Single LED Gbps Visible Light Communication with Probabilistic Shaping

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Abstract—Using a single low-power LED, we present a probabilistic shaped (PS) VLC system with near Shannon capacity transmission rates. For the channel conditions under consideration and a single 21 MHz −3 dB modulation bandwidth LED, probabilistic shaped symbols resulted in Gbps transmission rates. Comparatively, the PS resulted in above 27 % higher transmission speed than the widely used adaptive bit-power loading algorithm under the same channel conditions.

Index Terms—Probabilistic shaping, adaptive bit-power loading, optical communications, VLC/LiFi, OFDM

I. INTRODUCTION

With the exponential growth of data traffic [1], there is growing effort towards the use of the optical frequencies to complement the radio frequency (RF)-based wireless communication systems [2]. Visible light communication (VLC), based on light-emitting diodes (LEDs), is an emerging optical wireless communication (OWC) technology that operates in the visible light spectrum and exploits the existing lighting infrastructure for communication. Moreover, energy-efficient, low cost and widely available front-end devices enable VLC to attract increasing interest for short reach wireless connectivity [2], [3].

The −3 dB modulation bandwidth of commercially available visible LEDs is relatively small, only a few MHz [3], [4]. This means that for high-speed VLC, it is imperative to exceed the −3 dB modulation bandwidth of LEDs and employ suitable signal processing techniques and/or equalisation at the receiver [5]. Furthermore, the frequency selective response of LEDs, front-end devices and interference from ambient light sources can impact the overall frequency response of the optical link. Thus, making the received signal-to-noise ratio (SNR) of a VLC system frequency-dependent [6], [7]. In this context, orthogonal frequency division multiplexing (OFDM) is regarded as a convenient modulation scheme. It offers efficient use of the available spectrum and is robust against channel frequency selectivity [8]. It allows cost-effective equalisation with single-tap equalisers in the frequency domain. Most importantly, it enables adaptive data and energy loading in individual subcarriers depending on the channel frequency response [4]. This has contributed to high data rate transmissions using a single LED [4], [9], [10]. However, the adaptive bit-power loading applies discrete integer level bit allocation onto each subcarrier which is not a perfect fit for the channel frequency response. Thus, there still exists a capacity gap to the channel capacity limit as formulated by Shannon [11]. It is known that to approach the channel capacity limit of an additive white Gaussian noise (AWGN) channel, under the power constraint of a transmitter, the channel must be fed by a Gaussian source [12]. This can be achieved by applying a probabilistic shaping (PS) to quadrature amplitude modulation (QAM) symbols, which gives a Gaussian-like distribution over the input constellation [13].

With PS, data symbols are no longer uniformly distributed but are assigned different probabilities of occurrence. This is realised by transmitting low energy symbols more frequently than high energy symbols. An important element to map input information bits to probabilistically shaped symbols is a distribution matcher. Constant composition distribution matcher (CCDM), proposed in [14], has drawn considerable interest to implement PS in optical fibre communication and achieve record-setting transmission rates and distances [13], [15]–[17]. Similar efforts have been put towards enhancing the achievable information rate (AIR) of OWC using PS [18]–[21]. In [18], symbol error performance of the probabilistically shaped OFDM system under AWGN channel condition is evaluated which outperforms the uniformly distributed system. In [19], using a phosphor-LED based VLC system that employs OFDM modulation with PS, a data rate up to 200 Mbps is reported over 1 m free-space transmission. However, the PS modulation order is limited to 256-QAM (PS-256-QAM) despite the channel’s capacity to accommodate higher orders. Besides, subcarriers that are assigned to a group with the same QAM modulation order in the bit-loading scheme, are allocated with the same entropy in PS-256-QAM. This is contrary to the continuous entropy allocation that should fit the channel SNR response. Laser diode (LD) based OFDM with PS-256-QAM has also been demonstrated to improve the capacity of underwater OWC in [20]. Using higher order format (PS-1024-QAM) is also...
reported with LD-based VLC system in [21].

In this work, PS in conjunction with OFDM modulation is investigated in a high data rate VLC system based on a single off-the-shelf commercially available blue-LED. The principle of PS and bit-power loading schemes are presented. The system parameters of the 1 m free-space VLC link are carefully optimised, and the channel response is measured. Based on the same channel conditions, a comparison is made between the performance of OFDM with PS and with adaptive bit-power loading. Our results show that with PS, the capacity can be increased by over 27% compared to the bit-power loading approach.

The remainder of the paper is organised as follows. Section II presents the system description and principle of PS and bit-power loading. Section III provides the experimental setup. The results and discussions are offered in Section IV. Finally, concluding remarks are provided in Section V.

II. SYSTEM DESCRIPTION AND PRINCIPLE

A. Optical OFDM

Various forms of OFDM modulation schemes have been proposed for VLC [8]. These modulation techniques should satisfy the requirement of intensity modulation (IM) to generate real and unipolar LED modulating signal. A DC-biased optical OFDM (DCO-OFDM) is one of the most widely used spectrally efficient optical OFDM modulation schemes. In DCO-OFDM, a direct current bias is added to generate a unipolar signal. Furthermore, to realise real-valued OFDM waveform, Hermitian symmetry is imposed on the subcarriers of the OFDM frames such that \( X[k] = X^*[N_{FFT} - k] \) and \( X[0] = X[N_{FFT}/2] = 0 \) where \( N_{FFT} \) is the number of subcarriers, and \( k \) is the subcarrier index [22], [23].

The response of a VLC channel is frequency-selective which is attributed to interference from ambient light sources, the limited modulation bandwidth of LEDs, and the channel itself [7]. Due to this, the OFDM subcarriers have different SNR response. Applying a fixed-rate OFDM by allocating QAM signal with a fixed modulation order, \((M\text{-QAM})\) in all of the subcarriers could lead to underestimating the channel capacity [9]. Consequently, the entropy of the system should be allocated adaptively at each subcarrier to maximise the AIR. This is attained by estimating the available SNR at each subcarrier, \( \text{SNR}_k \), by using pilots composed of multiple OFDM frames prior to the actual data transmission. In the following subsections, the principles of entropy allocation using the adaptive bit-power loading and PS as well as performance comparison metrics are presented.

B. Optical OFDM with Adaptive Bit-power Loading

In the bit-power loading scheme, the estimated SNR is used to adaptively assign the subcarriers with different QAM formats. It allows for higher modulation orders to be used in the subcarriers with higher estimated SNR. This is achieved while ensuring the target probability of error, \( P_e^T \), below the forward error correction (FEC) limit of \( 3 \times 10^{-3} \) and a constant SNR on all received subcarriers with the same constellation size. The adaptive bit-power loading which is based on the Levin-Campello algorithm [24], involves the following optimisation problem on each OFDM subcarrier:

\[
\begin{align*}
\text{maximise} & \quad m_k = \log_2 M_k \\
\text{subject to} & \quad \text{BER} \left( M_k, \text{SNR}_k \right) \leq P_e^T \\
& \quad \frac{1}{N_{FFT} - 1} \sum_{k=1}^{N_{FFT} - 1} \nu_k^2 = N_{act}. \quad (1c)
\end{align*}
\]

Here, \( m_k \) is the number of bits/symbol, \( N_{act} \) is the number of active data subcarriers with \( m_k > 2 \) bits/symbol, \( \nu_k^2 \) is the power loading factor, and \( \text{BER} \left( M_k, \text{SNR}_k \right) \) is the theoretical BER of \( M_k\text{-QAM} \) at a subcarrier \( k \) with the SNR, which can be approximated as [25]:

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

where \( Q(\cdot) \) is the Gaussian Q-function.

C. PS Based Optical OFDM

The adaptive bit-power loading technique applies discrete integer level bit allocation onto each subcarrier which is not a perfect fit for the channel frequency response. However, PS based entropy loading can provide a better fit to the channel response and thus approached the channel capacity limit. A common approach to maximise the channel capacity is to use shaped input distribution from the family of Maxwell-Boltzmann (MB) distribution [12], [17]. Assuming that the PS-\( M\text{-QAM} \) constellation points are taken from \( \chi = \{ x_1, x_2, \ldots, x_M \} \), the corresponding MB distribution probability mass function (PMF) \( P_X (x_i) \) can be written as:

\[
P_X (x_i) = \frac{1}{\sum_{j=1}^{M} e^{-\lambda |x_j|^2}} e^{-\lambda |x_i|^2}, \quad (3)
\]

where \( \lambda \) is a rate parameter used to search for the optimum PMF that maximises capacity. Note that, the PMF is uniform when \( \lambda = 0 \) and as \( \lambda \) increases, the constellation distribution becomes Gaussian with reduced variance.

For PS based optical OFDM scheme, different probabilistic constellation distributions with a fixed modulation order, \( M\text{-QAM} \) symbols are applied to individual subcarriers based on the pre-estimated SNR. This optimisation process can be summarised as follows:

\[
\begin{align*}
\text{minimise} & \quad \left| - \sum_{i=1}^{M_k} P_X (x_i) \log_2 P_X (x_i) - C_k \right| \\
\text{subject to} & \quad C_k = \log_2 (1 + \text{SNR}_k). \quad (4b)
\end{align*}
\]

In this work, CCDM is utilised to map input information bits to probabilistically shaped symbols and realise the above
optimisation process. Furthermore, binary reflected Gray code is used as a binary labelling rule. A square PS-MQAM signal is generated by using two orthogonal pulse-amplitude modulation (\sqrt{M}-PAM) symbols that represent real and imaginary parts of the $M$-QAM symbols.

### D. Generalised Mutual Information

Generalised mutual information (GMI) and normalised GMI (NGMI) have been considered as effective performance metrics to accurately predict the post-FEC performance of bit-interleaved coded modulation (BICM) system with ideal binary soft-decision (SD) decoding [26], [27]. Moreover, NGMI can be regarded as a reliable SD-FEC threshold for uniform as well as for probabilistically shaped QAM, which is given by $\text{NGMI} = 1 - (H - \text{GMI}/\log_2 M)$ where $H$ represents the entropy of PS-M-QAM. For uniform $M$-QAM, $H = m = \log_2 M$ [26]. The required amount of ideal FEC overhead (OH) to achieve error-free post-FEC can also be inferred from the NGMI using $(1-\text{NGMI})/\text{NGMI}$ [19].

FEC overhead (OH) to achieve error-free post-FEC can also be calculated through Monte Carlo simulations of $N$ samples as [17]:

\[
\text{GMI} \approx \frac{1}{N} \sum_{n=1}^{N} \left( -\log_2 P_X(x_n) \right) - \frac{1}{N} \sum_{n=1}^{N} \sum_{i=1}^{m} \left[ \log_2 \left( 1 + e^{-b_{n,i} \Lambda_{n,i}} \right) \right], \tag{5}
\]

where the first term in (5) is the entropy of the constellation, and the second term calculates the impact of channel noise from measured channel statistics and the probabilistic distributions. $b_{n,i}$ is the transmitted bit of the $n$th symbol at the $i$th bit level, and the soft bit-wise demapper output $\Lambda_{n,i}$ are the log-likelihood ratios (LLRs) which are computed with 2D Gaussian auxiliary channel as [17]:

\[
\Lambda_{n,i} = \log \frac{\sum_{x \in \chi_i^1} e^{-\frac{|y_k - x|^2}{2\sigma^2}} P_X(x)}{\sum_{x \in \chi_i^0} e^{-\frac{|y_k - x|^2}{2\sigma^2}} P_X(x)}, \tag{6}
\]

where $\chi_i^1$ and $\chi_i^0$ denote the set of constellation points whose $i$th bit is 1 or 0, respectively. $\sigma^2$ is the noise variance of the AWGN channel.

Once the the GMI in each of subcarriers is evaluated using (5), the overall data rate of the VLC system is obtained as:

\[
R_b = \frac{\sum_{k=1}^{N_{\text{FF}}-1} \text{GMI}_k}{N_{\text{FF}} + N_{\text{CP}}} \times R_s, \tag{7}
\]

where $R_s = 2B/(1 + \beta)$ is the symbol rate, $B$ is the electrical bandwidth required by the signal, $\beta$ is the roll-off factor of root-raised cosine filter, and $N_{\text{CP}}$ is the cyclic prefix size.

### III. Experimental Setup

The block diagram in Fig. 1 lays out the signal generation and detection process for the DCO-OFDM VLC system. This is the experimental setup used to measure the VLC channel response. In the transmitter DSP, a stream of binary input is generated and then mapped into $M$-QAM symbols. In the bit-power loading scheme, different QAM formats are applied, while for OFDM with the PS technique, a fixed $M$-QAM with different probabilistic constellation distributions is employed based on the pre-estimated SNR. After applying the Hermitian symmetry, each symbol is loaded onto the orthogonal subcarriers by employing an inverse fast Fourier transform (IFFT). The OFDM frame size is set to $N_{\text{FF}} = 1024$ subcarriers. Cyclic prefixes (CPs) are inserted at the start of each OFDM frame. A value of $N_{\text{CP}} = 5$ is found to be sufficient for the intersymbol interferes (ISI) to be removed [10], [28]. The symbols can then be multiplexed into serial time-domain output. Root-raised cosine (RRC) pulse shaping filter is used to utilise the limited bandwidth of the optical link effectively [29]. The waveform pattern is then uploaded to an arbitrary waveform generator (AWG: Keysight 81180A) to generate the electrical modulating signal. The sampling rate of the AWG is set to 2 GSa/s. The output of the AWG is superimposed on the DC bias current via a bias-tee (Bias-Tee: Mini-Circuits ZFBT-4R2GW+). The output signal from the bias-tee is connected to the LED (VLMB1500-GS08).

Since the half-power semi-angle of the LED is wide (i.e. about 65°), aspheric condenser lenses (Thorlabs ACL4532) are used to collimate the output light from the transmitter and focus it into the detection area of the photodetector.

At a receiver side with a link distance of 1 m, a photodetector (PD: ThorLabs PDA10A) is used to detect the intensity modulated signal. The receiver has a $-3$ dB bandwidth of 150 MHz and a built-in transimpedance amplifier (TIA) with a gain of 5 V/mA. The received electrical signal is captured by an oscilloscope (OSC: Keysight MSO7104B) followed by processing in MATLAB. The received waveform from the oscilloscope is synchronised and then matched filter is applied. This is followed by removal of CP, and fast Fourier transform (FFT) operation. This provides the received QAM signal in the frequency domain at each of the subcarriers. The estimated frequency response of the system is used to equalise the received signal which can then be demodulated using the QAM demodulator.

Primarily, the channel response and available SNR at each subcarrier, $\text{SNR}_k$, are estimated using pilots composed of multiple 4-QAM based OFDM frames. The SNR for each OFDM subcarriers is obtained by evaluating the error vector magnitude (EVM) of the received pilot 4-QAM signal [30]. Note that, in PS based OFDM, 1024-QAM symbols are mapped into individual subcarriers. The PS-1024-QAM symbols are generated from two orthogonal 32-PAM symbols.
The choice of this higher modulation order allows utilising the available SNR to the full extent. However, it comes with a requirement of a greater number of sample points which goes beyond the memory depth of the available devices. Consequently, the GMI performance of PS based system is evaluated offline from experimentally measured channel response. To carry out a fair comparison, this offline performance measurement is repeated for the bit-power loading technique as well and used to make a comparison with the PS technique. In addition, the performance of uniformly-loaded 8-QAM and 16-QAM OFDM technique are also investigated.

IV. RESULTS AND DISCUSSION

The VLC data transmission is performed at a 2 GS/s sampling rate with an oversampling factor of 4 samples per symbol. Hence, the symbol rate, $R_s = 500$ MBaud. The DC bias point of the LED is a crucial parameter of the experiment. Details of the DC bias optimisation process can be found in [31]. In this experiment, an optimum DC bias of 30 mA is applied to the LED which is measured to give approximately 21 MHz $-3$ dB electrical bandwidth. At the selected bias point, the system performance as a function of the modulation signal depth, (peak-to-peak voltage, Vpp) is investigated. The SNR distribution per subcarrier is shown in Fig. 2. As expected, the SNR improves as Vpp increases. For all measurements, there is a sharp SNR drop at the 256th subcarrier due to nonlinear harmonic distortion in the system. Despite reducing the number of bits that could be loaded onto this subcarrier, this will not affect the system error performance as bits are allocated based on the estimated SNR. Consequently, the VLC channel response at the optimised values for the DC bias at 30 mA and the modulation signal depth at 2 Vpp is used in the adaptive bit-power loading and PS based OFDM techniques.

The adaptive bit allocated per subcarrier is shown in Fig. 3 (a) along with the channel capacity which is also used as source entropy for PS based OFDM. The entropy of the bit-power loading system takes only discrete integers with a maximum of 9 bits/symbol. Among 511 data subcarriers, 364 subcarriers are loaded with 2 or more bits/symbol. The corresponding power loading per subcarrier is also shown in Fig. 3 (b). The PS scheme takes continuous entropy values and applies a fixed 1024-QAM signal. The graphical illustration of PS-1024-QAM signal at different subcarriers
is shown in Fig. 4.

Fig. 3. (a) Bit loading and channel capacity per subcarrier. (b) Power loading per subcarrier

Fig. 4. Graphical illustration of PS-1024-QAM with four different entropy values at subcarrier index of (a) 50 (b) 100 (c) 150 and (d) 200. Note that the distributions become more shaped as the entropy decrease, and the probability of occurrence of outer point may converge to zero.

Fig. 5 shows the GMI versus different subcarriers for bit-power loading and PS-1024-QAM. The GMI of uniformly-loaded 8-QAM and 16-QAM OFDM and the Shannon capacity limit of the channel are also presented as a performance reference. The uniform 8-QAM and 16-QAM OFDM schemes result in a maximum of 3 and 4 bits/symbol GMI per subcarrier, respectively in the high SNR region. Expectedly, this decreases with decreasing SNR. The GMI of the bit-power loading exhibits a gap to the capacity limit, while the GMI of PS-1024-QAM approaches the Shannon capacity across all subcarriers.

In terms of NGMI, for the bit-power loading, the lowest NGMI is 0.8260 and requires an overall FEC OH of approximately 7%. Meanwhile, for PS the minimum NGMI is 0.9679 and reduced the required overall OH to just below 2%. The aggregate data rate of bit-power loading is 888.82 Mbps. While for PS-QAM, 1.13 Gbps can be achieved, indicating an increase of 27.13% compared to the bit-power scheme. These results clearly demonstrate with PS, the VLC information rate can be enhanced substantially.

V. Conclusion

In this work, we have studied PS for an OFDM based visible light communication system using an LED over 1 m free-space transmission. Based on the estimated SNR response of the VLC channel, the achievable rates of PS and the adaptive bit-power loading techniques are compared. Unlike the bit-power loading optimisation method, PS provides continuous entropy loading that makes efficient use of the available bandwidth well beyond the $-3$ dB point. The PS scheme results in an aggregate AIR of 1.13 Gbps, a 27.13% increase over the bit-power loading AIR. The results demonstrate that PS can be utilised to closely approach the VLC system capacity and maximise the information rate. In addition to a free-space VLC application presented here, PS can be beneficial in different fading channel conditions including underwater links. Furthermore, a wavelength division multiplexing (WDM) VLC system with PS is an interesting future work to investigate.

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