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Citation: Chvojka, Petr, Haigh, Paul Anthony, Darwazeh, Izzat, Ghassemlooy, Fary and Zvanovec, Stanislav (2019) Duobinary Modulation for Visible Light Communications. In: 2019 European Conference on Networks and Communications (EuCNC): 18-21 June 2019, Valencia, Spain. IEEE, Piscataway, NJ, pp. 52-56. ISBN 9781728105475, 9781728105468, 9781728105451

Published by: IEEE

URL: https://doi.org/10.1109/EuCNC.2019.8801992 <https://doi.org/10.1109/EuCNC.2019.8801992>

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Duobinary Modulation for Visible Light Communications

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Abstract—**The paper proposes and experimentally investigates the performance of the duobinary transmission technique for a highly bandlimited VLC system. By adding a controlled amount of inter-symbol interference (ISI) into the transmit pulse shaping filters, the supported data rate can be doubled requiring the same signal bandwidth. To gain full insight into duobinary signalling, the so-called modified binary scheme is also tested. The bit error rate (BER) performance of both systems is measured for a range of data rates, before comparison with the ideal binary and traditional on-off keying non-return to zero (OOK-NRZ) formats across the same physical link. We show the duobinary system can support higher bit rates and lower BER than OOK-NRZ while requiring half the bandwidth of the binary scheme.**

I. INTRODUCTION

The effective utilization of the available signal spectrum represents a key challenge in designing visible light communication (VLC) systems due to the bandlimited nature of the light emitting diodes (LEDs) used for both illumination and data transmission. The trade-off between system complexity, achievable data rates, bandwidth and power efficiency should be considered to meet the ever-increasing requirements on communication infrastructure. Thus, the selection of an appropriate modulation scheme is of great importance in VLC. Subcarrier based modulations such as orthogonal frequency division multiplexing (OFDM) [1], [2] and (multiband) carrierless amplitude and phase (CAP) [3], [4] can be utilized in VLC alongside baseband schemes such as on-off keying (OOK) and pulse amplitude modulation (PAM). The simplicity of implementation and relatively low power efficiency make OOK one of the most popular and attractive schemes in VLC [5]–[10].

Besides traditional binary schemes such as OOK, duobinary modulation can also be used, which offers several advantages such as lower bandwidth requirement (i.e., by half) compared to OOK for a given data rate. This is achieved by adding a controlled amount of inter-symbol interference (ISI) to the pulse shape filters at the transmitter [11]. The duobinary modulation (also known as partial response signalling [12] or correlative coding [13]) belongs to the family of a polybinary signalling techniques introduced by Lender [14], [15]. Polybinary signalling is a multi-level extension of duobinary, consisting of correlated symbols so that the overall frequency spectrum can be shaped for different applications. However, using more than 3 levels was shown to be impractical in bandlimited systems due to the increased signal-to-noise ratio (SNR) requirement and greater sensitivity to ISI [11]. The duobinary (i.e., a number of levels $M = 3$) signalling has been implemented mostly for optical fibre networks to compensate the effect of fibre dispersion and to improve the transmission distance [16]–[18]. Furthermore, polybinary shaping was implemented in spectrally efficient optical fibre wavelength division multiplexing (WDM) and ultra-high speed systems in [19] and [20], respectively. Although the duobinary technique was successfully demonstrated to support a 614 Mb/s VLC system in [21], there is still the lack of detailed analyses and experimental validations of polybinary signalling for VLC in the literature.

Hence, in this paper we focus on the investigation of the duobinary scheme for bandlimited intensity modulation/direct detection (IM/DD) VLC systems in terms of bit error rate (BER) performance for a range of transmission speeds. Moreover, we compare the measured results with the ideal binary and OOK-NRZ schemes using the same physical link. We show that duobinary offers improved BER performance while reducing the bandwidth requirement by half at the cost of marginally increased system complexity, due to the necessity of a precoding process before transmission (described in Section II).

II. PRINCIPLES OF DUOBINARY SYSTEMS

The general limitation to achieving higher data rates in VLC is the ISI introduced by LEDs with limited modulation bandwidth (a few MHz for standard white LEDs). However, this limitation can be eliminated or reduced by adopting appropriate pulse shaping filters, which satisfy the first Nyquist criterion for zero ISI for signal $x(t)$ as given by:

$$x(nT_s) = \begin{cases} 1, & n = 0 \\ 0, & \text{otherwise} \end{cases} \tag{1}$$

where n is the integer sample number and T_s is the symbol period. Thus, the signalling rate of $R_s = 1/T_s < B_c$ can

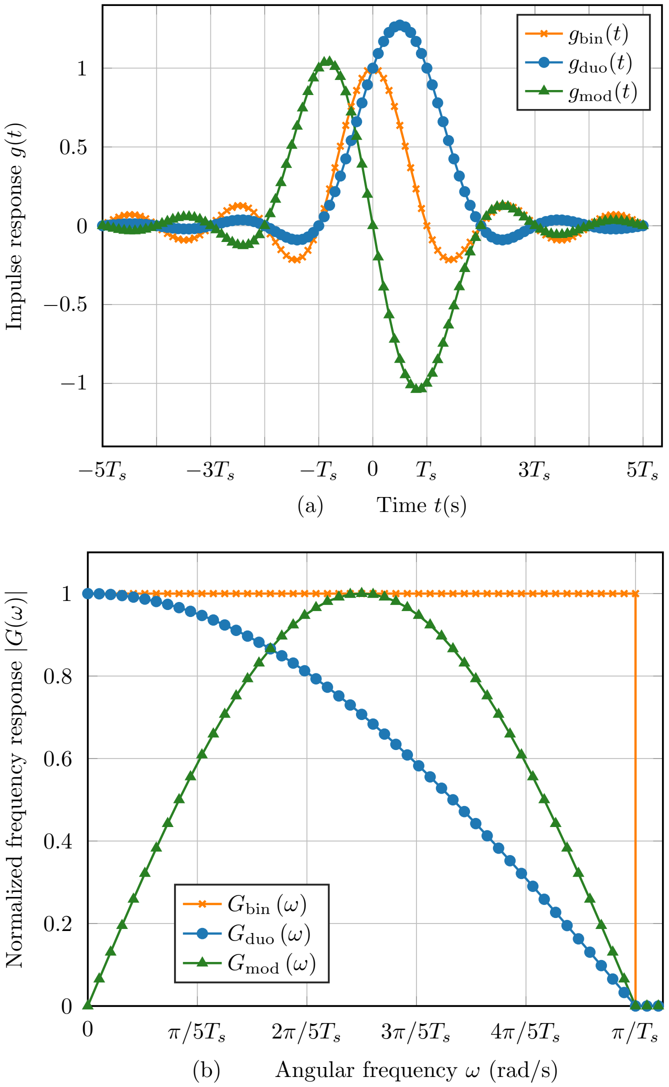

Fig. 1. The ideal binary, duobinary and modified duobinary pulses: (a) impulse responses and (b) normalized magnitude of frequency responses.

be supported, where B_c is the channel bandwidth. Contrary, if the condition for zero ISI is relaxed (i.e., allowing a controlled amount of ISI at the transmitter), $R_s = 2B_c$ can be achieved thus leading to the condition given as:

$$x(nT_s) = \begin{cases} 1, & n = 0, 1 \\ 0, & \text{otherwise} \end{cases} \tag{2}$$

An example of the filter pulse shape $g(t)$, which satisfies the condition in (2) for controlled ISI, is given by [11]:

$$g(t) = \sum_{k=0}^{M-2} sinc\left(\left(t - kT_s\right)\left(\frac{\pi}{T_s}\right)\right) \tag{3}$$

Note, $M = 3$ for the duobinary scheme and the duobinary pulse shape is denoted as $g_{\text{duo}}(t)$ in this paper. The corresponding pulse spectrum is given as [11]:

$$G(\omega) = \begin{cases} T_s \sum_{k=0}^{M-2} e^{-jk\omega T_s}, & |\omega| \leq \dfrac{\pi}{T_s} \\ 0, & |\omega| > \dfrac{\pi}{T_s} \end{cases} \tag{4}$$

where ω is the angular frequency. Another special case of a pulse shape with $M = 3$, allowing $R_s = 2B_c$, is the modified duobinary pulse as given by [22]:

$$\begin{aligned} g_{\text{mod}}(t) = \sum_{k=0}^{M-2} & sinc\left(\left(t + kT_s\right)\left(\frac{\pi}{T_s}\right)\right) \\ & - sinc\left(\left(t - kT_s\right)\left(\frac{\pi}{T_s}\right)\right) \end{aligned} \tag{5}$$

Thus, the relaxed condition for controlled ISI defined in (2) is now modified to:

$$x(nT_s) = \begin{cases} 1, & n = -1 \\ -1, & n = 1 \\ 0, & \text{otherwise} \end{cases} \tag{6}$$

The corresponding frequency spectrum for the modified duobinary pulse is given by [22]:

$$G_{\text{mod}}(\omega) = \begin{cases} 2T_s \sin\left(\omega T_s\right) e^{-j\left(\frac{\pi}{2} - \omega T_s\right)}, & |\omega| \leq \dfrac{\pi}{T_s} \\ 0, & |\omega| > \dfrac{\pi}{T_s} \end{cases} \tag{7}$$

To provide a full insight into duobinary signalling, an ideal binary system needs to be also considered. The ideal filter impulse response $g_{\text{bin}}(t)$ follows the sampling function for $M = 2$ and satisfies (1) and its corresponding frequency spectrum represents an ideal square filter, which is physically unrealizable due to its requirement for an infinite filter length. The filter pulse shapes and its corresponding frequency spectrum for ideal binary, duobinary and modified duobinary systems are illustrated in Figs. 1(a) and (b), respectively.

Before the transmission of the partial response signal, the encoding of the signal at the transmitter is carried out in order to eliminate possible error propagation at the receiver [11], [15], [22]. Thus the encoded data is given by [11], [22]:

$$d_i = a_i \oplus d_{i-1} \oplus d_{i-2} \oplus \cdots \oplus d_{i-M+2} \tag{8}$$

where a_i is the input data stream and $\oplus$ denotes a modulo-two addition. The generated precoded sequence is given as [22]:

$$p_i = 2d_i - 1 \tag{9}$$

Note, for $d_i = 1$ and $d_i = 0$ the amplitudes of p_i are 1 and -1, respectively. Finally, the transmitted signal following filter shaping, which is used for IM of the LED, is given as:

$$x(t) = \sum_{n=-\infty}^{\infty} p_i g\left(t - nT_s\right) \tag{10}$$

Considering noise-free and distortion-free transmission, at the sampling instance, there are M discrete levels that the received signal $y(t)$ may adopt at the output of the receiver filter following $y_i = p_i + p_{i-1}$ [22], namely -2, 0 and 2 for $M = 3$ with corresponding probabilities of 1/4, 1/2 and 1/4. Following the detection process for the duobinary signal in [22], which is adopted here, the decoded data stream $a_{D,i}$ is given by:

$$a_{D,i} = \begin{cases} 1, & |y_i| < 1 \\ 0, & |y_i| \geq 1 \end{cases} \tag{11}$$

For the modified duobinary signalling, it is given as [22]:

$$a_{D,i} = \begin{cases} 0, & |y_i| < 1 \\ 1, & |y_i| \geq 1 \end{cases} \tag{12}$$

Although the received signal takes one of M possible levels at the detector, one must note that a duobinary is a binary transmission system since two discrete values are possible following threshold detection. The example of data encoding and decoding is shown in Table I.

TABLE I
ENCODING AND DECODING PROCESS FOR DUOBINARY TRANSMISSION

a_i	-	1	0	0	0	0	1	0	1	1	0
d_i	1	0	0	0	0	0	1	1	0	1	1
p_i	1	-1	-1	-1	-1	-1	1	1	-1	1	1
y_i	-	0	-2	-2	-2	-2	0	2	0	0	2
$a_{D,i}$	-	1	0	0	0	0	1	0	1	1	0

III. EXPERIMENTAL SETUP

The experimental setup of the system is illustrated in Fig. 2. Firstly, a pseudorandom binary sequence (PRBS) a_i of length $\sim 10^6$ is generated to allow BER measurement up to 10^{-6}, which is well below the 7% forward error correction (FEC) limit of 3.8×10^{-3}. Note, for both duobinary schemes the data is then encoded (see 'COD' in Fig. 2) as described in the previous section. The data stream a_i (or p_i for the duobinary systems) is then up-sampled by a factor of $n_{ss} = 6$ samples/symbol and passed through the pulse shaping filters $g(t)$ to generated the modulated signal $x(t)$. The signal $x(t)$ is applied to a Rohde & Schwarz SMW200A arbitrary waveform generator (AWG) the ouput of which is then dc biased prior to IM of the LED. For the LED (Osram Golden Dragon) used in this work, the dc bias current I_b was set to 500 mA at $V_b = 3.25$ V. Note, *(i)* the amplitude of the input signal is set to 1 V to ensure maximum peak-to-peak signal swing around I_b (well within the linear region of the power (voltage)-current characteristics of the LED) and therefore higher SNR and *(ii)* the 3 dB modulation bandwidth of the LED is ~1.2 MHz as measured previously in [23].

The modulated light beam is transmitted over a free space channel of length 1 m. At the receiver side, an aspheric lens with a focal length 4.51 mm is used to focus the incoming light onto an optical receiver (Thorlabs APD430A) with 400 MHz bandwidth, which is composed of an avalanche photodetector (APD) and an ultra-low noise transimpedance amplifier (TIA). The output of the optical receiver is captured using a real-time digital oscilloscope (LeCroy WaveRunner Z640i) with a fixed sampling frequency $f_s^{rx} = 100$ MS/s for further offline data processing in MATLAB. A low-pass filter (LPF) with cut-off frequency $f_c = 0.75B_s$, where B_s is the signal bandwidth, is used to filter out-of-band noise. After resampling ('RES') and down-sampling ('DWN'), hard-decision decoding is performed in order to regenerate the estimate ('EST') bit stream $\widehat{a_{D,i}}$ for BER measurement.

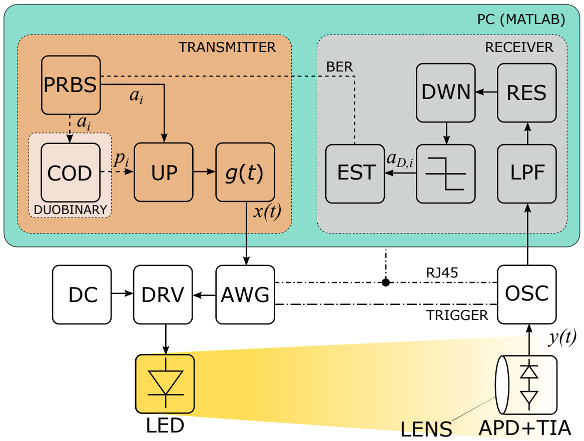

Fig. 2. The experimental setup. The used abbreviations are used as follows: COD encoder, UP upsampling, DRV driver, RES resampling, DWN down-sampling. Note, the whole measurement process is controlled from PC via Ethernet connection using RJ45 sockets.

IV. RESULTS AND DISCUSSION

To analyse the performance of the duobinary signal transmission in a bandlimited VLC system, we have carried out BER measurement for a range of R_b from 1 to 25 Mb/s with a step of 1 Mb/s. The upper bound of R_b was set to 25 Mb/s due to the maximum sampling frequency $f_s^{tx} = 150$ MHz of the AWG and n_{ss} used in the experiments. Ideal binary, duobinary, modified duobinary and OOK-NRZ (with rectangular pulse shaping filter) signal formats were compared under the same experimental conditions (i.e., the physical link, LED bias point and signal amplitude). Note, this work has aimed to investigate the performance of the duobinary signalling for VLC links, and therefore any pre- or post-equalisers have not been implemented in order to extend the system bandwidth and to set a record in achievable data rates.

As previously mentioned, the duobinary signalling uses $M = 3$ levels for transmission of a binary signal, where two levels are used to represent binary 0 and just one level represents binary 1, and vice versa for the modified version (see also [11], [12]). However, due to the precoding process before transmission, the probabilities of decoding binary 1 or 0 are the same for both duobinary and binary communication systems as illustrated in Fig. (3).

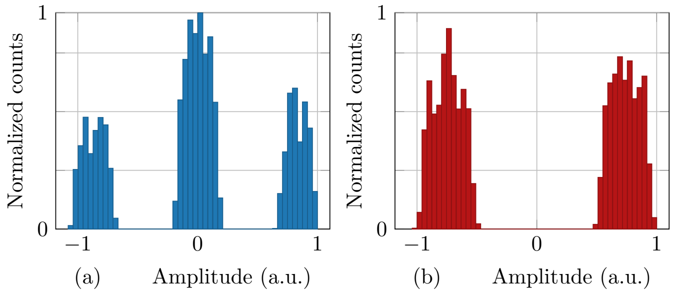

Fig. 3. The normalized histograms of the received signals: (a) duobinary, and (b) OOK-NRZ showing the equal probabilities of decoding binary 1 and 0.

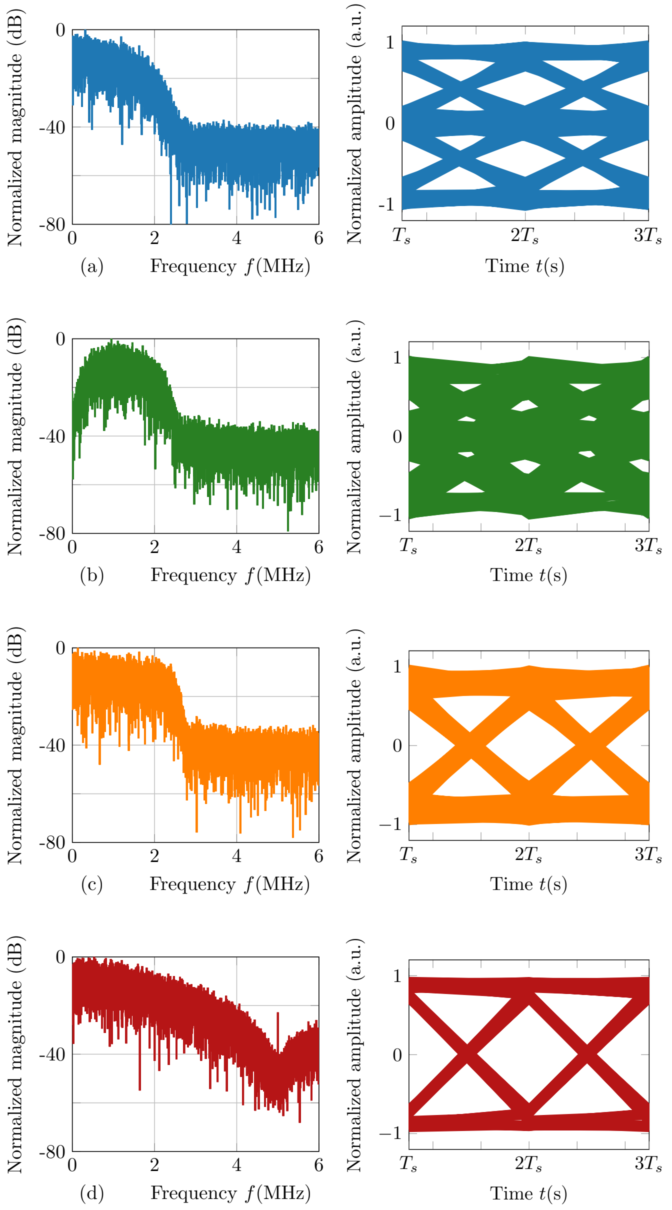

Fig. 4. Measured electrical spectra of the received signals and corresponding eye diagrams after down-sampling at 5Mb/s for: (a) duobinary, (b) modified duobinary, (c) ideal binary and (d) OOK-NRZ, respectively. Note, the amplitudes of the signals are normalized.

The measured electrical spectra of the received signals at $R_b = 5$ Mb/s with the corresponding eye diagrams are illustrated in Fig. 4. Note, the spectra are captured before the LPF at the receiver and the eye diagrams depict the processed and normalized signal after down-sampling and prior to hard-decision making (see Fig. 2). Clearly, we can see the allocated transmission bandwidth of OOK-NRZ signal is doubled compared to the other signalling schemes as expected. On the other hand, the eye diagram of the OOK system shows clear both horizontal and vertical eye openings, which is slightly better than the ideal binary data format. As for duobinary signalling schemes, the eye openings are decreased as shown in Figs. 4(a) and (b) compared binary systems in Figs. 4(c) and (d). This is due to the requirement for higher SNR in 3-level signal transmission. This stays in line with the BER plots reported in [11], [14] showing higher power requirements (i.e., ∼2–3 dB) for a given BER target for a duobinary system compared to that of binary signalling. In addition, we observe further degradation in the modified duobinary system due to it's passband nature. As reported in [24], for a CAP system the optimum sampling region becomes much smaller when dealing with passband signals due to additional sensitivity to timing impairments, thus resulting in the additional eye closure as illustrated in Fig. 1(b).

Next, the measured BER performance for a range of R_b for all four signalling formats and under the same experimental conditions is depicted in Fig. 5. Note, each of the systems tested demonstrates error-free transmission for $R_b < 10$ Mb/s. The duobinary signalling offers the best BER performance and supports R_b up to 14 Mb/s at a BER below 7% FEC limit of 3.8×10^{-3} (see the dashed black line in Fig. 5). This is nearly 8% gain over the ideal binary and OOK-based VLC systems, which could achieve 13 Mb/s, and ∼27% improvement over the modified duobinary scheme (11 Mb/s

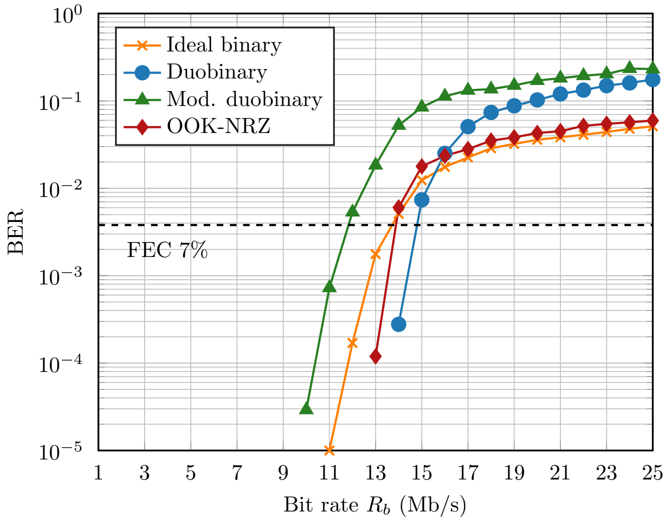

Fig. 5. Measured BER performance of the ideal binary, duobinary, modified duobinary and OOK-NRZ schemes for a range of bit rates using the same physical link.

supported) for the same BER target. The modified duobinary signalling shows the worst performance as can be also seen in Fig. 4. Although we demonstrate a slight increase in the measured R_b compared to traditional OOK-NRZ, the transmission bandwidth requirement of the duobinary system is reduced by 50%, which is significant to note. The reasons for limitation in the performance improvement of duobinary signalling are *(i)* a higher power requirement compared to other three signalling formats and *(ii)* the ISI (but not the noise) that dominates at higher R_b thus resulting in increased BER. Contrary, a controlled amount of ISI added to the transmitted signal decreases the bandwidth requirement thus introducing a significant advantage over OOK, but at the cost of increased computational complexity due to the bit coding process at the transmitter

V. CONCLUSION

In this paper, we investigated the performance of duobinary and modified duobinary signalling for highly bandlimited VLC systems. We demonstrated the duobinary scheme could support higher data rates compared to the traditional OOK-NRZ (nearly 8% improvement) with just half of the bandwidth and slightly increased system complexity due to the precoding process at the transmitter. We showed that the duobinary system is a suitable modulation scheme for VLC, whereas the modified version does not offer any tangible advantages compared to other signalling schemes that were tested. Since the raw performance of the duobinary scheme was investigated, further work will be focused on the implementation of equalisation techniques as well as on the implementation of duobinary pulse shaping to other modulation formats in VLC domain in order to increase the link spectral efficiency.

ACKNOWLEDGMENT

This work was supported in part by the UK EPSRC under Grant EP/P006280/1: Multifunctional Polymer Light-Emitting Diodes with Visible Light Communications (MARVEL), in part by the European Unions Horizon 2020 research and innovation programme under the Marie Slodowska-Curie grant agreement no 764461 (VISION) and in part by the Czech Science Foundation Project GACR 17-17538S.

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