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Alrasah, Hussien Theeb; Gutema, Tilahun Zerihun; Sinanovic, Sinan; Popoola, Waisu O.

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PAPR Reduction in DCO-OFDM Based WDM VLC

Hussien Theeb Alarakah, Tilahun Zerihun Gutema, Sinan Sinanovic, and Wasuu O. Popoola

Abstract—Visible light communication (VLC) can achieve high data rate transmission with multicarrier modulation techniques. The common variant is direct current (DC) optical orthogonal frequency division multiplexing (DCO-OFDM) which offers a spectral efficient modulation solution for VLC. However, similar to other multicarrier modulation schemes, DCO-OFDM suffers from a high peak-to-average power ratio (PAPR). In this paper, the efficacy of pilot-assisted (PA) PAPR reduction system in DCO-OFDM based VLC is demonstrated experimentally. Wavelength division multiplexing (WDM) is applied using three off-the-shelf light emitting diodes (LEDs). PA DCO-OFDM is compared to the conventional DCO-OFDM based on achievable data rate and bit error rate (BER). The available modulation bandwidth of each LED is utilised by adaptive bit and power loading in both systems. The proposed system reduces the high PAPR values of the system, hence, reduces the clipping noise and minimises the nonlinearity effect of each wavelength. Thus, the PA DCO-OFDM has achieved more than 7% data rate higher than that of the conventional DCO-OFDM with no PAPR reduction.

Index Terms—Optical wireless communication, visible light communication, optical OFDM, DCO-OFDM, peak-to-average power ratio (PAPR), pilot-assisted (PA), wavelength division multiplexing (WDM).

I. INTRODUCTION

In wireless communications (WC), there is high interest in using the visible light communication (VLC) as it offers huge and unlicensed spectrum for high data rate transmission. The use of low-cost commercially available off-the-shelf front end devices, such as light emitting diodes (LEDs) and photodiodes (PDs), further highlight the attraction of VLC system. VLC system is a potential candidate for many applications such as indoor positioning, underwater communications and internet of things (IoT). In addition, VLC system offers inherent security and can be employed in homes, offices and places where sensitive electronic devices exist such as in hospitals and areas where wired and radio-frequency (RF) wireless communications are not suitable [1], [2], [3]. Furthermore, it can enable significant energy and cost saving by reusing the existing lighting infrastructures for communication purposes [4].

The transmission mechanism in VLC system is intensity modulation with direct detection (IM/DD) which restricts the

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Hussien Theeb Alarakah, Tilahun Zerihun Gutema, and Wasuu O. Popoola are with the Institute for Digital Communications, School of Engineering, The University of Edinburgh, Edinburgh, EH9 3FD, UK. Hussien Theeb Alarakah is also with Jazan University, Jazan, Kingdom of Saudi Arabia. (e-mail: h.alarakah@ed.ac.uk; tilahun.gutema@ed.ac.uk; w.popoola@ed.ac.uk).

Sinan Sinanovic is with Glasgow Caledonian University, School of Engineering and Built Environment, Glasgow, Scotland, UK. (e-mail: sinan.sinanovic@gcu.ac.uk).

transmitted waveform to be real and positive [5]. Single carrier modulation techniques such as on-off keying (OOK), pulse-width modulation (PWM) and M -ary pulse-amplitude modulation (M -PAM) can be implemented for VLC systems. However, for high data rate transmission, single carrier modulation schemes require complex equalisation process at the receiver. As a result, the performance of such schemes degrades as their spectral efficiency increases [1].

Another modulation approach for VLC systems implementation is single-carrier frequency division multiplexing (SCFDM) which is a promising key technology for long term evolution (LTE) network [6]. SCFDM has similar throughput and complexity performance of the well-known orthogonal frequency division multiple access (OFDMA) however, the SCFDM has better peak-to-average power ratio (PAPR) [6]. SCFDM variants including asymmetrically clipped optical (ACO-SCFDM), enhanced ACO-SCFDM and layered/enhanced ACO-SCFDM are proposed for VLC system in [7], [8], [9]. In L/E-ACO-SCFDM, multiple information layers transmitted simultaneously to increase the spectral efficiency of ACO-SCFDM with its inherited low PAPR [9].

On the other hand, multi-carrier modulation (MCM) techniques such as discrete multi-tone (DMT) modulation variants are regarded as convenient modulation candidates for VLC systems. This is due to their advantages such as simplified equalisation process, multi-path propagation resilience, inter-symbol interference (ISI) mitigation and robustness against channel frequency selectivity [10], [11], [12].

Different DMT modulation variants have been proposed for the IM/DD systems such as direct current (DC) optical orthogonal frequency division multiplexing (DCO-OFDM), asymmetrically clipped optical OFDM (ACO-OFDM) and pulse-amplitude-modulated DMT (PAM-DMT). DCO-OFDM is a widely used modulation scheme for VLC system due to its high spectral efficiency when compared to other DMT techniques [13]. In addition, the light sources such as (LEDs) require DC current I_{DC} to turn them on which already exists in DCO-OFDM for unipolar waveform conversion purpose [10]. Moreover, using DCO-OFDM in VLC offers an efficient use of the limited modulation bandwidth of illumination LEDs used in VLC [14]. However, DC bias is required to create the unipolar signal which results in significant energy losses [15]. ACO-OFDM and PAM-DMT systems are proposed in [16] and [17] respectively. In ACO-OFDM and PAM-DMT systems, the properties of Fourier transformation are used to exploit the frame structures. Therefore, the time domain signal is clipped at the zero level to realise the unipolar signal and the DC bias is required only to turn on the light source [11]. However, the spectral efficiency of these schemes is half of the spectral efficiency in DCO-OFDM [18].

Despite MCM techniques advantages, they are affected by

high PAPR. Various solutions have been proposed to address the PAPR challenge. This includes signal clipping which is the simplest and most common used peak reduction technique. In signal clipping, any desired level of PAPR reduction gain can be attained, where part of the signal is clipped to fit in the operating region of the dynamic range of the light source. This is achieved at the cost of deteriorating the system bit error rate (BER) performance [10], [19]. Another clipping method in DMT for optical network was proposed by clipping the signal symmetrically then apply clipping-noise-cancellation (CNC) algorithm to mitigate the clipping noise effect [20]. Classical selected mapping (SLM) algorithm is another approach, where alternative sequences U carrying the same information are produced by multiplying the data vector by random phase sequences to change the PAPR properties. The data with lowest PAPR values is selected for transmission. The PAPR reduction gain increases with the number of phase sequences used increases. This method is limited by the spectral efficiency loss due to the number of side information that is transmitted with each data sequence for recovery [10], [19] and [21]. Various methods based on SLM scheme is reported in [22], [23]. Tone injection (TI) scheme uses correction method for PAPR reduction by remapping the original data that produces large PAPR peak into several new positions [19]. This method reduces the PAPR of the signal at the cost of complex transmitter, more signal power for transmission and additional inverse fast Fourier transform (IFFT) operations [19]. Tone reservation (TR) scheme is another method to reduce PAPR peaks which reserves subset of the transmitted subcarriers called peak reduction tones (PRT) for PAPR reduction [24]. The TR scheme requires optimised PRT position to perform efficiently and avoid performance degradation with non-optimal PRT position. The PRT position can be achieved with the iterative gradient algorithm (IGA). However, it is not straightforward to find the optimal PRT position and IGA requires long iteration times to converge which make the TR scheme with IGA is not suitable for real time implementation [24]. Pilot-assisted (PA) technique is an effective solution for the PAPR reduction in optical OFDM systems which was proposed in [10]. PA technique is used to rotate the data frame phase by a randomly generated pilot in order to avoid coherent addition of the subcarriers as much as possible. The pilot symbol's phase is chosen based on the SLM algorithm while the maximum likelihood (ML) algorithm is used to recover the pilot phase at the receiver side [25]. Details of the PA technique including its PAPR reduction gain in DCO-OFDM based VLC system is presented in this work.

In this paper, experimental demonstration of PA DCO-OFDM based VLC using three different low-cost off-the-shelf LEDs is presented. Wavelength division multiplexing (WDM) system is utilised to efficiently modulate the three different wavelengths. DCO-OFDM is considered in this study and due to its high PAPR peaks and the limited dynamic range of VLC front-end devices, the PA technique is applied to reduce the system high PAPR. The reduction of PAPR minimises the signal clipping and nonlinearity distortion caused by the optical source. Furthermore, each wavelength available bandwidth is utilised using adaptive bit and power loading.

Specific contributions of this work are as follows:

- Experimental demonstration of a PAPR reduction using PA scheme in PA DCO-OFDM based VLC system.
- For the first time, the PA technique is applied to a WDM based VLC system to reduce clipping/nonlinear distortion, and maximise achievable data rate while maintaining error performance.
- Evaluation of PA DCO-OFDM system's data rate and BER per wavelength and then compared to that of conventional DCO-OFDM without PAPR reduction.

The PA DCO-OFDM based WDM VLC system has achieved more than 7% data rate higher than that of conventional DCO-OFDM without BER degradation.

The rest of this paper is organized as follows: In Section II the VLC system is presented, while experimental setup is described in Section III. The data transmission results and discussions are in Section IV. The paper is concluded in Section V.

II. VLC SYSTEM

A. Optical Pilot-assisted OFDM

Different OFDM modulation variants have been proposed for VLC systems i.e. DCO-OFDM. DCO-OFDM with PAPR reduction is considered for this work. Conventional OFDM waveform is complex and bipolar. However, the IM/DD requirement can be met by imposing Hermitian symmetry on the OFDM subcarriers frame which results in real-valued OFDM waveforms, $X[k] = X^*[N-k]$, where N is the OFDM frame length, and k is the subcarrier index. In the frequency domain, subcarriers at $X[0]$ and $X[N/2]$ are assigned to zero values. In DCO-OFDM, DC bias is used to convert most of the negative real-valued into positive samples.

In OFDM system based VLC, the available modulation bandwidth of the light source results in signal-to-noise ratio (SNR) response variation, which restricts the assigned constellation size and leads to spectral efficiency losses. To overcome this, larger constellation format can be assigned on the subcarriers that have higher SNR. Therefore, the spectral efficiency can be maximised by bit and power loading algorithm. This is achieved by estimating the available SNR per subcarrier (SNR_k). To generate the real-valued OFDM signal, a random bit sequence generation for each light source of the WDM system is performed off-line in MATLAB as shown in the transmitter's digital signal processing (Tx-DSP) of the system block diagram in Fig. 2. Primarily, estimation of the VLC channel response and the available SNR_k of each light source (LED) is performed by multiple OFDM frames. This estimation is obtained by the error vector magnitude (EVM) method [26]. Given the estimated SNR_k , QAM constellation size per subcarrier (M_k) is adaptively allocated into subcarrier k with its corresponding relative energy, ν_k^2 , based on the Levin-Campello Algorithm [27]. The constellation format and power adaptive allocation are performed based on a predefined error probability target P_e^T . This allows for higher modulation formats to be loaded into the subcarriers with higher SNR while ensuring that, the error probability P_e^T is kept below a forward error correction (FEC) target of 3.8×10^{-3} [28]. In

addition, the algorithm allows for more power to be loaded into the subcarriers that required additional minimal energy to be elevated to higher constellation format while preserving the P_e^T . The adaptive bit and power allocation can be formulated to optimise the following problems on each active subcarrier k [12]:

$$\text{maximise } b_k = \log_2 M_k \quad (1a)$$

$$\text{subject to } \text{BER}(M_k, \text{SNR}_k) \leq P_e^T \quad (1b)$$

$$\sum_{k=1}^{\frac{N}{2}-1} \frac{\nu_k^2}{\frac{N}{2}-1} = 1, \quad (1c)$$

where b_k is the number of bits per symbol with $b_k > 2$ bits, and ν_k^2 is the power loading factor at subcarrier k . $\text{BER}(M_k, \text{SNR}_k)$ is the theoretical BER equation of M_k -QAM at subcarrier k with the available corresponding SNR_k and can be approximated by the following [12]:

$$\text{BER}(M_k, \text{SNR}_k) \approx \frac{4}{\log_2(M_k)} \times \left(1 - \frac{1}{\sqrt{M_k}}\right) \times \sum_{l=1}^2 Q\left((2l-1) \sqrt{\frac{3 \times \text{SNR}_k}{M_k - 1}}\right) \quad (2)$$

where $Q(\cdot)$ is the Gaussian Q-function. The overall data rate, R_b of the bit and power allocation system per wavelength can be evaluated by the following [28]:

$$R_b = \frac{\sum_{k=1}^{\frac{N}{2}-1} \log_2 M_k}{(N + N_{\text{CP}})} \times R_s \quad (3)$$

where R_s is the symbol rate, and N_{CP} is the cyclic prefix length.

The allocated bits and power based on the available SNR_k per light source (LED) are mapped into QAM symbols. The QAM symbols are then transformed from serial to parallel to form columns of active subcarriers length N_{subs} . Then the Hermitian symmetry is imposed to the QAM symbols and loaded into orthogonal subcarriers of length N with subcarrier spacing equal to the symbol duration. Due to the high PAPR peaks of the time domain waveform, the PAPR is reduced using PA scheme as detailed in Section II-B, in the frequency domain. The symbols are then multiplexed into a time domain signal by size N IFFT followed by cyclic prefixes (CPs) insertion. This is followed by up-sampling process then PAPR reduction evaluation and parallel to serial conversion prior to a pilot signal insertion for synchronisation purposes for each wavelength waveform.

At the receiver side as illustrated in the off-line receiver's (Rx-DSP) part of the system block diagram in Fig. 2, the received waveforms are processed with synchronisation then down-sampling processes followed by serial to parallel conversion, and CPs removal. A fast Fourier transform (FFT) operation is then applied to each waveform which provides the QAM symbols in the frequency domain. The QAM symbols carrying data are then extracted from the PA embedded pilots. The phase and amplitude of the embedded PA pilots are estimated based on the ML technique. The estimated pilots phases are used to recover the phase of the corresponding received

data QAM symbols. A prior estimated channel response of each light source is used to equalise the corresponding signal based on the single-tap zero-forcing equalisation process. The equalised signals are QAM demodulated, followed by BER calculation based on the demodulated binary streams.

B. PAPR Reduction with Pilot Assisted Technique

DCO-OFDM is a spectral efficient optical OFDM variant that requires DC bias to produce an unipolar signal for intensity modulation. However, the DCO-OFDM signal comprises of the sum of independent subcarriers in the time domain which results in individual subcarriers added up coherently to produce high PAPR [29]. Consequently, high electrical peaks must be clipped at lower and/or upper levels to contain the signal swing inside the dynamic range of the light source [30]. The high electrical PAPR values must be reduced to benefit from the dynamic range of the optical light source in full. Reducing the high PAPR values will help the light source to operate inside its linear dynamic region and hence, reduces the clipping distortion of the transmitted signal caused by the system frond-end devices [10].

To address the PAPR problem, the pilot assisted (PA) technique is applied to reduce the high PAPR values of the system. PA rotates the phase of individual subcarriers to avoid the possibility of them added up coherently. The implementation process of PA for DCO-OFDM based VLC WDM system is described in this section.

The electrical PAPR values of the time domain signal of DCO-OFDM is defined as follows [10]:

$$\text{PAPR} = \frac{\max_{0 \leq n \leq N-1} (|x[n]|^2)}{E[|x[n]|^2]} \quad (4)$$

where $E[\cdot]$ is the statistical expectation. To evaluate the PAPR reduction, the complementary cumulative distribution function diagram (CCDF) is used as the most used measure [10]. The CCDF is defined as the probability that the DCO-OFDM frames block PAPR exceeds a given reference value.

The procedure of PAPR reduction using PA technique in DCO-OFDM is described as follows [10]:

- Group the frequency domain frames of DCO-OFDM into U blocks comprise of active subcarriers N_{subs} ; where, $X^u[k]$, $u = 1, 2, \dots, U$.
- Generate R multiple iterations of pilot sequence candidates with N_{subs} length, X_p^r , where $r = 1, 2, \dots, R$.
- Select the sequence X_p^r amplitude $A_p[k]$ to be ± 1 only.
- Randomly set the pilot sequence phase $\theta_p[k]$ to 0 or π values only, where $k = 1, 2, \dots, N_{\text{subs}}$.
- Rotate the block U phase by $\theta_p[k]$ of every pilot iteration r .
- Calculate the PAPR_r value of iteration X_p^r .
- Select the pilot iteration $X_p = X_p^{\tilde{r}}$ with minimum PAPR value for transmission; where [30],

$$\tilde{r} = \underset{1 \leq r \leq R}{\text{argmin}} (\text{PAPR}_r) \quad (5)$$

- Embedded the pilot sequence $X_p[k]$ into the corresponding block U of frames for high PAPR reduction, and thus the number of frames per block U will be $\hat{U} = (U + 1)$.

In this work, the high PAPR peaks of each LEDs is reduced where the DCO-OFDM number of frames are grouped to form a block U , and $U = 5$ frames per block. This value is selected because the PAPR increases as U increases [10]. The considered number of iterations are selected to $R = 10$ iterations because it shows a good trade off between performance and complexity [31]. Cyclic prefix is not used during the PAPR evaluation as it has negligible impact on the PAPR results. At the receiver, the received PA sequences are extracted from the data blocks, then estimated using ML technique. The ML is an optimum detection method to estimate the statistical parameter θ where the parameter values that are most likely to generate the observed data are chosen [25]. The ML technique is used in our work as follows [10]: at the receiver, the received PA sequences are extracted from the data blocks, then its noise corrupted phase $\hat{\theta}_p[k]$ is estimated using ML technique to improve the data recovery. The estimate of the angle is taken between two values, ($\hat{\theta}_i = 0$ and π) that has the minimum Euclidean distance from the received pilot's phase $\hat{\theta}_p$. The estimate argument is given by the following:

$$\hat{\theta}_p[k] = \underset{1 \leq i \leq 2}{\operatorname{argmin}} [(\hat{\theta}_p[k] - \theta_i)^2] \quad (6)$$

The estimated pilot sequence becomes $\hat{\theta}_p[k] = e^{j\hat{\theta}_p[k]}$, which is equivalent to the following condition [10]:

$$\hat{\theta}_p[k] = \begin{cases} +1, & \text{if } \cos(\hat{\theta}_p[k]) \geq 0 \\ -1, & \text{otherwise.} \end{cases} \quad (7)$$

In addition, the pilot's sequence amplitude, $\hat{A}_p[k]$ is maintained to unity using the condition given in (7). The estimated PA phase $\hat{\theta}_p[k]$ with recovered amplitude, $\hat{A}_p[k]$, is then used to recover the phase of the corresponding subcarrier k for the corresponding block U of the received data.

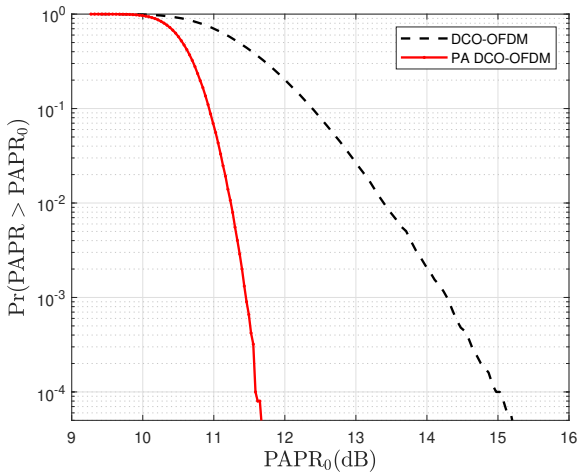


Fig. 1. PAPR CCDF plot for PA DCO-OFDM and DCO-OFDM using $N_{\text{subs}} = 1023$ active subcarriers, 16-QAM, up-sampling factor = 16, $U = 5$ data frames per block and PAPR reduction at $R = 10$ iterations

The system PAPR reduction gain by 10 iteration PA scheme is shown in Fig. 1. This result quantifies the PAPR reduction gain compared to the conventional DCO-OFDM scheme. For instance, at a CCDF of 10^{-4} , the PA DCO-OFDM yield almost 3.5 dB compared to the DCO-OFDM. The PAPR

reduction gain for specific parameters can be evaluated using the analytical framework in our previous work in [31].

III. EXPERIMENTAL SETUP

The experimental setup details are presented in this section. The WDM system is considered for this work which uses three different single colour LEDs for the PAPR reduced PA DCO-OFDM transmission. The WDM light sources are selected from Dialight with three different colours (wavelengths) namely, red (R), green (G) and blue (B). The module numbers of the RGB LEDs are Red: 598-8D10-107F, Green: 598-8081-107F and Blue: 598-8D90-107F with dominant wavelengths of 635 nm, 525 nm and 470 nm respectively [33]. The RGB single colour beams are combined at the transmitter side (Tx) by two Thorlabs dichroic mirrors that are dependent on the incident light wavelength. The light beams are separated at the receiver side (Rx) using two similar dichroic mirrors as an optical bandpass filter as shown in the system block diagram in Fig. 2.

The experimental setup starts with generation of PA DCO-OFDM signal for each wavelength of the WDM system as detailed in Section (II). The generated digital signal is then loaded to an arbitrary waveform generator (AWG: Keysight M8195A) for digital to analogue conversion. The sampling rate of the AWG is set to 16 GSa/s. The AWG outputs are amplified by an amplifier (Mini-Circuits ZHL-1A-S+). Each amplified signal is then fed into a bias-tee (Mini-Circuits ZFBT-4R2GW). The amplified bipolar information signal is then superimposed with the DC-bias. Low DC bias values result in large zero-level clipping of the signal which degrades the system performance. High DC bias values cause upper level clipping of the waveform and optical power saturation at the LEDs which results in system performance degradation. As a result, DC bias optimisation is required for each wavelength to avoid system performance degradation. Therefore, the optimum DC bias point of each LED is evaluated as detailed in Section (IV). The bias-tees outputs are then connected to the corresponding LEDs for intensity transmission over a free space channel. The half power angles of the selected LEDs are wide (i.e. 70°), therefore, aspheric condenser lenses (L1-3: Thorlabs ACL50832U-A) are used at the output of each LED to collimate its light into a set of dichroic mirrors (M1 and M2). The dichroic mirror (M1: Thorlabs DMLP567L) has a transmission band of 584-800 nm and cut-off wavelength of 567 nm. This mirror is used to pass the light of the red LED and reflects the output of the green LED into the transmission path. The second dichroic mirror (M2: Thorlabs DMLP490L) has a transmission band of 505-800 nm with cut-off wavelength of 490 nm. M2 is used to pass the red and green LEDs' lights while reflecting the light of the blue LED. The LEDs' lightwaves are combined by the dichroic mirrors into a single beam and transmitted simultaneously over the channel for a distance of $d = 1$ m.

At the receiver, the same setup configuration of the mirrors is used to separate the received light intensity of the three LEDs as shown in the receiver side of the system block diagram in Fig. 2. Two different dichroic mirrors are used in the

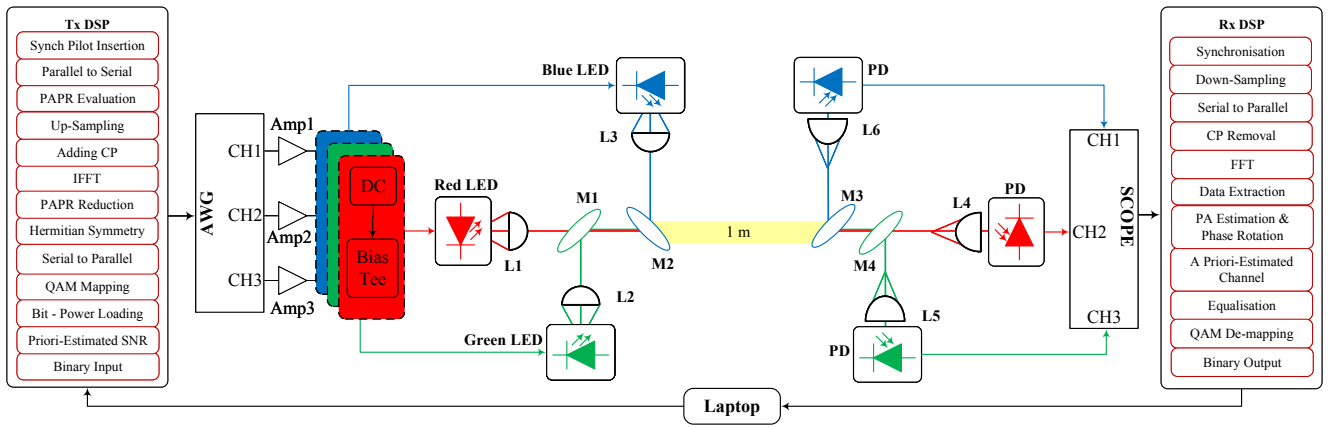


Fig. 2. Experimental setup block diagram [32]

path of the received light beam to direct the light intensity of each LED into the desired wavelength region. The first mirror (M3) is similar to (M2) which reflects the blue LED light to its corresponding receiver while passes the red and green lights through. Similar to (M1), another mirror (M4) is used to pass the red LED light towards its receiver while reflects and directs the green wavelength towards its desired receiver. Each LED wavelength is then focused into the desired receiver detection area by an aspheric condenser lens (L4-6). The selected receivers are PIN diode photodetector (PD: New Focus 1601 AC) with a 3 dB bandwidth of 1 GHz each. The PDs convert the incoming optical radiations into electrical current signals. Each PD has a built-in transimpedance amplifier (TIA) with a gain of 10 V/mA, which converts the received current signal into a voltage signal. Then, the received signals are captured by a high speed oscilloscope (OSC: Keysight MSO-X 3104T) and sent back to MATLAB for offline processing. In the receiver DSP domain, each waveform is synchronised and down sampled. This followed by the CP removal and FFT operation which provides the QAM signals in the frequency domain. The carrying information subcarriers are extracted and the phase and amplitude of the embedded PA pilots are estimated using ML technique. The pilots estimated phases are used to recover the corresponding received subcarriers phase. This process is followed by the equalisation and QAM demodulator processes in the DSP domain. The BER of each LED is then evaluated from the QAM demodulated symbols.

IV. DATA TRANSMISSION RESULTS AND DISCUSSIONS

The WDM system optimisation, data transmission and results discussion are presented in this section. The experimental data transmission in this work is WDM based VLC system using DCO-OFDM with PA PAPR reduction technique. The considered WDM system uses three single colour LEDs in the visible light spectrum. The simultaneous data transmission and reception over the three communication channels includes crosstalk between all channels which makes the system very close to practical applications. Moreover, the modulation bandwidth of each wavelength in the WDM system is utilised with adaptive bit and power loading for spectral efficiency maximisation. In addition, The DCO-OFDM PAPR

is reduced per wavelength by 10 iterations PA to minimise their nonlinearity effect and clipping distortion. The driving bias current (I_{DC}) and peak-to-peak voltage (V_{pp}) of each LED are optimised. The I_{DC} of LEDs determine the output optical power and the achievable data rates. Therefore, the optimum I_{DC} points of LEDs are found where the amount of nonlinear distortion is minimised and the available SNR is maximised for each LED. Selecting the I_{DC} points allows for scaling the transmitted DCO-OFDM to fit the linear dynamic region of each LED. The selected LEDs are assumed to be the main nonlinearity source in the overall system due to their limited dynamic ranges compared to the other system components. The modulation signal depth of the waveforms are performed at the AWG output by adjusting the V_{pp} of each LED.

The optimisation process starts with selecting the driving bias current point I_{DC} of each LED using the system experimental setup in section (III). The available channel bandwidth and SNR at each subcarrier, SNR_k , per wavelength are estimated by transmitting multiple pilot frames of 4-QAM based optical OFDM. The available SNR_k of received pilot frames is estimated by EVM method [26]. The I_{DC} per wavelength is selected to minimise LEDs nonlinearity effect and maximise the available SNR_k , and as a result, increase the achievable data rate per wavelength.

The following parameters are used for system optimisation and data transmission: the data symbol rate R_s is set to 1 GBaud and with oversampling factor of 16 samples per symbol, the WDM data transmission is performed at a 16 GSa/s sampling rate per wavelength. The number of data carrying subcarriers, N_{subs} is set to 1023. The length of the OFDM frame (IFFT/FFT) is set to $N = 2048$ subcarriers to utilise the available modulation bandwidth of each light source. CPs with adequate size is then inserted at the start of each OFDM frame to efficiently eliminate the ISI by single-tap equalizer. A size of $N_{CP} = 5$ is found to be sufficient for ISI removal at spectral efficiency loss of less than 0.20%. To optimise the driving bias current point (I_{DC}), the V_{pp} of the AWG is set to its minimum possible value which is found to be 75 mV, to avoid LEDs nonlinearity effect. Next, the I_{DC} is increased gradually, and the data rate of the system is

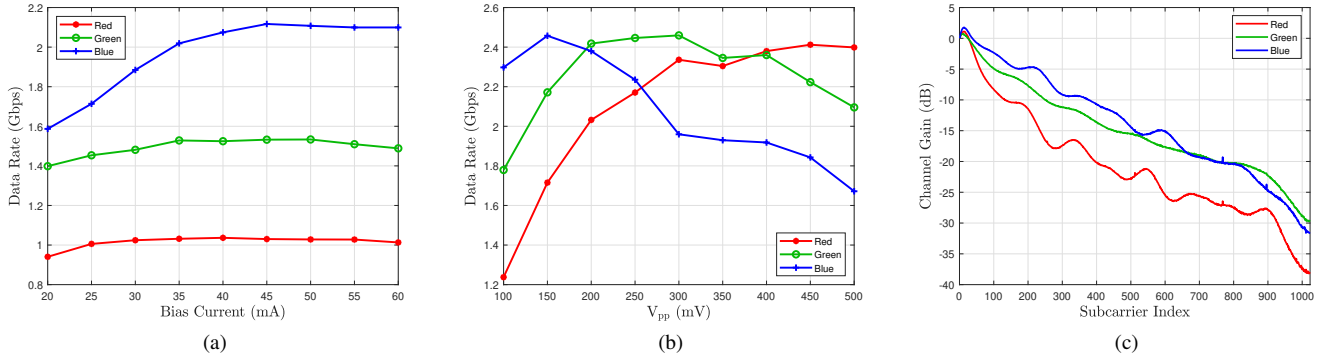


Fig. 3. The system measured data rates for optimisation process. (a) data rate versus bias current (b) data rate versus signal depth (c) channels gain per subcarrier k

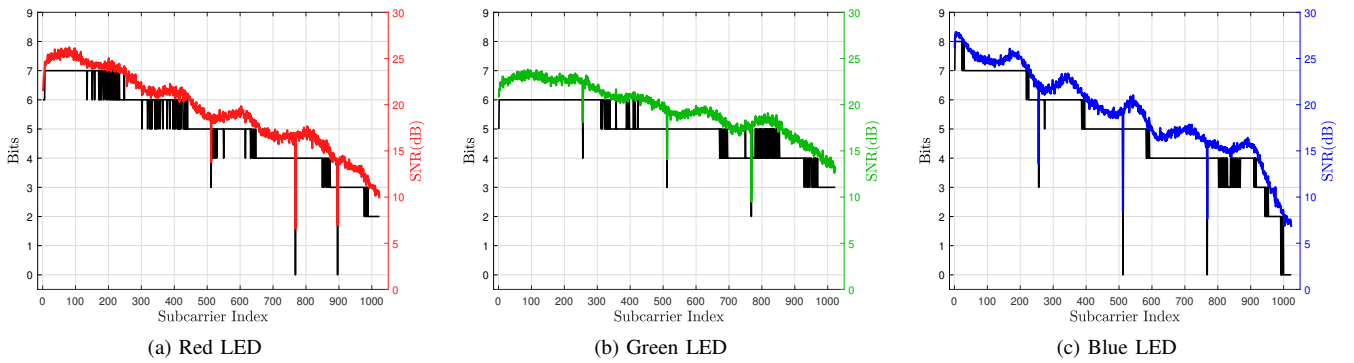


Fig. 4. SNR and bits loaded per subcarrier for each LED

measured for each LED. The optimum I_{DC} for the red and blue LEDs are found to be 45 mA, while for the green LED is 50 mA as shown in Fig. 3 (a). The measured I_{DC} points are used to find the optimum V_{pp} points by increasing its value gradually and measuring the data rate for each LED. The optimum V_{pp} values are found to be as follows: 450 mV for the red LED, 300 mV for the green LED and 150 mV for the blue LED as shown in Fig. 3 (b). The optimum I_{DC} points and V_{pp} values for each LED are used to estimate the available SNR $_k$ at subcarrier k based on the channel gain at subcarrier k shown in Fig. 3 (c). The available measured SNR $_k$ determines the QAM modulation format and corresponding power to be loaded adaptively at the subcarrier k for each LED as shown in Fig. 4. In the setup, the I_{DC} and V_{pp} values are optimised for conventional DCO-OFDM and applied directly to PA DCO-OFDM for comparison. As a result, the highest possible data rates are achieved per wavelength for the used equipment, setup and parameters.

Subsequently, the achieved data rate of the PAPR reduced PA DCO-OFDM per wavelength is compared to that of conventional DCO-OFDM without PAPR reduction. Both systems are using the same parameters, experimental equipment, setup and bit and power loading. The achieved data rates and BER results of PA DCO-OFDM compared with DCO-OFDM per LED spectrum are tabulated in Table. I. The aggregate data rate for the PA DCO-OFDM is 7.41 Gb/s for the WDM system, whereas, the conventional DCO-OFDM WDM system

achieved 6.92 Gb/s. This shows that, an increment of more than 7% in data rate without BER degradation when the high PAPR values are reduced by PA DCO-OFDM.

TABLE I
PA DCO-OFDM AND DCO-OFDM PERFORMANCE COMPARISON AT OPTIMUM VALUES

Achieved Data Rate in Gbps and BER				
Scheme	Metric	Red	Green	Blue
DCO-OFDM	Rb	2.37	2.36	2.19
	BER	0.0025	0.0018	0.0014
PA DCO-OFDM	Rb	2.45	2.47	2.49
	BER	0.0024	0.0015	0.0012

V. CONCLUSION

The DCO-OFDM with PAPR reduction is demonstrated experimentally using WDM system at three different wavelengths using low-cost available LEDs. The system parameters such as the driving bias current points, I_{DC} , and peak-to-peak voltage, V_{pp} , of the LEDs are optimised. In addition, each LEDs' available modulation bandwidth is fully utilised with adaptive bit and power loading. The PAPR of DCO-OFDM is reduced by $R = 10$ iterations pilot-assisted PA scheme. Therefore, the nonlinearity effect and the clipping distortion of the system caused by the limited dynamic range

of the LEDs and high PAPR of the modulation scheme are reduced. In such a way, the PA DCO-OFDM system results in data rate increment by more than 7% when compared to that of conventional DCO-OFDM without PAPR reduction. PA DCO-OFDM increases the system data rate by maximising the system SNR and reducing the clipping noise without BER degradation. The SNR and BER gain of PA DCO-OFDM system can be employed for longer distance and/or higher data rate transmissions while keeping the BER below a predefined FEC target. In addition, PAPR reduction of the system allows for higher input power levels and minimises the nonlinearity effects caused by the LEDs' upper and lower clipping points. The PA scheme has the potentials to reduce the transmitted average optical power which results in increasing the reliability of the LEDs and hence, the lifetime of the used LEDs.

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