



This is a repository copy of *White Light Constrained Multi-Primary Modulation for Visible Light Communication*.

White Rose Research Online URL for this paper:
<http://eprints.whiterose.ac.uk/129236/>

Version: Accepted Version

Proceedings Paper:

Singh, R., Pergoloni, S., O'Farrell, T. orcid.org/0000-0002-7870-4097 et al. (3 more authors) (2018) White Light Constrained Multi-Primary Modulation for Visible Light Communication. In: 2017 IEEE Globecom Workshops (GC Wkshps). 2017 IEEE GLOBECOM (Global Hub: Connecting East and West), 04-08 Dec 2017, Marina Bay Sands Expo and Convention Centre, Singapore. IEEE .

Reuse

Unless indicated otherwise, fulltext items are protected by copyright with all rights reserved. The copyright exception in section 29 of the Copyright, Designs and Patents Act 1988 allows the making of a single copy solely for the purpose of non-commercial research or private study within the limits of fair dealing. The publisher or other rights-holder may allow further reproduction and re-use of this version - refer to the White Rose Research Online record for this item. Where records identify the publisher as the copyright holder, users can verify any specific terms of use on the publisher's website.

Takedown

If you consider content in White Rose Research Online to be in breach of UK law, please notify us by emailing eprints@whiterose.ac.uk including the URL of the record and the reason for the withdrawal request.



eprints@whiterose.ac.uk
<https://eprints.whiterose.ac.uk/>

White Light Constrained Multi-Primary Modulation for Visible Light Communication

Ravinder Singh[§], Stefano Pergoloni[#], Timothy O’Farrell[§], Gaetano Scarano[#], John David[§], and Mauro Biagi[#]

[§]The Department of Electronic and Electrical Engineering, University of Sheffield, UK, S1 3JD and [#]the Department of Information, Electrical and Telecommunication (DIET) engineering, “Sapienza” University of Rome, Via Eudossiana 18, 00184, Italy. email: {*r.singh, t.ofarrell, j.p.david*}@sheffield.ac.uk. and {*stefano.pergoloni, mauro.biagi, gaetano.scarano*}@uniroma1.it.

Abstract—The application of visible light communication (VLC) systems is to transmit data while maintaining efficient and good quality illumination service. In order to meet standard lighting requirements when multi-colored modulation techniques are used, such as color shift keying (CSK), the color fluctuation becomes a relevant issue. This paper presents a multi-primary (multi-color) modulation technique which provides reliable data transmission while keeping a strong constraint on the light color illuminated by every symbol of the modulation alphabet. The number of possible primary color combinations that ensure white light are calculated for a given set of multi-color light sources. The system performance in terms of bit error rate for different constellation is evaluated and compared against other multi-color VLC schemes in the literature, considering a range of channel impairments due to the optical front-end components.

Index Terms—Visible Light Communication, Multi-color LEDs, Signal Space, VLC Color Control, Constant Hue Modulation, Color Shift Keying.

I. INTRODUCTION

The idea of transmitting information through light, formally known as visible light communication (VLC), has emerged as an attractive technique to overcome the expected capacity crunch due to the ever growing high data transmission rate demand on the existing RF networks. There has been a tremendous development in VLC technology in the last couple of decades which includes development of standards [1][2], advanced test-beds [3] and many interesting modulation techniques including MIMO systems [4].

The abundant unlicensed visible spectrum [5], simple transceiver design and high data-link secrecy are some of the key benefits of VLC technology [6]. The main driving force behind the development of the VLC technology is the idea of providing lighting and communication through a common medium by utilising energy efficient solid-state lighting infrastructure. Therefore, any VLC system should not compromise the primary lighting purpose, ensuring that lighting standards are met as well as high data transmission reliability.

In the IEEE 802.15.7 physical layer III standard, color shift keying (CSK) modulation is specified as a flicker-free multi-color VLC scheme in which the information is mapped into the instantaneous output color of trichromatic LEDs (TLEDs), thus the information is encoded into a specific color for the transmission system [1]. A performance evaluation of CSK is available in [7][8].

In the multi-color VLC literature, a communication performance gain is obtained by using four coloured LEDs instead of three as in TLED CSK. The adoption of an additional primary, namely a yellow LED [9], increases the color gamut dimensional space, creating a four-dimensional signaling scheme named QuadLED (QLED), which leads to a more power efficient and reliable modulation scheme in comparison with classic (TLED) CSK specified in IEEE 802.15.7.

In order to fully meet the standard lighting requirements, in color-based VLC modulation schemes the color fluctuation issue should be addressed, thereby improving the color rendering quality of the modulated light. Several studies in the literature have tried to address the color rendering issue of CSK by optimizing the constellation design for TLED [10] [11] and QLED [12] [13] systems, which lead to bit error rate (BER) performance degradation caused by smaller Euclidean distances between the transmitted symbols. In [14], codes based on finite state machines are used in order to produce coding gain while reducing the fluctuation in the perceived color. A different approach to color rendering improvement is tackled in [15] and [16] where the principle of metamerism has been exploited in order to transmit, with differing triplets of primary colors, symbols that are perceived by the human eye as equal in color or hue.

Keeping the two key requirements of lighting quality and high data transmission reliability in mind, this work introduces a new multi-primary modulation (MPM) technique for VLC which provides the capability of binding a single output light color to every transmitted symbol vector. Thereby eliminating any unwanted color fluctuation in a multi-color VLC signalling scheme. The concept is to have a large number of transmitted symbols with a stringent constraint on the light produced, while using more than three primary colours. Thus the MPM scheme improves the number of possible primary combinations producing same output light while achieving reliable communication even when the cardinality of the M-ary constellation grows.

The proposed MPM scheme uses more than three multi-color LEDs and these LED are switched in different combinations using carefully selected power levels (including turning off some LEDs) in order to define a symbol which will result in output light being white. The number of combinations leading to obtain white light are evaluated and allowing spectral efficiency to be measured. At this point, the aim of

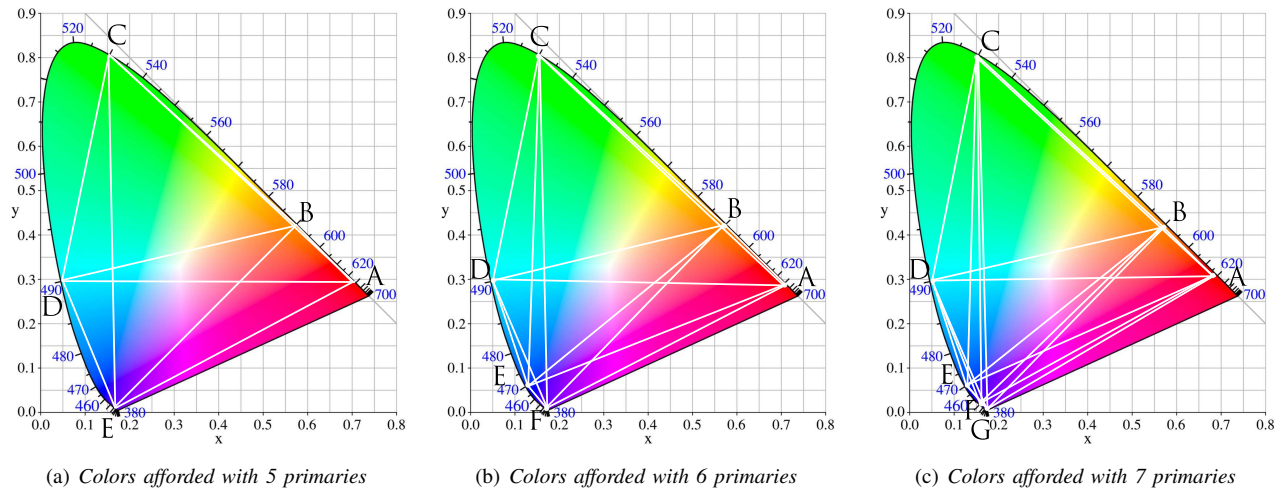


Fig. 1. Representation of considered primaries on CIE 1931 diagram.

this work is not to optimize the bit and symbol distances, therefore, two different solutions to evaluate the MPM scheme are investigated. One maximizes the number of symbols (hence the spectral efficiency) while the other one selects a smaller number of color combination, omitting those with the least symbol distances.

The numerical results show that the MPM system provides robust data transmission performance while considering the stringent lighting constraints. The results show that for an AWGN channel, the MPM scheme outperforms the TLED CSK and provides similar performance to QLED CSK for higher spectral efficiencies. The MPM system performance evaluation over the VLC channel shows that for increasing spectral efficiency given the number of primaries increase and the signalling space is enhanced, the SNR penalties for increasing the data rate will be small. Additionally, the channel estimation results also show that the MPM scheme provides robust communication link with respect to imperfect channel knowledge.

The paper is organized as follows. After introducing the system model and the working of MPM scheme in terms of symbol mapping in sec. II, the implementation of the receiver is described in sec. III. The performance of the proposed scheme is reported in sec. IV where the behaviour of detection procedure in an Additive White Gaussian Noise (AWGN) scenario and in a typical indoor optical wireless channel is detailed along with the effect of channel estimation errors. Lastly, the concluding remarks are provided.

II. MULTI-PRIMARY MODULATION AND SYSTEM MODEL

Let us consider use of L different primary colors. That is each LED is able to emit a distinct light according to its emission spectrum. Having defined the number of primaries, each transmission symbol is given by a distinguishable combination of primaries (and their optical powers or intensities) leading to obtain the target color and light intensity, which in

TABLE I
COMBINATIONS OF PRIMARIES ALLOWING WHITE COLOR RENDERING.
THE COMBINATIONS REFER TO FIG. 1(C)

| |
|---|
| $L = 5$ |
| (ABD), (ACD), (ACE), (BCE), (BDE), (ABCD), (ABCE), (BCDE), (ACDE), (ABCDE), |
| $L = 6$ |
| (ABD), (ACD), (ACE), (ACF), (BCE), (BCF),(BDE), (BDF), (ABCD), (ABCF), (ABCE), (ABDE), (ABDF), (ACDE), (ACDF), (ACEF), (BCDE), (BCDF), (BCEF), (ABCDE), (ABCDF), (ABCEF), (ABDEF), (ACDEF), (BCDEF), (ABCDEF) |
| $L = 7$ |
| (ABD), (ACD), (ACE), (ACF), (ACG), (BCE), (BCF), (BCG), (BDE), (BDF), (BDG), (ABCD), (ABCE), (ABCF), (ABCG), (ABDE), (ABDF), (ACDE), (ACDF), (ACDG), (ACEF), (ACEG), (ACFG), (BCDE), (BCDF), (BCDG), (BCEF), (BCEG), (BCFG), (BDEF), (BDEG),(BDFG), (ABCDE), (ABCDF), (ABCDEG), (ABCEF), (ABCEG), (ABCDFG), (ABDEF), (ABDEG), (BCDEF),(BCDEG), (BCDFG), (BCEFG), (ACDEF), (ACDFG),(ACDEG), (ACEFG), (BDEFG), (ABCDEF), (ABCDEG), (ABCDFG), (ABCEFG), (ABDEFG), (ACDEFG), (BCDEFG), (ABCDEFG) |

this case is white. The set collecting the symbols is denoted as \mathcal{G}_L . The number of primaries and their spectra cannot be chosen arbitrarily since the goal is threefold: 1) to obtain the target light and color, 2) have a high spectral efficiency for the proposed modulation scheme and 3) to achieve a negligible bit-error-rate (BER) level. To address this problem, one can resort to the CIE 1931 color diagram (see Fig. 1) that reports all the colors visible to human eye. Once L is chosen, the maximum number of color combinations is given by (1).

$$C = \sum_{i=1}^L \binom{L}{i} \quad (1)$$

However, the number of color combinations that produce the target light color is less than C and it is characterized by $|\mathcal{G}_L|$, which is, the number of polygons that contain the target color on the CIE 1931 diagram. The amount of light to be emitted

by each LED is determined by the solution of the L -stimula system [17]. While the cases of using L of 2, 3 and 4 are known from the literature, (see [17] for L equals 2,3 and [9] for $L = 4$) Fig. 1 detail the behavior for $L = 5, 6, 7$ for the presented MPM system.

Table I lists combinations of primary colors that yield white light. The triplets, quadruplets, quintuplets, sextuplets and septuplets, which correspond to the target white are indicated with capital letters by referring to the visual description provided in Fig.1. It is important to note that the primaries characterized by capital letters A, B, C, D are the same for L ranging from 5 to 7, while primaries corresponding to the other letters do not overlap. Hence, in Table I, the parenthesis indicate that the white light is obtained by turning on (for that symbol) only those primaries/letters while the others remain turned off. As an example, the symbol (ABD) for $L = 7$, means that C, E, F and G are turned off. The presented MPM scheme relies up on the chosen central wavelengths and chromaticity values (presented in Table II) that are compliant with existing LEDs and also to have very limited crosstalk.

In order to construct the symbols from the power levels of a primary combination, (i.e. the light intensity that each primary must emit for each symbol), we exploit the colorimetry gamut and obtain a target light intensity and color described by chromaticities X, Y, Z (see [17]). This amounts to obtaining the reference white intensity by using L primaries with their multi-stimula coefficients T_k can be used. We define a matrix of coordinates of the L primaries P_1, \dots, P_L in the CIE diagram as

$$\mathbf{F} = \begin{bmatrix} x(P_1) & x(P_2) & \dots & x(P_L) \\ y(P_1) & y(P_2) & \dots & y(P_L) \\ z(P_1) & z(P_2) & \dots & z(P_L) \end{bmatrix}, \quad (2)$$

where $x(P_1) = X(P_1)/(X(P_1) + Y(P_1) + Z(P_1))$, $y(P_1) = Y(P_1)/(X(P_1) + Y(P_1) + Z(P_1))$ and $z(P_1) = Z(P_1)/(X(P_1) + Y(P_1) + Z(P_1))$. Then we write

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \mathbf{F} \cdot \begin{bmatrix} a_1 & 0 & \dots & 0 \\ 0 & a_2 & \dots & 0 \\ \vdots & \ddots & \ddots & \vdots \\ 0 & 0 & \dots & a_L \end{bmatrix} \cdot \begin{bmatrix} T_1 \\ T_2 \\ \vdots \\ T_L \end{bmatrix}, \quad (3)$$

where the scalar coefficients a_k determine the required reference white (W). The coefficients a_k are obtained from (4) as

$$[a_1 \ a_2 \ \dots \ a_L]^T = \mathbf{F}_{\text{RI}} \cdot \begin{bmatrix} x(W) & & & \\ & 1 & & \\ & & z(W) & \\ & & & y(W) \end{bmatrix}^T. \quad (4)$$

where $\mathbf{F}_{\text{RI}} = \mathbf{F}^T (\mathbf{F} \cdot \mathbf{F}^T)^{-1}$ is the right inverse. The above solution represents the *minimum norm* solution [18]. Analogously, the stimula solution is given by (5).

$$[a_1 T_1 \ a_2 T_2 \ \dots \ a_L T_L]^T = \mathbf{F}_{\text{RI}} \cdot [X \ Y \ Z]^T. \quad (5)$$

The above analysis provides the stimula coefficients that must be used in order to compute the power to be allocated to each primary corresponding to each symbol considering

the emission, given the spectrum of each LEDs. The last step needed to compute the power level to be allocated to each symbol is obtained by solving the following system of equations¹ with respect to $\beta_k(W)$ and the target white light fixed by $W(\lambda)$

$$\int W(\lambda) P_j(\lambda) d\lambda = \sum_{k=1}^L \beta_k(W) \int P_k(\lambda) P_j(\lambda) d\lambda, \quad j, k=1, \dots, L \quad (6)$$

where $P_j(\lambda)$ is the spectrum of the j^{th} primary. Solving (6) gives the $\beta_k(W)$ values related to the target white light. Finally, the power for obtaining the target white is given by (7).

$$x_k = \beta_k T_k \int P_k(\lambda) d\lambda \quad (7)$$

Hence, the transmitted signal for the ℓ^{th} symbol, where $\ell \in \mathcal{G}_L$, is given by (8).

$$s_\ell(t) = \sum_{k=1}^L x_{\ell,k} p_k(t) \quad (8)$$

where $p_k(t)$ is the signal emitted by the k^{th} LED (k^{th} color) and $x_{\ell,k}$ is the optical power associated to the k^{th} LED for the ℓ^{th} symbol. Fig. 2 shows a top level MPM transceiver schematic.

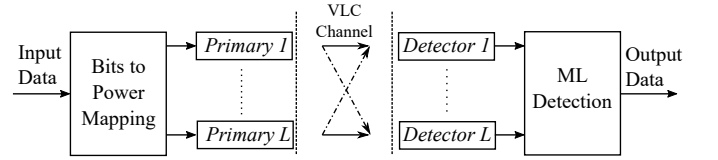


Fig. 2. Schematic of a MPM VLC transceiver.

For the system performance evaluation, we assume an indoor VLC channel model as shown in Fig. 3, where the transmitter (Tx) is located at the center of the room ceiling and the receiver (Rx) is located 0.85m (approximate table height) above the floor. The impulse response of the wireless channel between the Tx and Rx is typically composed of a line-of-sight (LoS) path and multiple reflected paths [19]. Given the LoS path gain is usually substantially higher than the reflected path powers, in this paper we study the system performance considering the LoS path only. The multi-primary LoS channel gain matrix for the system set-up shown in Fig. 3 can be written as:

$$\mathbf{H}_{i,k} = \frac{(m+1)A_i}{2\pi d_{i,k}^2} \cos^m(\phi_k) \cos(\psi_i) \mathbf{G}_{i,k}. \quad (9)$$

In (9), m is the Lambertian emission order, given as $-\log_2[\cos(\phi_{\frac{1}{2}})]$, where $\phi_{\frac{1}{2}}$ is the LED's semi-angle at half-power. In (9), d is the physical distance between the Tx and Rx, A_i is the physical area of the i^{th} detector, ϕ_k is the angle

¹In (6) we used $V(\lambda) = P_j(\lambda)$ while the general expression is $\int W(\lambda)V(\lambda)d\lambda = \sum_{k=1}^L \beta_k(W) \int P_k(\lambda)V(\lambda)d\lambda$ with $V(\lambda)$ the generic spectrum.

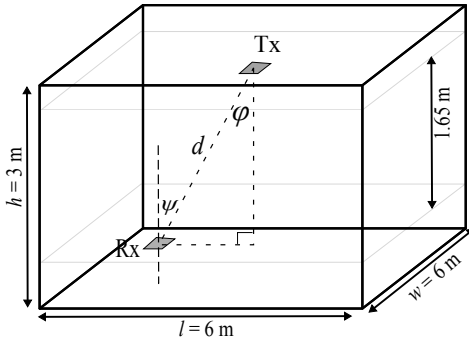


Fig. 3. Indoor system configuration.

of irradiance of the k^{th} primary, ψ_i is the angle of incidence to the i^{th} detector and lastly, $\mathbf{G}_{i,k}$ represents the effective responsivity between the receive band i and transmit band k , which is calculated as:

$$\mathbf{G}_{i,k} = \int_{\lambda_{min}^{T_i}}^{\lambda_{max}^{T_i}} P_k(\lambda) T_i(\psi, \lambda) R_i(\lambda) d\lambda \bigg/ \int_{\lambda_{min}^{F_k}}^{\lambda_{max}^{F_k}} P_k(\lambda) d\lambda, \quad (10)$$

where, $T_i(\psi, \lambda)$ is the transmission of filters and $R_i(\lambda)$ is the responsivity of the photo-detector(s) (PDs). Using (8), (9) and the receiver AWGN vector \mathbf{n} , the multi-primary VLC system can be expressed through (11).

$$\mathbf{y}(t) = \mathbf{H}\mathbf{s}(t) + \mathbf{n}(t) \quad (11)$$

In (11), $\mathbf{y}(t)$ is the received signal in a vector form which contains the intensities detected across i PDs and $\mathbf{n}(t)$ vector contains the instantaneous AWGN values for each PD with standard deviation of $\sigma = \sqrt{\mathcal{N}_0/2}$, where \mathcal{N}_0 is the single-sided noise power spectral density.

III. DIGITAL DEMODULATION

The optimal receiver we consider is based on the Maximum Likelihood (ML) criterion and channel information is needed at the receiver in order to perform detection. We will discuss in the numerical results section the role played by channel information and estimation. Such estimation is obtained by sending training symbols with an assigned sequence tuned to the channel coherence time. Before detailing the detection procedure we briefly explain how the channel estimation procedure works. We transmit M consecutive pilot symbols every QT_s seconds, where T_s is the symbol period. The value of Q should be chosen so as to guarantee that QT_s is smaller than the channel coherence time. The value of Q determines the accuracy of the estimated channel. Since the symbols are known at the receiver, an MMSE channel estimation procedure can be used. As a consequence the estimated channel is

$$\tilde{\mathbf{H}} = \mathbf{H} + \mathbf{E} \quad (12)$$

where the $(L \times L)$ matrix \mathbf{E} is zero mean Gaussian with diagonal covariance matrix (see [18] for further details) whose

diagonal elements are given by K in (13), where $\text{SNR}_e = \mathbb{E}\{\mathbf{s}(t)^2\}/\sigma^2$ is the electrical SNR at the Rx with $\mathbb{E}\{\cdot\}$ being the expectation operator.

$$K = (1 + (\text{SNR}_e \cdot M)^{-1})^{-2} - 2(1 + (\text{SNR}_e \cdot M)^{-1})^{-1} + 1 + \frac{\sigma^2}{M}(1 + (\text{SNR}_e \cdot M)^{-1})^{-2}. \quad (13)$$

Considering the detection algorithm, the receiver should calculate the conditioned probability on the L -length vector by spanning all possible symbols emitted \mathbf{x} , which is given by the symbols combinations belonging to \mathcal{G}_L . Then the ML detection criterion can be defined as

$$\hat{\mathbf{x}} = \underset{\mathbf{x} \in \mathcal{G}_L}{\text{argmax}} p(\mathbf{y}|\mathbf{x}), \quad (14)$$

where \mathbf{y} is the $(1 \times L)$ row vector collecting the (sampled) values at each time slot. Under the hypothesis, largely verified, of zero mean \mathcal{N}_0 -variance white Gaussian distributed noise, (14) can be expanded as follows

$$p(\mathbf{y}|\mathbf{x}) = \frac{1}{(2\pi)^{N/2}} \exp\left(-\frac{1}{2\mathcal{N}_0}[\mathbf{y} - \tilde{\mathbf{H}}\mathbf{x}]^T[\mathbf{y} - \tilde{\mathbf{H}}\mathbf{x}]\right). \quad (15)$$

The above expression leads to the comparison among all the $|\mathcal{G}_L|$ possible combinations that can be done by computing the distance metric

$$\hat{\mathbf{x}} = \underset{\mathbf{x} \in \mathcal{G}_L}{\text{argmin}} \|\mathbf{y} - \tilde{\mathbf{H}}\mathbf{x}\|^2 \quad (16)$$

IV. NUMERICAL RESULTS

The system level performance of the uncoded MPM system is evaluated using AWGN and LoS VLC channels in this section, through Matlab modelling. The optical characteristics of Thorlab's multi-colour LEDs [20], Thorlab's multi-colour bandpass optical filters [21] and Hamamatsu's PD array [22] are used to provide realistic system model of the optical components. The optical properties of these front-end components were used to estimate the effective responsivity \mathbf{G} and thereby the channel matrix \mathbf{H} . The central wavelength and chromaticity values of the assumed LEDs are given in table II.

TABLE II
MULTI-PRIMARY LED CENTRAL WAVELENGTH AND CHROMATICITY VALUE.

| LED | A | B | C | D | E | F | G |
|------------------|------|-------|------|------|------|-------|------|
| λ_c (nm) | 625 | 590 | 530 | 490 | 470 | 455 | 385 |
| x | 0.71 | 0.58 | 0.15 | 0.05 | 0.13 | 0.155 | 0.17 |
| y | 0.21 | 0.415 | 0.8 | 0.3 | 0.06 | 0.02 | 0.01 |

A. BER evaluation using AWGN model

We begin by analyzing the average BER performance of the MPM system in an AWGN channel. The average BER is calculated from the the symbol error rate (SER) by dividing the SER by the number of bits per symbol. Fig. 4 shows the average BER performance of the MPM system on a scale of received electrical SNR (SNR_e). As mentioned previously, two

aspects of the MPM scheme were explored; a) maximising the number of symbols for a given number of primaries (L) used and b) by using selected symbols only with maximum Euclidean distance from each other. These two cases lead to different number of total symbols per L leading to 10-MPM, 26-MPM and 57-MPM for case (a) and 8-MPM, 16-MPM and 32-MPM for case (b). The results in Fig. 4 for both the cases clearly show that the BER performance can be significantly improved by using only a selected number of symbols with large Euclidean distances amongst themselves, at the cost of small reduction in the spectral efficiency. The non-optimal case of using maximum number of symbols suffer high SNR penalties due to decreased Euclidean distances between the symbols. This is due to the fact that we do not aim, in this work, at maximizing the Euclidean distances amongst symbols.

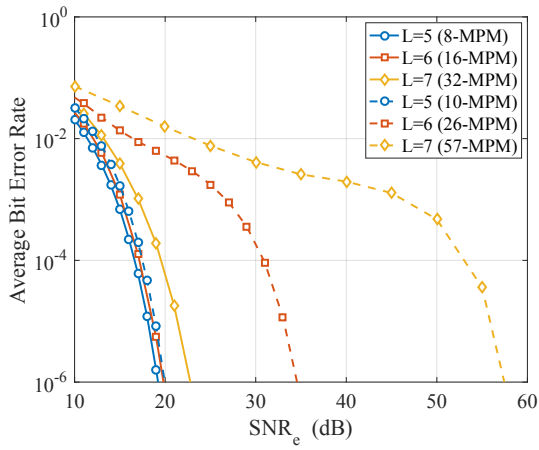


Fig. 4. The BER vs SNR_e performance of the MPM system in AWGN channel, considering both the solution of a) maximum number of symbol and b) optimised distance between symbols, given a set of L primaries.

Overall, in the case of selected symbols, the BER results show that for 8-MPM and 16-MPM, the results are almost identical and the 32-MPM requires approximately 3 dB more SNR than 8-MPM and 16-MPM cases. This shows that for the selected symbols case, the SNR requirements do not change significantly when the spectral efficiency is increased. This is because for higher spectral efficiency MPM relies on increase in the number of primaries, i.e. increase in the signalling dimensions and hence the Euclidean distances between the symbols. These results show that by increasing the number of primaries the spectral efficiency can be further improved at the cost of small increase in the SNR requirements.

Further a BER performance comparison between the MPM and CSK systems is made for the same spectral efficiency requirements. Table III compares the SNR requirements of the MPM scheme against the well known TLED and QLED CSK systems for the same BER of 10^{-6} . The results show that MPM scheme outperforms the TLED CSK and provide similar performance to QLED CSK with increasing spectral efficiency. This, given the ultimate control over white light, makes the MPM scheme highly competitive VLC scheme,

especially being a lighting constrained scheme.

TABLE III
THE SNR REQUIREMENTS OF TLED CSK, QLED CSK AND MPM VLC SCHEMES FOR A BER OF 10^{-6} OVER AWGN CHANNEL.

| Modulation Order | TLED SNR_e (dB) | QLED SNR_e (dB) | MPM SNR_e (dB) |
|------------------|--------------------------|--------------------------|-------------------------|
| 8 | 19.3 | 15.2 | 19.2 |
| 16 | 23.7 | 18.1 | 19.9 |
| 32 | – | – | 22.7 |
| 64 | – | 24.9 | – |

B. BER evaluation in LoS indoor channel model

Given the selected symbols MPM scheme provides robust BER performance in the AWGN channel, we focus on this case for the system BER performance evaluation over the VLC channel. In this case, it is assumed that the Tx is located on the room ceiling at co-ordinates (3,3,2.5) (m) and the Rx is located at (4.5,4.5,0.85) (m), i.e. approximately 2m away from the centre of the room. The BER results considering this set-up are shown in Fig.5. The results show that all the modulation formats are able to provide robust communication link achieving 10^{-6} for SNR values between 24 to 27 dB.

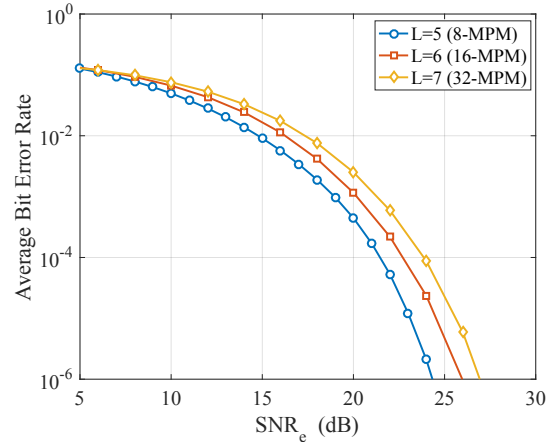


Fig. 5. The BER vs SNR_e performance of the optimised Euclidean distance MPM system in LoS indoor VLC channel. The Tx is located on the room ceiling at co-ordinates (3,3,2.5) (m) and the Rx is located at (4.5,4.5,0.85) (m).

The system BER performance was also tested by placing the Rx at the centre of the room (3,3,0.85) (m). These results are identical to those shown in Fig. 5 for the same SNR values at the Rx. However, given the LoS is stronger at the centre of the room (see Fig. 3) where the Tx and Rx are fully aligned, ~ 12 dB transmit power can be saved, in comparison to the Rx being located at (4.5,4.5,0.8) (m), to provide same SNR at the Rx. For the result in Fig. 5, a perfect channel estimation was assumed. As mentioned earlier, the channel matrix \mathbf{H} can be estimated through the use of pilot symbols. In the next section, the number of pilot symbols needed to fully estimate the MPM channel given certain SNR at the Rx is further investigated.

C. Effect of channel state information accuracy

To study the effect of the accuracy of channel estimation, the same Tx-Rx set-up as in previous section was considered. Fig. 6 plots BER versus number of pilots M for L equal to 5, 6 and 7 when the SNR at the Rx is 22 dB. These results show the impact of M on BER performance. A very high value of M will reduce the achievable data transmission rate. Therefore, we look for the smallest M which minimised the BER to the same levels as shown in Fig. 5 for SNR = 22dB. For $L = 5$, $M = 8$ satisfies this requirement whereas for $L = 6$ and 7, $M = 4$ is sufficient. However, the lowest achievable BER corresponds to small values of L .

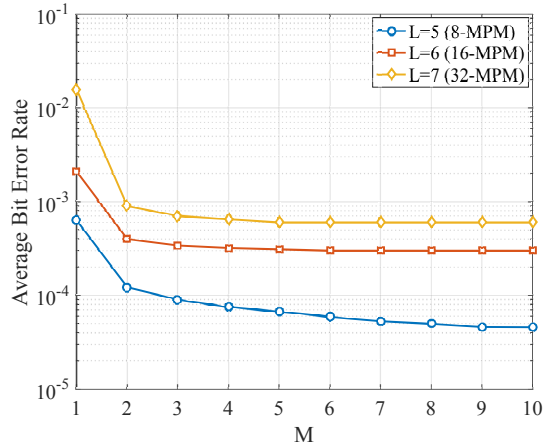


Fig. 6. BER achieved by $L = 5, 6$ and 7 by considering a SNR = 22dB when the number of channel estimating pilot symbols range from 1 to 10.

V. CONCLUSION

This paper has presented a modulation technique that uses multi-primary transmitters (i.e. multi-colored LEDs) in order to have a system that satisfies color rendering constraint while providing robust error performance with increasing data rate of VLC systems. This has been achieved by selecting unique primary combinations that generate white light and utilise the multi-dimensional signal space for data transmission. The system error performance results show that the MPM scheme is more robust than the IEEE standardised TLED CSK modulation and with increasing spectral efficiencies MPM leads QLED CSK equivalent BER performance. The BER estimation over indoor VLC channel shows that the MPM scheme, through the use of small number of pilot symbols, provides robust data-links.

As part of the future developments in MPM systems, the authors are working on optimising the symbol selection mechanism to further enhance the BER performance and also exploring opportunities to further increase the number of primaries for higher spectral efficiencies for lighting constrained VLC systems.

REFERENCES

[1] "IEEE Standard for Local and Metropolitan Area Networks—Part 15.7: Short-Range Wireless Optical Communication Using Visible Light," *IEEE Std 802.15.7-2011*, pp. 1–309, 6 2011.

[2] IEEE 802.15 WPANTM. 15.7 Revision: Short-Range Optical Wireless Communications Task Group (TG 7r1) (Accessed June 2017). [Online]. Available: http://www.ieee802.org/15/pub/IEEE%20802_15%20WPAN%2015_7%20Revision1%20Task%20Group.htm

[3] A. Burton, H. L. Minh, Z. Ghassemlooy, E. Bentley, and C. Botella, "Experimental demonstration of 50-mb/s visible light communications using 4x4 mimo," *Photon. Technol. Lett., IEEE*, vol. 26, no. 9, pp. 945–948, May 2014.

[4] L. Zeng, D. O'Brien, H. Minh, G. Faulkner, K. Lee, D. Jung, Y. Oh, and E. T. Won, "High data rate multiple input multiple output (mimo) optical wireless communications using white led lighting," *J. Sel. Areas Commun., IEEE*, vol. 27, no. 9, pp. 1654–1662, 2009.

[5] T. O'Farrell and M. Kiatweerasakul, "Performance of a spread spectrum infrared transmission system under ambient light interference," in *Personal, Indoor and Mobile Radio Communications, 1998. The Ninth IEEE International Symposium on*, vol. 2. IEEE, 1998, pp. 703–707.

[6] T. Komine and M. Nakagawa, "Fundamental analysis for visible-light communication system using led lights," *Consumer Electronics, IEEE Transactions on*, vol. 50, no. 1, pp. 100–107, 2004.

[7] R. Singh, T. O'Farrell, and J. P. David, "Performance evaluation of IEEE 802.15.7 csk physical layer," in *Globecom Workshops, IEEE*, Dec 2013, pp. 1064–1069.

[8] —, "Analysis of forward error correction schemes for colour shift keying modulation," in *Personal, Indoor, and Mobile Radio Communications (PIMRC), 2015 IEEE 26th Annual International Symposium on*. IEEE, 2015, pp. 575–579.

[9] R. Singh, T. O'Farrell, and J. David, "An enhanced color shift keying modulation scheme for high-speed wireless visible light communications," *J. Lightw. Technol., IEEE*, vol. 32, no. 14, pp. 2582–2592, July 2014.

[10] E. Monteiro and S. Hranilovic, "Design and implementation of color-shift keying for visible light communications," *Journal of Lightwave Technology*, vol. 32, no. 10, pp. 2053–2060, May 2014.

[11] R. J. Drost and B. M. Sadler, "Constellation design for color-shift keying using billiards algorithms," in *2010 IEEE Globecom Workshops*, Dec 2010, pp. 980–984.

[12] X. Liang, M. Yuan, J. Wang, Z. Ding, M. Jiang, and C. Zhao, "Constellation design enhancement for color-shift keying modulation of quadrichromatic leds in visible light communications," *Journal of Lightwave Technology*, vol. PP, no. 99, pp. 1–1, 2017.

[13] S. Igata, Y. Kozawa, Y. Umeda, and H. Habuchi, "Ber performance of digital color shift keying with target color control," in *2016 10th International Conference on Signal Processing and Communication Systems (ICSPCS)*, Dec 2016, pp. 1–6.

[14] C. E. Mejia, C. N. Georghiadis, and Y. H. Al-Badarnah, "Code design in visible light communications using color-shift-keying constellations," in *2016 IEEE Global Communications Conference (GLOBECOM)*, Dec 2016, pp. 1–7.

[15] P. Butala, J. Chau, and T. Little, "Metameric modulation for diffuse visible light communications with constant ambient lighting," in *Optical Wireless Communications (IWOW), 2012 International Workshop on*, Oct 2012, pp. 1–3.

[16] S. Pergoloni, M. Biagi, S. Rinauro, S. Colonnese, R. Cusani, and G. Scarano, "Merging color shift keying and complementary pulse position modulation for visible light illumination and communication," *Journal of Lightwave Technology*, vol. 33, no. 1, pp. 192–200, Jan 2015.

[17] A. K. Jain, *Fundamentals of Digital Image Processing*. Prentice-Hall, Inc., 1989.

[18] C. R. Rao, *Linear Statistical Inference and its Applications*. Wiley, 1973.

[19] J. Grubor, S. Randel, K.-D. Langer, and J. Walewski, "Broadband information broadcasting using led-based interior lighting," *Lightwave Technology, Journal of*, vol. 26, no. 24, pp. 3883–3892, Dec 2008.

[20] Thorlabs. 4-Wavelength High-Power LED Source (Accessed June 2017). [Online]. Available: https://www.thorlabs.de/newgrouppage9.cfm?objectgroup_id=3836

[21] —, UV/VIS Bandpass & Laser Line Filters: 340 - 694.3 nm Center Wavelength (Accessed June 2017). [Online]. Available: https://www.thorlabs.de/newgrouppage9.cfm?objectgroup_id=1001

[22] Hamamatsu. 46-element Si photodiode array for UV to NIR (Accessed June 2017). [Online]. Available: <https://www.hamamatsu.com/jp/en/product/category/3100/4001/4204/4105/S4114-46Q/index.html>