

# Transmitter Distribution for MIMO Visible Light Communication Systems

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**Abstract**—In the future, buildings will be lit using solid state lighting, particularly white light emitting diodes (LEDs). Solid state lighting is a rapidly expanding area of research due to the reliability of LEDs and the numerous applications possible including Visible Light Communications (VLC), where a white LED is used to illuminate a room at the same time as providing a data communications system. VLC systems are restricted by limited modulation bandwidths of typically only a few MHz. This can be overcome however, since multiple arrays of LEDs are manipulated, allowing a multiple-input multiple-output (MIMO) technique which simultaneously illuminates the room uniformly and provides parallel data transfer. In this paper, a non-imaging MIMO technique is employed, with results showing that the system does not perform consistently at all receiver positions, owing to symmetry. The simulations performed show that aggregate speeds up to 12Mbps can be achieved using this transmitter distribution.

**Keywords**—LED; Optical wireless communications; Visible light communications; Optical MIMO; Non-Imaging.

## I. INTRODUCTION

White LEDs are an excellent candidate for the future of indoor lighting. The LED is advantageous when compared with halogen or fluorescent lighting due to their resistance to humidity, lower power consumption and longer life expectancy. The emergence of commercially available highly efficient blue and green LEDs to accompany highly efficient red LEDs means that it is possible to mix the three colours to produce a white light. These three LEDs can be individually modulated to increase data rates but a problem occurs in that the individual LEDs emissions must be spectrally consistent with the white light. A more conventional way to produce a white light would be to use a blue LED with a yellowish phosphor coating. Data rates of up to 32Mbps have been reported using this method with a non-return to zero (NRZ), on-off keying (OOK) modulation scheme with post-equalization at the receiver [1]. Alternatively a Luxeon Star can be used, with data rates up to 100Mbps reported using the same modulation scheme which requires a blue filter in order to filter the slower yellow component [2]. The Luxeon Star parameters are used in the simulations involved in this paper. A VLC communication system offers many advantages over more traditional RF based systems due to the fact that it offers no electromagnetic interference (EMI), so could be installed in

electromagnetically sensitive places, such as hospitals to provide high speed broadband.

Many MIMO systems have been described [3-5], all of which present numerous square MIMO makes use of multiple transmitters and multiple receivers for parallel data transmission. This paper presents a MIMO system that has two transmitters and two receivers. A pseudo-random bit sequence (PRBS) stream is converted into two parallel streams prior to intensity modulating the the visible LED. At the receiver there are two photodetectors to receive the signal from both transmitters via line of sight (LOS) links. The MIMO transmitters are arranged into two rows of one thousand LEDs. The paper investigate the bit error rate (BER) performance at all points within the room relative to the receiver position. The BER will also be plotted as a function of the received optical power.

The rest of the paper will be organised as follows. In Section II, the parameters of the channel are outlined, and the transmitter, channel and receiver models are defined, including the system diagram. In Section III, the results are presented and in Section IV, conclusions are drawn.

## II. MODELLING THE OPTICAL CHANNEL

The system model is built in MATLAB, before developing the transmitting arrays, a channel model and receiving photodiodes (PD), the physical dimensions of the room. The room dimensions are 5m x 5m x 3m ( $x, y, z$ ), with the transmitter mounted on the ceiling and the receiver placed 0.85m from the floor plane, see Fig. 1. The other parameters used in the simulation can be seen in Table I.

TABLE I.

MATLAB Simulation Parameters	Values [1]
Room size	5x5x3 (m)
N <sup>o</sup> LED arrays	2
N <sup>o</sup> LEDs per array	2000 (2*1000)
LED array pitch	0.01
Ceiling – receiver plane distance	2.15 (m)
Mean LED transmitted power	10 (mW)
Lambertian order	1
Transmitter semi-angle	60
PD responsivity $\gamma$	0.4 (A/W)
Receiver FOV $\psi_c$ (half angle)	60 (°)
Pre-amplifier noise density $i_{amp}$	5 (pA/Hz <sup>-1/2</sup> )
Ambient light photocurrent $\chi_{amb}$	10.93 (A/m <sup>2</sup> /Sr)
Receiver bandwidth $B$	$0.7 \cdot Rb_{NRZ-OOK}^a$

a.  $Rb_{NRZ-OOK}$  is the modulation data rate

The transmitter ceiling positioning diagram can be seen in (a). The room width and length are shown in the figure.

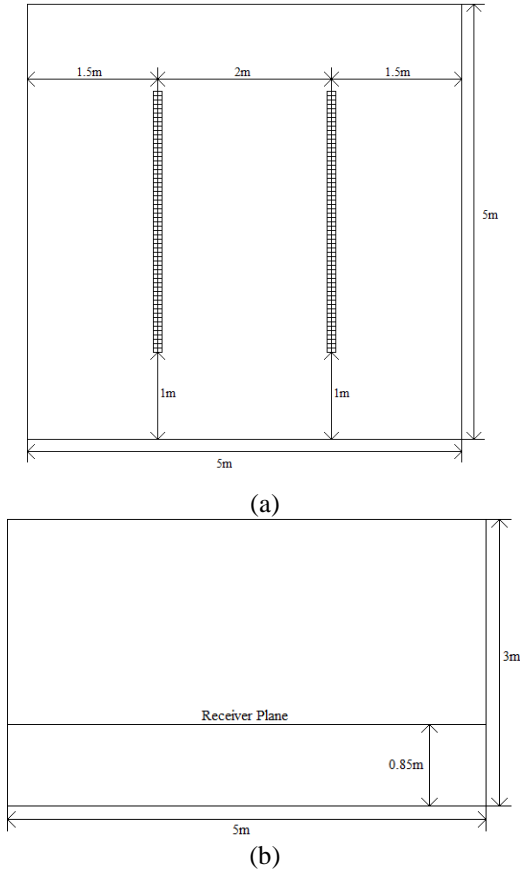


Figure 1: (a) Transmitter position top view, and (b) the receiver plane.

The receiver can be moved around on the receiver plane in two dimensions, but no analysis will take place at any other elevation other than 0.85 m from the ground (or 2.15 m from the ceiling). The receivers can be placed anywhere along the width or length of the room.

#### A. Transmitters

The room will be illuminated by two transmitter arrays, two elements deep and one thousand elements wide, where a single white LED corresponds to a single element within the array. This paper presents an example using two transmitter arrays and two receivers, but it is possible to consider up to  $N_T$  transmitters and  $N_R$  receivers.

The LEDs are assumed to have a Lambertian radiant intensity profile; such that:

$$R_0(\phi) = \left[ \frac{m+1}{2\pi} \right] \cdot \cos(\phi) \quad (1)$$

where  $m$  is the order of Lambertian emission and  $\phi$  is the angle of emission with respect to the emitter.

The simulation input is a random data stream generated by MATLAB, then converted to a parallel data stream (two in the case of this paper, but up to  $N_T$  streams). The parallel streams are then convolved with the impulse response of the LED and inserted into the vector  $T = [t_1, \dots, t_i, \dots, t_{N_T}]^T$ ,  $T$  indicates the transpose of the vector. The impulse response of the LED [6] was taken from real data and the equation of the line was extracted using the Curve Fitting Toolbox that can be found in MATLAB. The raw data and the LED curve fit can be seen below in Figure 2.

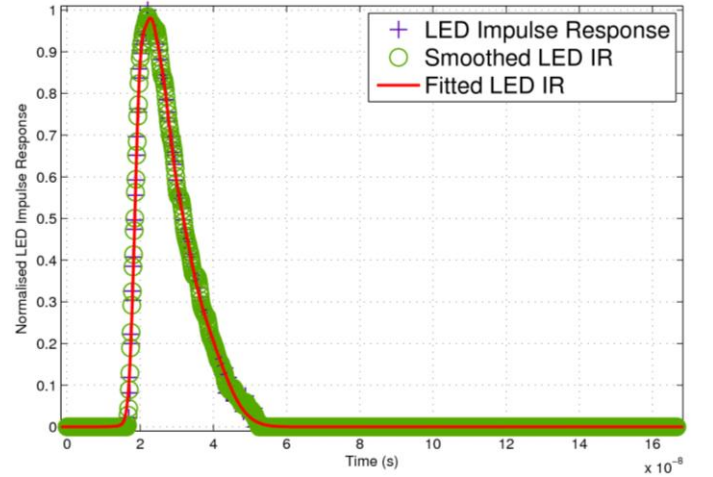


Figure 2: LED impulse response

In Figure the original raw data is indicated by crosses, the smoothed data (to simplify the fit) is indicated by circle markers and the final fit is the solid line.

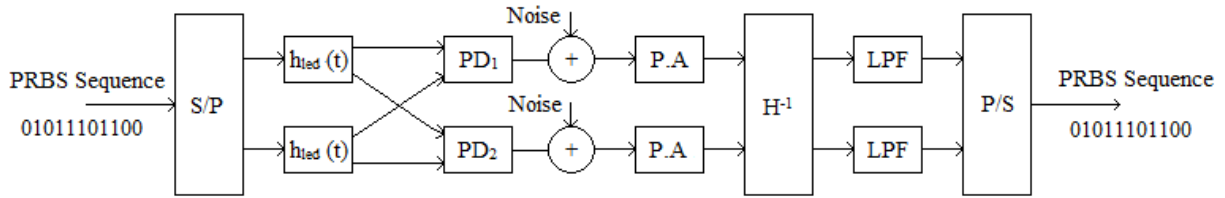


Figure 3: System block diagram, P.A. indicates pre-amplifier

The system block diagram is shown in Figure 3. Data is convoluted with the impulse of the LED and then emitted as light radiation into the channel. This radiation is detected by the photodiodes. Additive white Gaussian noise is added to the signal. The inverse of the H-matrix is known at the receiver so can therefore be used to estimate the transmitted signal. The estimated signal is then passed through a low pass filter and converted back to the serial data.

The illumination of a single LED is shown in Figure 4.

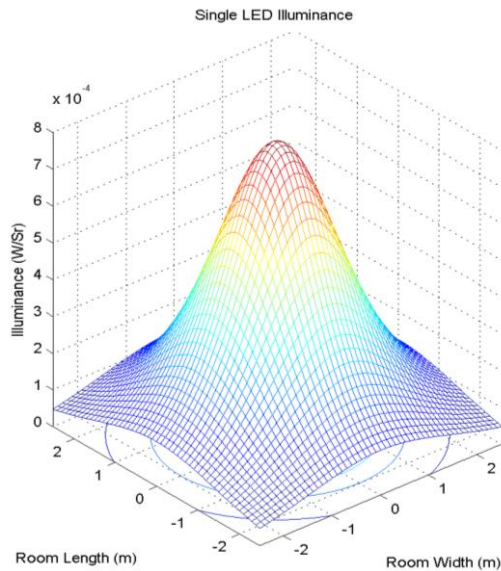


Figure 4: Single LED illuminance

From Figure 4 it is clear to see that the majority of the illuminance is found directly underneath the LED, which is placed directly in the center of the room in this case. Close to the limits of the room, i.e. the walls, there is essentially no luminance. Therefore these areas would be dark and in the case of a single LED transmitter would offer a higher BER performance, which is undesirable. Next, the group illuminance will be shown.

The transmitters will have two rows of one thousand LEDs. The total group illumination can be seen below in Figure 5. It is clear from Figure 5 that the illuminance of a single transmitter is highest directly beneath it. This means most of the power will be concentrated in this area, thus expecting the lowest BER performance.

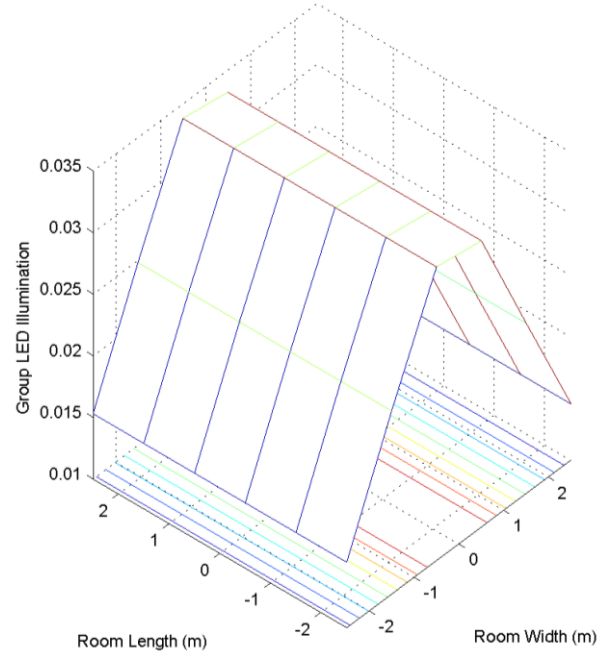


Figure 5: Group LED illumination

From Figure 5 it is possible to see that the room now has a much wider illumination spread. It is noteworthy that at two edges of the room, there is still not much light, indicated by the deep blue lines. This indicates that a high BER can be expected in these areas and therefore a low signal quality.

### B. Channel Model

There are two major components to consider for the propagating light beam; the LOS and the non-LOS (i.e. diffused). In a diffused system, due to the nature of Lambertian emission, the optical signal will arrive at the receiver from a multiple directions, except for the LOS path. In [1] it is shown that there is a 7 dB electrical power difference between the LOS and diffuse components. As a result of this, the diffuse component will be ignored in this paper.

There is a time difference in the LOS component that needs to be accounted for in the simulation. That is, due to the fact that LEDs are arranged in a straight line, the position of the receiver on the receiver plane will constantly have different path lengths relative to each LED in the array. This implies that the channel bandwidth is limited by the propagation time through the longest LOS path length.

The H-matrix of the channel contains the information relating to the channel DC gain. If there are  $K$ - LEDs in the  $i_{th}$

array, transmitting to the  $j_{th}$  receiver, the DC gain  $h_{ij}$  is given by:

$$h_{ij} = \begin{cases} \sum_{k=1}^K \frac{A_{rj}}{d_{ij}^2} R_0(\phi) \cdot \cos(\varphi_{ijk}) & \text{for } 0 \leq \varphi_{ijk} \leq \varphi_c \\ 0 & \text{for } \varphi_c > \varphi_{ijk} \end{cases} \quad (2)$$

where  $A_j$  is the collection area of the  $j_{th}$  receiver,  $d_{ij}^2$  is the distance from the  $i_{th}$  transmitter to the  $j_{th}$  receiver,  $\varphi_{ijk}$  is the angle of incidence on the receiver and  $\varphi_c$  is the receiver field of view (FOV). The DC gains make up the H-matrix as shown:

$$H = \begin{bmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \end{bmatrix} \quad (3)$$

The H-matrix will be used at the receiver to obtain an estimate of the transmitted signals. In addition the rank of the H-matrix affects the MIMO system performance. If the H-matrix is not full rank, the speed of the system must decrease in order to compensate for this.

### C. Receivers

There are two receivers, each made up of p-i-n photodiodes, followed by a pre-amplifier and then a low-pass filter. The received signal on the  $j_{th}$  signal is defined by:

$$r_j = \gamma \cdot P_{LED} \sum_{i=1}^{N_T} h_{ij} \cdot t_i + \sqrt{i_{nj}^2} \quad (4)$$

where  $\gamma$  is the photodiode responsivity,  $P_{LED}$  is the average communications transmitted power,  $i_{nj}^2$  is the mean square noise current for the  $j_{th}$  receiver, where a full description can be found in [1]. The received signals are inserted into the vector  $R$ , where  $R = [r_1, \dots, r_j, \dots, r_{NR}]^T$ , for the general case, but for this paper,  $R = [r_1, r_2]^T$ .

The received data is estimated using the inverse of the H-matrix and the convoluted data:

$$T_{est} = R \bullet H^{-1} \quad (5)$$

The estimated data can then be compared with the transmitted data to find the BER. The power distribution can also be found for all areas of the room at the level of the receiver plane.

## III. RESULTS

A comparison of a sample of data transmitted at 1 Mbps can be seen in Figure 6.

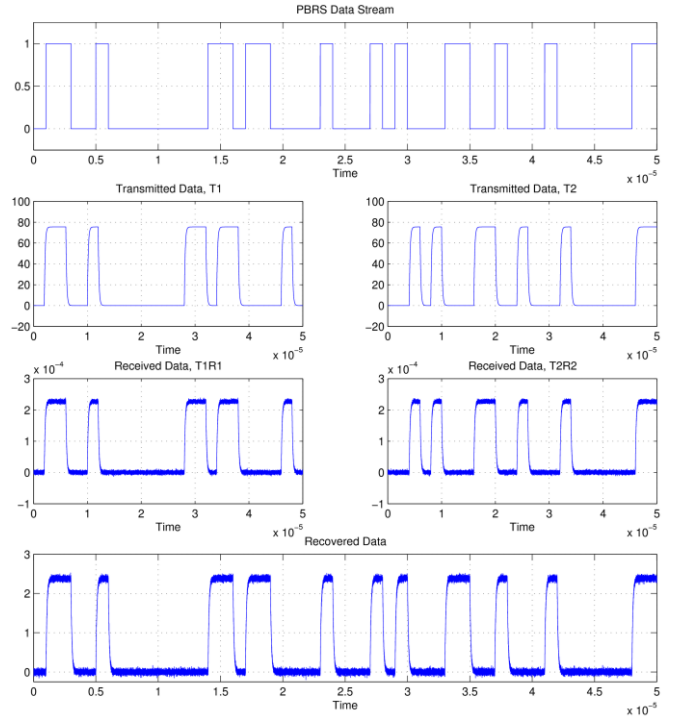


Figure 6: Comparison of selected data signal time waveforms

The serial data can be seen at the top of Figure 6, which is split into two parallel streams as identified as ‘Transmitted Data, T1 and T2’. The received signals as well as the recovered data signal are also shown. The system can achieve aggregate speeds up to 12Mbps, as shown in Figure 7.

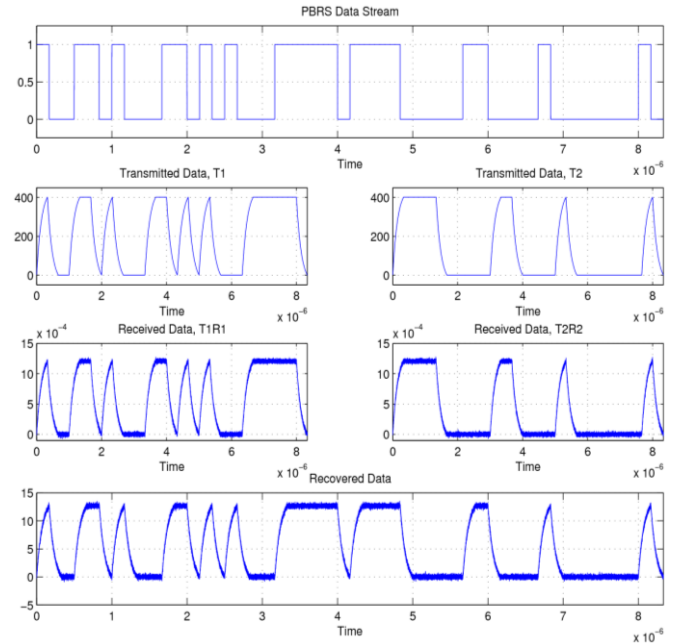


Figure 7: Comparison of selected data signal time waveforms at a data rate of 12 Mbps

These results were obtained when each receiver is directly beneath the corresponding transmitter. In this position, probability of error is calculated using the Q-factor of the received eye diagram at different data rates. The probability of error and Q-factor are related as follows:

$$P_e = \frac{1}{2\pi} e^{-\frac{Q^2}{2}} \quad (6)$$

Where  $Q$  is the Q-factor of the eye diagram and  $P_e$  is the probability of error. Probability of error is linked to BER as follows:

$$P_e \cong BER = \frac{1}{2} \operatorname{erfc} \left\{ \frac{Q}{\sqrt{2}} \right\} \quad (7)$$

The plot of probability of error against eye diagram Q-factor can be seen in Figure 8.

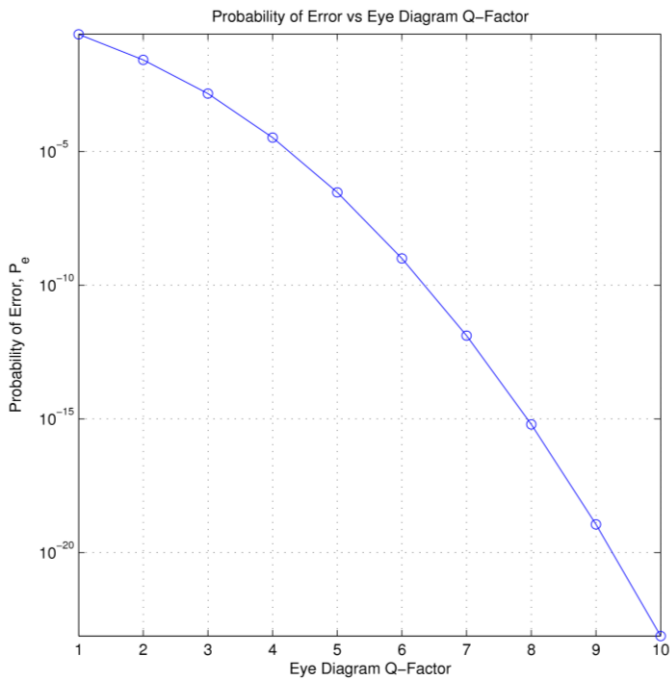


Figure 8: Probability of error plotted against Q-factor

Figure 8 shows clearly that the proposed system would have no trouble in offering acceptably error free transmission provided an eye diagram Q-factor of approximately four or higher can be maintained.

#### IV. CONCLUSION AND FURTHER WORK

To conclude, this paper provides a new alternative for the distribution of VLC transmitters. Results show that error free transmission is possible at data rates of up to 12Mbps. These data rates are not as fast as other MIMO VLC systems that have been demonstrated, but here the number of transmitters has been cut by half, at least.

Future work includes further investigation into the layout of VLC transmitters for MIMO systems, breaking the line of symmetry between transmitters and observing the effects. A data rate increase is expected, since the number of transmitters can also be increased.

#### ACKNOWLEDGMENT

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