Proceedings Paper:

Al-Hameed, A, Hussein, AT, Alresheedi, MT et al. (2 more authors) (2017) Transmitters Mapping of Visible Light Communication System. In: 19th International Conference on Transparent Optical Networks (ICTON 2017). 19th International Conference on Transparent Optical Networks (ICTON 2017), 02-06 Jul 2017, Girona, Spain. IEEE . ISBN 978-1-5386-0859-3

https://doi.org/10.1109/ICTON.2017.8024794

Transmitters Mapping of Visible Light Communication System

Aubida A. Al-Hameed[1], Ahmed Taha Hussein[1], Mohammed T. Alresheedi[2], Safwan Hafeedh Younus[1] and Jaafar M. H. Elmirghani[1]
[1]School of Electronic and Electrical Engineering, University of Leeds, Leeds, LS2 9JT, UK
[2]Department of Electrical Engineering, King Saud University, Riyadh, Saudi Arabia
E-mail: {elaawj@leeds.ac.uk, ml12ath@leeds.ac.uk, malresheedi@ksu.edu.sa, elshy@leeds.ac.uk
j.m.h.elmirghani@leeds.ac.uk}

ABSTRACT
In this paper, we propose, design, and evaluate the use of transmitters mapping with a symbols encoding techniques to mitigate inter-symbol interference (ISI) and improve the overall VLC system performance while using a very simple receiver (single element wide field of view, (FOV)) with an OOK modulation scheme. The proposed technique with the laser diodes transmitters are able to provide data rates of 2.5 Gbps with 10^{-5} of BER in the worst case in a scenario of multi-users.

1. INTRODUCTION

Visible light communication (VLC) is becoming more popular everyday due to its inherent advantages over radio frequency (RF) systems. The advantages include a large unregulated spectrum, low complexity of transceiver unit, freedom from fading, confidentiality and immunity against interference from electrical devices. The concept of VLC systems revolves around the use of light emitting diodes (LEDs) for both lighting and communications. The main drives for this new technology include the recent development of solid state lighting, longer lifetime of high brightness LEDs compared to other artificial light sources, high data rate, low power consumption and green communications [1]-[3]. There are two major limitations in VLC systems. The first is the low modulation bandwidth of the LEDs, which limits the transmission data rates. The second is the spread of the received pulse due to the reflections from walls and ceiling in an indoor environment which causes multipath dispersion that leads to inter symbol interference (ISI). Many techniques in the transmitter and receiver side have been proposed in order to improve the modulation bandwidth of LED and to mitigate the effect of ISI. A simple pre-equalization circuit in the transmitter side has been demonstrated to achieve a bandwidth of 45 MHz [4]. On the other hand, post equalization at receiver side has improved the bandwidth up to 65 MHz [5]. However, recently a high modulation bandwidth VLC transmitter architecture involving laser diodes (RGB-LD) with combiner and diffuser has been proposed in [6]. Orthogonal frequency division multiplying (OFDM) has been used in VLC system in order to minimize the ISI. A DC-biased Optical DCO-OFDM was proposed with a data rate of 513 Mbps [7]. An adaptive receiver using rake reception with equalization has been proposed in [8]. The achieved data rate was 200 Mbps with a bit error rate (BER) of 10^{-5}. An adaptive equalizer with decision feedback equalization (DFE) method has been developed to combat ISI, which showed that a simple equalizer with multi-taps could improve data rates up to 1 Gbps [9]. An indoor VLC system with very complex RGB-LD transceiver has been proposed that can achieve 4 Gbps data rates [10]. A high data rate, up to 6.5 Gbps, was achieved using an LD with OFDM and an adaptive loading method [11]. A number of scenarios have been used with wavelength division multiplexing (WDM) and parallel streams to examine the abilities of LDs in terms of potentially achieving data rates of 100 Gbps [12]. Costly and highly complex receivers, such as an angle diversity receiver (ADR) and an imaging receiver, have been proposed to combat ISI and improve the performance of the OW system to provide multi-gigabit data rates [13], [14]. The ADR consists of multiple photodetectors elements with a narrow field of view (FOV) that are aimed in different directions, each light signal received by the elements is amplified independently, and then they can be combined to increase the signal to noise ratio (SNR) [15],[16]. The imaging receiver includes an array of pixels covered by a concentrator. Each pixel is a photo diode (PD) with small FOV to limit the range of optical rays [17]-[22]. A delay adaptation technique with imaging receiver has been demonstrated to provide high data rates [6].

In this paper, we propose, design, and evaluate novel transmission techniques for a multi-user VLC system to provide simplicity in a multi-user environment when operating at high data rates (2.5 Gbps) for a broadcast service. We evaluated the transmitter mapping and symbol encoding technique, for a multi-user scenario in the presence of inter-transmitter-interference.

2. SIMULATION ENVIRONMENT AND ROOM SETUP

To evaluate the performance of the proposed transmission techniques for indoor VLC, a simulation was performed in an empty room with dimensions of 4 m × 8 m × 3 m (width × length × height) with eight light units were used to satisfy ISO and European standards [6], [23]-[25]. The height of the communication floor (CF), where the transmitters and receivers for the user's equipment were placed was 1 m. Our simulation tool was similar to one developed by Barry et al. [26]. In our evaluation, the channel response, delay spread, 3 dB channel bandwidth, and SNR were determined in a similar way as that used in [6], [27]-[30].

3. VLC SYSTEM CONFIGURATION

The VLC system consisted of eight transmitters that were located in the ceiling of the room, integrated with the controller through fibre links. The wide-FOV detector had a photosensitive area of 4 mm^2 with a semi acceptance angle of ψ=90°, which was used in the receiver for each user. In this section, two VLC transmission modes are presented, analysed, and compared to identify the most appropriate system for the VLC broadcast services.

3.1 Traditional Transmission Mode (TTM)

In this mode, the eight transmitters were ON and activated to send the same data symbol during the transmission time. The symbols s_1 and s_2 were sent at t_1 and t_2, respectively, so that the received LOS power, P_{LOS}, for the user equipment (UE) UE1 and UE2 were as shown in Fig. 1a :

$$P_{LOS}(t_1) = \sum_{i=1}^{k} \alpha_i P_{txi}(t_1 - d_i) \quad (1)$$

$$P_{LOS}(t_2) = \sum_{i=1}^{k} \alpha_i P_{txi}(t_2 - d_i) \quad (2)$$

where t is the symbol duration time, k is the number of active transmitters, which was equal to eight in the TTM, d is the time delay from each transmitter, and α is the attenuation factor due to the signal propagation, where $\alpha_1 < \alpha_2 \ldots << \alpha_n$. The received power and delay depends on the user location in the CF, in the TTM scenario, severe ISI occurs when the symbol time t is much smaller than the maximum delay ($t << D_{Max}$). The delay spread of TTM is given as:

$$D_{(UE1)} = \sqrt{\frac{\sum_{i=1}^{k}(t_i - \mu_i)^2 \left(\alpha_i P_{txi}(t_i - d_i)\right)^2}{\sum_{i=1}^{k}\left(\alpha_i P_{txi}(t_1 - d_i)\right)^2}} \quad (3)$$

3.2 Transmitter Mapping with Linear Coding Mode (TMLCM)

In this mode, a linear encoder with transmitter mapping algorithm were combined to minimize the interference, increase the data rate, and serve more users in the broadcast mode. Collaboration between the transmitters was implemented to encode the data symbols to create the transmission matrix so that every two adjacent transmitters operated in complementary ON-OFF mode. The main effective interference was from the next neighbour transmitter, hence reducing the active transmitters in a given time slot led to minimizing the delay spread and the interference due to the optical wireless channel. In the full load case, the interference was reduced by half when compared with the TTM, which was due to the maximum number of active transmitters being four. In the transmitter mapping algorithm, each transmitter was allocated to a single user, or more, according to the number of active users and their locations on the CF. To initialize the transmitter mapping technique a communication setup (CS) algorithm identified the closest transmitter for each receiver according to the following steps:

1. The controller transmitted a pilot signal to activate the listening mode for all users.
2. A low data rate signal was sent from all the transmitters in a sequence in 0.1 ms slot times, to estimate the SNR and delay for each user and for each transmitter. For the VLC system proposed in this paper, each user reported eight values for the SNRs and delays.
3. The feedback signal is sent to the controller by the user through an IR uplink connection.
4. The controller created a map of transmitters for all users according to the feedback signal.
5. The transmitter with the best SNR value was allocated to each user. However, if a user was located between two neighbouring transmitters and the SNRs difference was ΔSNR≤2dB, the controller allocated both transmitters to the user.
6. The data symbols were set into two encoding modes for the broadcast service.
7. A pilot signal was sent before the start of the data transmission to inform all users about their allocated transmitter and encoding mode, to enable the decoding of the received data correctly.
8. The controller deactivated the non-allocated transmitters and activated the remaining transmitters to start sending data to the users.

Given a typical pedestrian speed in the indoor environment of 1 m/s, the algorithm repeated the initial setup procedures periodically at the start of a 1 s frame [31]. It should be noted that in the TMLCM when the controller deactivated the unallocated transmitters, this did not affect the illumination in the room, because the illumination threshold was achieved through direct current (DC) bias level on each LD in the light unit [32]. In this paper, non-return to zero on–off keying (NRZ-OOK) was used (encoding a single bit per symbol). For example, in Table I the encoding was done for the multi-user scenario when T_{x1} and T_{x8} were allocated to U_{E1} and U_{E3}, respectively. T_{x6} and T_{x7} were allocated to U_{E3} due to its location between two neighbouring transmitters, as illustrated in Fig 1c.

TABLE I
THE ENCODING AND TRANSMITTERS ALLOCATIONS

T_X allocated	T_{x1}	T_{x6}, T_{x7}	T_{x8}
User	U_{E1}	U_{E2}	U_{E3}
Time (t_1)	C1= S_1	$\overline{C}1$	C1
Time (t_2)	C2= S_2	$\overline{C}2$	C2
Time (t_3)	C3= S_3	$\overline{C}3$	C3
Encoding Mode	1	2	1

We considered the LOS as well as the first and second order reflections. In the mathematical analysis below we focused only on the LOS component to simplify the explanation of the equations. TMM involves transmitters mapping mode without the symbols encoding technique. For the two allocated transmitters case (T_{x1} and T_{x2}), sending the same data symbols without using linear encoding for U_{E1} and U_{E2}, as shown in Fig. 1a, the transmission matrix can be written as:

$$\begin{bmatrix} P_{r(UE1)} \\ P_{r(UE2)} \end{bmatrix} = \begin{bmatrix} h_{tx1}(t) & h_{tx2}(t) \\ h_{tx2}(t) & h_{tx1}(t) \end{bmatrix} \begin{bmatrix} S_1 \\ S_1 \end{bmatrix} \tag{4}$$

where h_{tx1} and h_{tx2} are the LOS impulse responses of T_{x1} and T_{x2}. For the transmitted data symbol is logic 1 ($S_1 = "1"$), the LOS received power P_{LOS} for U_{E1} and U_{E2} is:

$$P_{LOS(UE1)} = \alpha_1 P_{tx1}(t - d_1) + \alpha_2 P_{tx2}(t - d_2) \tag{5}$$

$$P_{LOS(UE2)} = \alpha_1 P_{tx2}(t - d_1) + \alpha_2 P_{tx1}(t - d_2) \tag{6}$$

The delay spread of TMM for U_{E1} can be written as:

$$D_{(UE1)} = \sqrt{\frac{(t-\mu_1)^2 (\alpha_1 P_{tx1}(t-d_1))^2 + (t-\mu_2)^2 \ (\alpha_2 P_{tx2}(t-d_2))^2}{((\alpha_1 P_{tx1}(t-d_1) + \alpha_2 P_{tx2}(t-d_2))^2}} \tag{7}$$

In the TMLCM, for the two allocated transmitters case (T_{x1} and T_{x2}), sending the same data symbols for U_{E1} and U_{E2}, as shown in Fig. 1b, the transmission matrix is written as:

$$\begin{bmatrix} P_{r(UE1)} \\ P_{r(UE2)} \end{bmatrix} = \begin{bmatrix} h_{tx1}(t) & h_{tx2}(t) \\ h_{tx2}(t) & h_{tx1}(t) \end{bmatrix} \begin{bmatrix} C_1 \\ \overline{C}1 \end{bmatrix} \tag{8}$$

For data symbol ($S_1 = "1"$), the linear encoded symbol $C_1 = "1"$ and $\overline{C}1 = "0"$, the LOS received power P_{LOS} for U_{E1} and U_{E2} is:

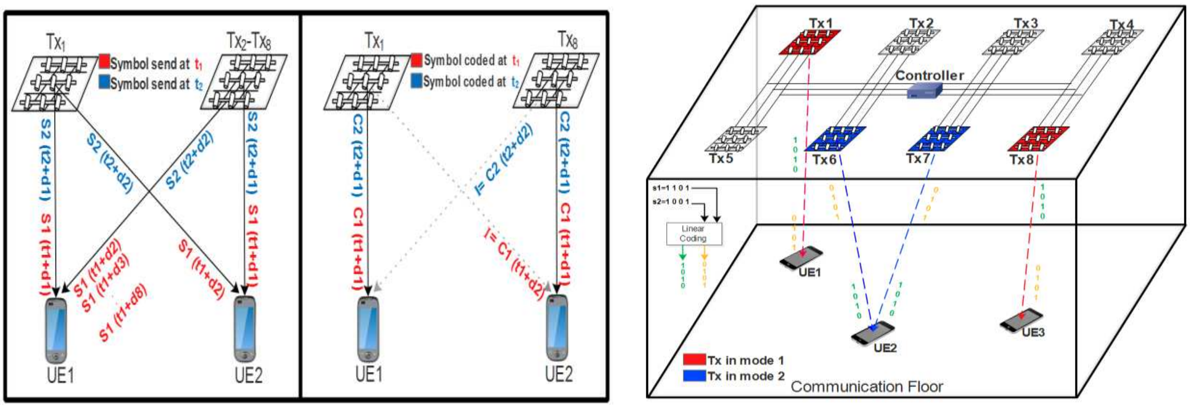
$$P_{LOS(UE1)} = \alpha_1 P_{tx1}(t - d_1) \tag{9}$$

$$P_{LOS(UE2)} = \alpha_2 P_{tx1}(t - d_2) \tag{10}$$

The delay spread equation of the TMLCM for U_{E1} can be given as:

$$D_{(UE1)} = \sqrt{\frac{(t - \mu_1)^2 (\alpha_1 P_{tx1}(t - d_1))^2}{((\alpha_1 P_{tx1}(t - d_1))^2}} \tag{11}$$

In equation (11), it can be seen that the delay spread was reduced by a factor of ($\alpha_2 P_{tx2}$), compared with the delay spread in equation (7), due to the encoding symbols.



(a) (b) (c)

Figure 1: (a) TTM transmission mode, (b) TMLCM transmission mode, (c) an example of transmitter allocation for multiple users.

4. SIMULATION RESULTS AND DISCUSSION

In this section, we assess the performance of the transmitter mapping and symbol encoding for the VLC system using a simple wide-FOV receiver in an empty room in the presence of multipath propagation, mobility, and interference for a multiuser broadcast service system. We examined the performance of the TTM and the TMLCM techniques in the two user scenario. U_{E1} was a stationary user located in the room corner at (x=1m, y=1m, z=1m) and U_{E2} was a portable user that experienced mobility and was considered in 14 different locations on the CF, as shown in Fig. 2. The results are presented in terms of the delay spread, 3 dB channel bandwidth, and SNR for U_{E2} along x=1 and x=2. Due to the symmetry of the room, the results for x = 3 m equalled the results for x = 1 m due to the symmetry; therefore, only x = 1 m and x = 2 m results are shown along the y-axis. According to the transmitters mapping algorithm, as explained in Section 3.2, the assigned transmitters in the encoding modes had fair to optimum decisions for all users. Table II illustrates the parameters used in the simulation which is similar to the one that developed in [6], [25] and [31].

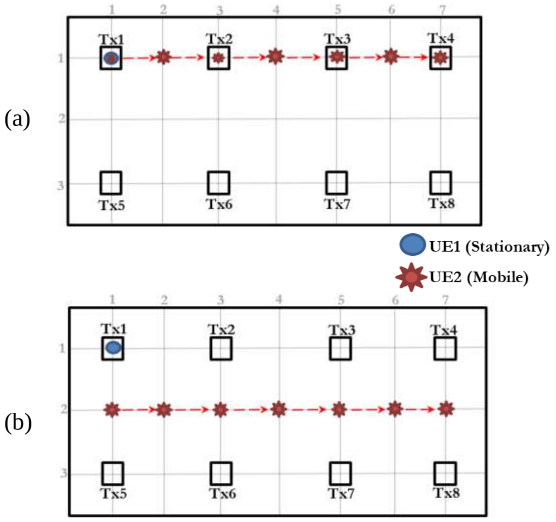


Figure 2: Locations of the two users on the CF, (a) U_{E1} is stationary and U_{E2} moves along x=1, (b) U_{E1} is stationary and U_{E2} moves along x=2.

TABLE II
SIMULATION PARAMETERS

Parameters	Configurations
Transmitters	
Txs units locations (x , y, z)	(1,1,3), (1,3,3), (1,5,3), (1,7,3) (3,1,3), (3,3,3), (3,5,3), (3,7,3)
Elevation	90^0
Azimuth	0^o
Number of LDs in each unit	9 (3×3)
Transmitted optical power LD	2 W
LD semi-angle at half power beam width	70^o
LD-Centre luminous intensity	162 cd
Receiver	
Photodetector’s Area	4 mm^2
Photodetector Responsivity	0.4 A/W
Acceptance Semi-angle	90^o
Concentrator Reflective Index (N)	1.7
Room	
Length	8m
Width	4m
Height	3m
Time bin duration	0.01ns

4.1 Delay Spread and 3dB Channel Bandwidth

The root mean square delay spread was used to measure the signal spread. A time bin of 0.01 ns was considered for the delay spread calculations. The delay spread was evaluated for the two proposed communication modes as presented in Fig. 3a. It can be seen that the TMLCM had a lower delay spread compared to TTM. The delay spread of U_{E2} at the centre of the room (x=2 and y=2) is reduced from almost 0.65 ns to 0.15 ns in TMLCM. This significant reduction is due to minimizing the number of active transmitters at the same time and using the symbols encoding technique, which leads to a limited range of rays being collected by the wide-FOV receiver. For the TMLCM when U_{E2} was located at (x=1 and y=1, 3, 5, 7) under any transmitter, the delay spread was lower than in the other locations due to the higher peak power received from the LOS rays in these locations (underneath the transmitter), which reduced the delay spread.

Fig. 3b depicts the 3 dB channel bandwidth of the TTM and the TMLCM when U_{E2} moves along x=2, which is the worst communication path according to the delay spread results. It should be noted that TMLCM can provide a high bandwidth compared with TTM. The results show that the minimum channel bandwidth obtained at x=2 and y=2 is 1.82 GHz for TMLCM. However, for the same location at x=2 and y=2, the bandwidth for TTM is 120MHz. According to Personick’s analysis in [33] the optimum receiver bandwidth is 0.7 times the bit rate. Therefore, the channel bandwidth obtained in the TMLCM with wide-FOV receiver can support up to 2.5 Gbps.

4.2 SNR Analysis

Figs. 3c show the SNR of the TTM and the TMLCM at a bit rate of 2.5 Gbps, a wide band PIN-FET optical receiver was considered for the SNR calculations [34]. The results show the significant improvement in the SNR under the TMLCM when compared with the TTM. For the worst case scenario, the TMLCM achieved a 12 dB SNR gain over the TTM when U_{E2} moved along x=1, and a 7 dB SNR gain along x=2. As shown in the results, the minimum SNR for the TMLCM is about 8.5 dB at location (x=1 and y=3), and for the OOK modulation an SNR of 8.5 dB can provide a 10^{-5} of BER. A low-complexity forward error correction (FEC) technique can be used to improve the BER for optical systems operated at a few gigabits [35]. From the results in this section it can be clearly seen that TTM does not support high data rates with an acceptable BER.

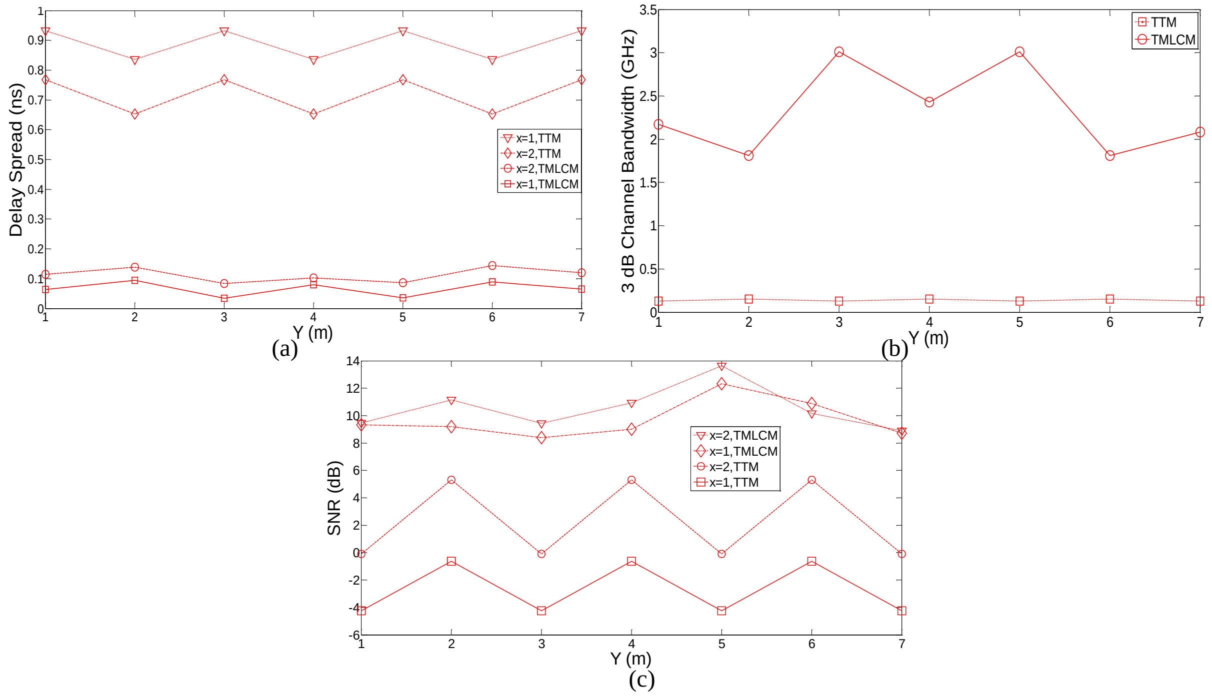


Figure 3. (a) Delay spread of UE2 moving at x=1m and x=2m (b) 3dB channel bandwidth of UE2 moving at x=2m (c) SNR of UE2 moving at x=1m and x=2m.

5. Conclusions

In this paper, we proposed, designed, and evaluated a novel VLC system with different transmission techniques (TTM and TMLCM) using a single photodetector wide FOV receiver. The proposed TMLCM technique for VLC system had the ability to enhance the channel bandwidth and achieved 2.5 Gbps with a BER of 10^{-5} at the least successful point when users were in an empty room with the simple OOK modulation format. Our proposed TMLCM employed an OOK modulation scheme that added simplicity to the VLC system for various multi user scenarios and provided full mobility within the test area in the presence of multipath propagation.

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