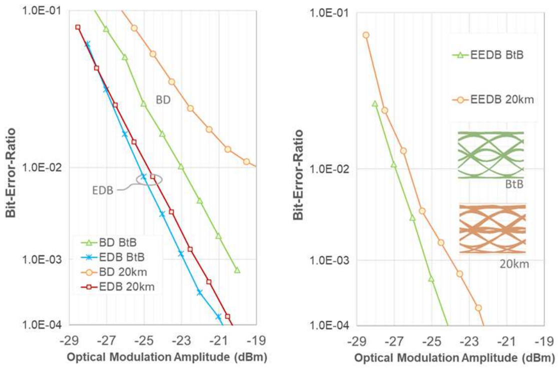
Following the same assumption as for Eq. (1), when consecutive errors are obtained from Eq. (2), then we invert $y[n-2]$.

Simulation results

To make a first verification of the proposed EEDB scheme, we performed simulations in VPI TransmissionMaker™. We generate a pseudo-random binary sequence (PRBS) of 2^{15}-1 bits, which modulates the light emitted from a distributed feedback (DFB) laser at 1342 nm through an electro-absorption modulator. The optical signal is detected by an APD (with R=0.8 A/W, M=10, and k_A=0.4) followed by a transimpedance amplifier (TIA) with an input referred noise of 10 pA/Hz$^{1/2}$. A 4th order Bessel filter with a 3 dB cutoff frequency of 15 GHz limits the Rx BW. The filtered signal is processed and the BER is computed.

Fig. 2 shows the BER results from the simulations. For the LDPC FEC code input BER of 10^{-2}, the OMA Rx sensitivity in back-to-back (BtB) is calculated as -23.5 dBm, -25.7 dBm, and -27.4 dBm for BD, EDB, and EEDB respectively. EEDB outperforms BD by almost 4 dB. This can be understood as the eye-opening is very small (upper inset of Fig. 2b). EDB gives a better Rx sensitivity than BD as, for this Rx BW, the EDB eye is more open. For higher BW (Fig. 3), BD is better than EDB; however for lower BW, the situation is reversed. As was noticed in [3], there is a point where the Rx sensitivity of the BD and EDB cross and one might change the detection scheme depending on the Rx BW. EEDB aims to improve the Rx sensitivity of EDB at low BW and so avoids the need to switch between detection schemes. After 20 km of fibre (total CD = 70 ps/nm) EEDB penalty is 0.3 dB. Since the total CD preserves the 1-bit memory channel, the EDB eye is almost identical after transmission and in BtB (insets of Fig. 2b). In contrast, the BD has a penalty of 4 dB due to eye closure. Even if EEDB OPP is 0.3 dB worse than EDB, EEDB sensitivity is still 1.2 dB better after fibre.

Fig. 3 plots the Rx sensitivity penalty with respect to the sensitivity of a full BW NRZ Rx (37.5 GHz) in BtB. For the ideal components simulated, at BW < 20 GHz, the EEDB scheme results in the lowest penalty. The scheme breaks down ~10 GHz, when the BD contribution to the EEDB scheme only adds noise. On the contrary, for BW > 20 GHz, the EDB part is the one that limits the EEDB performance because the eye-opening at the crossing point reduces. The EEDB algorithm assumes that EDB is more likely to be correct but, at higher BW, this assumption is no longer valid and the EEDB sensitivity degrades.



(a) (b)

Fig. 2: BER vs. OMA with (a) BD, EDB, and (b) EEDB in BtB and after 20km transmission

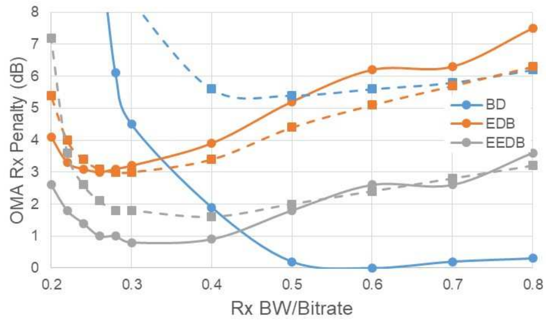


Fig. 3: Penalty against Rx BW for BD, EDB, and EEDB at BtB (solid) and after 20 km SMF (dotted)

Experimental setup

The experimental setup is shown in Fig. 4a. At the Tx side, a 2^{15}-1 PRBS is generated by a pulse pattern generator (PPG). This signal modulates a 1342 nm electro-absorption modulated laser (EML). The EML produces a modulated optical signal with an extinction ratio (ER) of 6 dB. The optical signal is then fed to 20 km of fibre (SMF, G.652), and passes through a VOA to emulate splitter losses in the optical distribution network (ODN). The SMF has a total CD = 66 ps/nm, which gives a channel memory slightly less than 1 bit. At the Rx, a III-V based 25G APD followed by a TIA detects the optical signal. The electrical signal is captured with a digital sampling oscilloscope (DSO) at 8 Sa/bit. In the DSO, the samples are processed with a continuous time linear equalizer (CTLE) with 1 zero and 2 poles in an attempt to boost the high frequencies. The sampled signal is then filtered at 37.5 GHz to limit the electrical noise from the DSO and afterwards it is processed following the EEDB algorithm. Finally the BER is computed with 2^{16} bits.

Experimental results

The reception schemes depicted in Fig. 4b and 4c are tested. In order to improve the Rx BW, we apply a CTLE equalizer with 2 dB gain, following the OIF CEI standard for VSR NRZ modulation (CEI-56G-VSR-NRZ)[5]. The CTLE has a DC gain of 0.794, a zero frequency of 14.2 GHz, and pole frequencies of 37.2 GHz and 28.2 GHz.

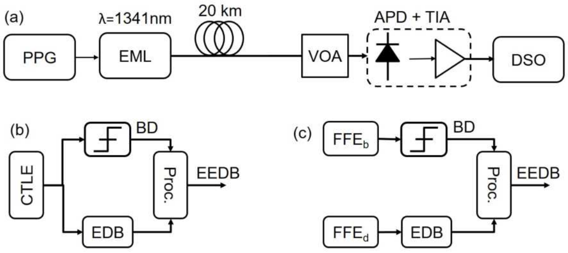


Fig. 4: Experimental setup

Fig. 5a plots the BER curve after applying the CTLE and Table 1 summarizes the OMA Rx sensitivities in BtB and after SMF. There is no OPP observed with EDB as the limited BW channel and the dispersion produce a similar 3-level signal. We observe that the Rx sensitivities are 2.3 dB and 6 dB better than BD in BtB and after 20 km respectively. In addition, the slope of the EDB BER line is steeper. We can explain this by a more open eye for EDB. Note that for the EDB BER, we compare the detected signal with a differentially encoded version of the Tx signal.

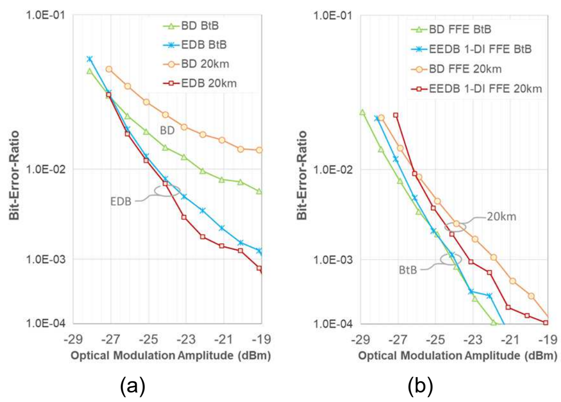


Fig. 5: BER against Rx OMA for (a) BD and EDB and (b) with 6-taps FFE BD and 2-taps FFE EEDB.

Table 1: Rx sensitivities for BD, EDB, and EEDB

	BtB (dBm)	20km (dBm)	OPP (dB)
BD	-22.3	-16.6	5.7
EDB	-24.6	-24.6	0
BD FFE	-26.5	-25.4	1.1
EEDB 2DI	-26.7	-26.2	0.5
EEDB 1DI	-25.7	-25.3	0.4
EEDB-FFE	-26.7	-26.2	0.5

Next, we apply the new EEDB scheme to the captured data with CTLE. The results in BtB and after SMF are plotted in Fig. 6a and the Rx sensitivities are included in Table 1. The EEDB Rx sensitivity is 2 dB and 4 dB better than EDB and BD respectively. Furthermore, the OPP is limited to 0.5 dB, achieving an Rx sensitivity of -26.2 dBm after SMF. The optimum 2-DIs are shown in Fig. 6b and correspond to the maximum EDB eye-aperture and a half-bit time before.

For comparison, we also process the BD with a 6-tap, 2-precursor FFE. In this case, the samples are quantized to 5 bits to represent a real ADC. The BER curves are shown in Fig. 5b and the Rx sensitivities in Table 2. The Rx sensitivity values are similar to those obtained using EEDB with 2 DI. However, 2 DI is, in effect, 2x oversampling. For a fairer comparison, we also process EEDB with only 1 DI (Fig. 6a). In this case, the optimum DI is in the eye-diagram region where both DB and EDB like signals can be observed (Fig. 6c). There is a sensitivity penalty of 1 dB with respect to using 2 DI for EEDB. We observe a 0.8 dB penalty when comparing with FFE in BtB, and 0.1 dB penalty after transmission. We can compensate for this penalty by adding a 2-tap FFE in each branch of the EEDB with single DI (Fig. 4c). By doing so, the sensitivity of EEDB is similar to the 6-tap FFE as seen in Fig. 5b. These results show that, by taking advantage of the 1-bit memory channel, EEDB can achieve Rx sensitivities close to that from stronger FFE processing.

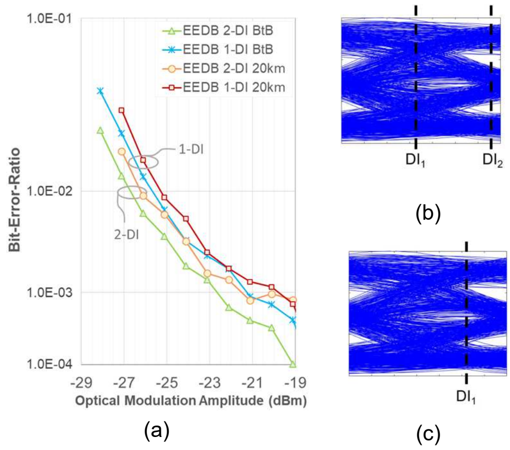


Fig. 6 (a): BER vs. Rx OMA with EEDB with 1 and 2 DI at BtB and after 20 km of SMF; (b): DI for EEDB with 2 DI, and (c) DI for EEDB with 1 DI.

Conclusions

A novel EEDB detection scheme with simplified DSP for PON applications is described and tested through simulations and experiments. The scheme takes into account the relation between BD and EDB to improve the inherent Rx sensitivity penalty of EDB in a 1-bit memory channel. In a 50 Gb/s link with CD = 66 ps/nm, the EEDB BtB Rx sensitivity (-25.7 dBm OMA) was 2 dB better than EDB and the OPP was only 0.4 dB. EEDB results are comparable to those with more calculation intensive DSP.

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