

Optical Power Distributions for 4×4 MIMO Visible Light Communications in Indoor Environment

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Received: 18/Dec/2019

Revised: 24/Sep/2020

Accepted: 24/Oct/2020

Abstract

Visible Light Communication (VLC) has emerged as a powerful technique for wireless communication systems. Providing high data rate and increasing capacity are the major problems in VLC. Recent evidence suggests that Multiple Input Multiple Output (MIMO) technique can offers improved data rates and increased link range. This paper describes the design and implementation of visible light communication system in indoor environment exploring the benefits of MIMO. The specific objective of this research was to implement a 4×4 Multiple Input (LEDs) Multiple Output (photodetectors)-VLC communication system, where a 16 white power LEDs in four arrays are setting up at transmitter and four RX modules are setting up at receiver side without the need for additional power or bandwidth as well as analyze a mathematical model for a VLC- 4 ×4 MIMO with different modes such as the suitable angles to cover the entire room.

The research designs practically an electronic circuit for the transmitter and receiver with inexpensive components. The power distribution of different propagation modes is calculated for Single Input Single Output (SISO) and MIMO channels in typical room dimensions. The results in this paper indicate that the power is distributed uniformly for entire room when implemented VLC-MIMO as compared to VLC-SISO. Furthermore, a 4×4 MIMO implementing VLC is compared in term of BER vs. SINR with SISO communication system for both Line of Sight (LOS) and Non Line of Sight (NLOS) propagation modes. Comparing the two results of LOS and NLOS, it can be seen that a 4×4 MIMO implementing VLC for LOS perform better than the same system with NLOS due to decreasing in the received power resulted from the multipath effect.

Keywords: MIMO; SISO; VLC; Optical; Indoor; Power Distribution.

1- Introduction

Recent developments in lighting industry have heightened the need for Visible Light Communication (VLC) which has been attracting a lot of interest in the short distances wireless communications [1]. There is an urgent need to address license spectrum, electromagnetic interference and security problems for radio frequency (RF) wireless communications; However, VLCs are one of the most promising complementary technologies for RF communications [2].

VLCs have emerged as a powerful solution for indoor high-speed data transmission, where high spectral

efficiencies and low latencies are the main requirements for next generation wireless networks. Fig. 1 shows the concept of VLC system [3-4]. Unlike RF signals, VLC modulated signals must be nonnegative and real valued signals. Moreover, intensity modulation and direct detection (IM/DD) schemes may be utilized at the transmitter and the receiver [5].

Due to the characteristics of LEDs, multiple LEDs are popularly employed to provide illuminations as well as translating data because of their higher efficiency, friendly manifest, long life time and better spectrum efficiency in indoor environment.

However, the common white LEDs have a limited bandwidth, which restrict the high data transmission rate [6-8].

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MIMO channels where multiple sources and multiple detectors are setting up at transmitter and receiver are predominantly used to combat multipath fading and optimize the data rate. MIMO is fundamental to achieve higher spectral efficiency and link reliability and or diversity [9-10].

Visible light communications implementing MIMO technique is a promising solution for wireless communication systems in beyond 5G networks. However, it provides high energy efficiency, low implementation cost, and high-speed data transmission [11]. Consequently, in a typical indoor VLC system, there are illuminated sources; therefore, it is natural to utilize MIMO technique to have parallel data [12]. On the other hand, due to the highly directional characteristics of light propagation, the communication through VLC channels has mainly relied on the availability of LOS link in addition to NLOS link where the transmitted signal at the receiver through different angles, different time delays and/or different frequency [13].

2- Related Works

More recent attention has focused on the provision of VLC-MIMO communication systems,

A great deal of previous research into 2×2 MIMO-VLC system for indoor environment has focused on the implementation of STBC and Repetition coding assuming LOS and NLOS links.

In their case study, a performance of VLC-MIMO system has been computed and demonstrated. This study indicates that the performance of the proposed system has a good improvement when compared with the system used single PD but they did not take in consideration how the power is distributed in entire room [14]. A number of authors have considered the analysis of a 2×2 VLC-MIMO system employing joint IQ independent component. This analysis involves a novel MIMO detection scheme to decompose the superposed signals. With the help of the proposed machine learning scheme, two received optical signals can be separated into two independent parallel signals. Detailed simulation showed that the unmixing matrix can be quickly converged by iterations.

They evaluated the performance of the algorithm where the Q factor yielded a gain of about 2.5 dB compared with the traditional Alamouti Space Time Block Coding (STBC) scheme [15]. Various studies have assessed the performance of an indoor optical wireless communication system with VLC technology with a spatially random receiver. Considering that the receiver is uniformly distributed on the floor, a 4 light emitting diode (LED) lamps are located at the center of the room. The receiver chooses the best channel link to receive the information from the LED lamps, which depends on the distance

between the receiver and each lamp by using stochastic geometry theory [16]. One of the most significant current discussions in VLC-MIMO is the inferiority of BER performance due to the multipath effects in indoor environment. Repetition coding (RC), STBCs, and spatial multiplexing (SMP) had been used to improve the BER performance.

Two different configurations (2×2 and 4×4) are taken into consideration with distinct transmitters spacing. Simulation results and a comparative analysis of their system with an existing system is given mainly in terms of bit error rate (BER), data-rate, and transmission range. The simulation and experimentation results showed that the RC scheme with significant diversity gain provides more robustness as compared to other MIMO schemes [17]. However, in all of the presented works, the analysis of the VLC-MIMO system for indoor environments has been investigated using either Line of Sight (LOS) or Non LOS (NLOS) propagation models.

In the current work, the power distribution has been simulated for two different propagation modes, LOS, also known as power distribution without reflection) and NLOS, known as power distribution with reflection).

There are two primary aims of this research: 1. To analyse a 4×4 MIMO-VLC system for both LOS and NLOS propagation modes. 2. To measure the power distribution in different cases according to system under study. The system is designed practically using inexpensive electronic circuits for both transmitter and receiver sides.

In the rest of this paper, part II introduces the mathematical model for the VLC-MIMO system. Part III introduces the two different Tx-Rx modules for the proposed system in addition to hardware experiments. In part IV, presents and discuss the MATLAB simulation results.

Notations: We use uppercase bold letters for matrices and lowercase bold-italic letters for vectors. $()^*$ stands for the complex conjugate.

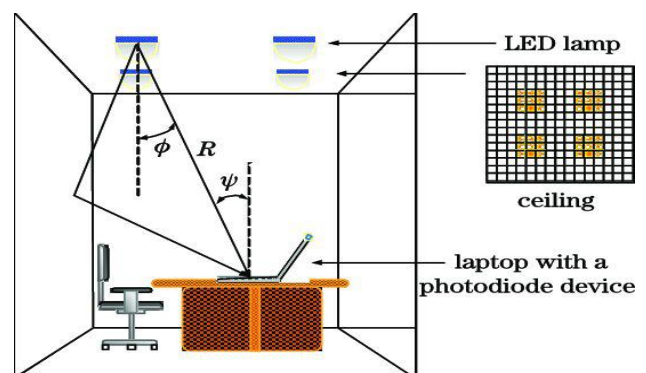


Fig. 1. Application of visible light communication

3- The Proposed Scheme

3-1- Indoor VLC Model

The typical room model for the present work is shown in Fig. 2 with dimensions of $3 \times 3 \times 5 \text{ m}^3$. The location of the receiver is assumed to be put at a height of 2-m from the ground. LOS, L-R1 and L-R1-R2 signals are reaching photodetector. LOS represented by Path d (red line), NLOS has been represented in Fig.2 by path d1d2 (blue line) for L-R1 channel and path d1-d3-d4 (green and blue lines) is for L-R1-R2 channel.

The average transmitted power from the light source is given by

$$P_t = \lim_{T \rightarrow \infty} \frac{1}{T} \int_0^T P_i(t) dt \quad P_i(t) > 0 \quad (1)$$

where P_i is the optical transmitted power. Through the channel model, the reflectivity of the walls (plastic wall, plaster wall...etc), ceiling, floor differs leading to intersymbol interference (ISI).

The first and second reflections are shown on wall-1 and wall-2 respectively. Thus, the power received at photodetector via direct and non-direct paths is calculated by equation (2)

$$Pr = (\mathbf{H}_{LOS}(0) + \mathbf{H}_{dif}(0)) p_t + \sigma_{noise}^2 \quad (2)$$

where $\mathbf{H}_{LOS}(0)$ and $\mathbf{H}_{dif}(0)$ are the direct gain (DC) of direct path and non-direct paths respectively and σ_{noise}^2 is the noise power.

Angles ϕ , ϕ_1 represent irradiance angles of LOS and diffuse signal respectively, α, γ are the incidence angles and β, δ are the exit angles at the surface of the wall. Angles $\varphi, \varphi_1, \varphi_2$ are the angles of incidence at the detector for direct path, first and second reflections respectively [12-13].

Emitted light intensity via an LED can be represented by Lambert formula and given by [18],

$$s(\varphi) = p_t \frac{m+1}{2\pi} \cos^m(\varphi) \quad (3)$$

where m is the Lambertian emission order which is given by

$$m = \frac{\ln(2)}{\ln(\cos\varphi_{1/2})} \quad (4)$$

where $\varphi_{1/2}$ is the half power angle of LED.

The channel impulse response of a LOS link due to the transmitted signal from the light source to the photodetector is

$$\mathbf{H}_{LOS}(0) = \begin{pmatrix} \frac{A_r(m+1)}{2\pi(d_1d_2)^2} \cos^m(\varphi) \cos(\varphi) g(\varphi) & 0 \leq \varphi \leq \varphi_{fov} \\ 0 & \varphi > \varphi_{fov} \end{pmatrix} \quad (5)$$

$$g(\varphi) = \begin{pmatrix} \frac{n^2}{\sin^2(\varphi_{fov})} & 0 \leq \varphi \leq \varphi_{fov} \\ 0 & \varphi > \varphi_{fov} \end{pmatrix} \quad (6)$$

where A_r is the active area at the receiver, φ_{fov} is the FOV of the receiver and n is the refractive index.

While, the channel impulse response of the first reflection signal is given by,

$$\mathbf{H}_{1stref}(0) = \begin{pmatrix} \frac{A_r \Delta A P^2 (m+1)}{2\pi(d_1d_2)^2} \cos^m(\varphi) \cos(\varphi) g(\varphi) & 0 \leq \varphi \leq \varphi_{fov} \\ 0 & \varphi > \varphi_{fov} \end{pmatrix} \quad (7)$$

where ΔA is the small grids area on the walls surface, the term P represents the wall's reflection coefficients. Similarly, the channel impulse response of the second reflected signal is given by

$$\mathbf{H}_{2ndref}(0) = \begin{pmatrix} \frac{A_r (\Delta A)^2 P^2 (m+1)}{2\pi(d_1d_2d_3d_4)^2} \cos^m(\varphi) \cos(\varphi) g(\varphi) \cos(\delta) \cos(\gamma) & 0 \leq \varphi \leq \varphi_{fov} \\ 0 & \varphi > \varphi_{fov} \end{pmatrix} \quad (8)$$

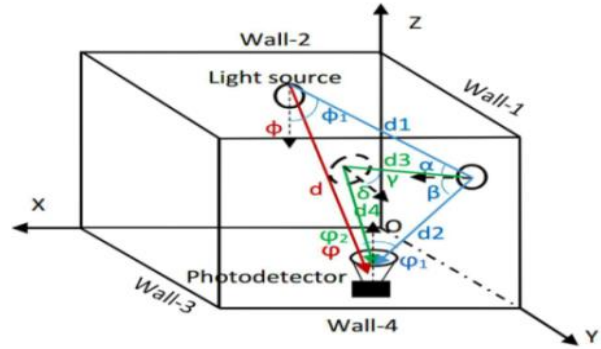


Fig. 2. Typical room model

3-2- VLC-MIMO Model

The case study approach is chosen to investigate the mitigation of multipath reflected signals coming from walls and ceiling owing uniform power distribution for entire room environment. In the block diagram of Fig. 3, consider a system of a 4×4 MIMO is applied to transmitter as well as the receiver.

Four symbols s_1, s_2, s_3 and s_4 are transmitted in four consecutive time slots T_{s1}, T_{s2}, T_{s3} and T_{s4} using four different arrays of sources at the transmitter and four different detectors at the receiver.

The emitted light signal via an LED is

$$\mathbf{x}(t) = 2p_t \sum_{i=0}^{l-1} d_i \quad (9)$$

Where p_t is the transmitted power via an LED and d_i is data symbols. Therefore, at high frequency, the driving circuit modulates the driver current to switch LEDs as ON and OFF. Now, consider a 4×4 matrix for symbols s_1, s_2, s_3 and s_4 are arranged as

$$\begin{bmatrix} s_1 & s_2 & s_3 & s_4 \\ s_2 & -s_1^* & s_4 & -s_3^* \\ s_3 & -s_4 & -s_1 & s_2 \\ s_4 & s_3^* & -s_2 & -s_1^* \end{bmatrix} \quad (10)$$

The transmitted light signals over four time slots from four arrays of white LEDs are specified in Table 1.

Table 1: light signals transmitted over four time slots of four arrays.

Time	s ₁ from LEDs _{s₁}	s ₂ from LEDs _{s₂}	s ₃ from LEDs _{s₃}	s ₄ from LEDs _{s₄}
[0, T _s]	s ₁	s ₂	s ₃	s ₄
[T _s , 2T _s]	s ₂	-s ₁ *	s ₄ *	-s ₃ *
[2T _s , 3T _s]	s ₃	-s ₄ *	-s ₁ *	s ₂
[3T _s , 4T _s]	s ₄	s ₃ *	-s ₂ *	-s ₁ *

Once the signals are transmitted via wireless channel with channel gain \mathbf{H} , the channel matrix between the LEDs and the PDs has been described by;

$$\mathbf{H} = \begin{bmatrix} h_{1,1} & \cdots & h_{1,i} \\ \vdots & \ddots & \vdots \\ h_{j,1} & \cdots & h_{j,i} \end{bmatrix} \quad (11)$$

where $h_{j,i}$ is a channel coefficient between j^{th} PD and i^{th} LED and the dimension of the MIMO channel matrix \mathbf{H} is $\mathbb{R} \times \mathbb{R}$.

The received signals on the Photodetector 1 (PD1) at the time periods [0, T_s], [T_s, 2T_s], [2T_s, 3T_s] and [3T_s, 4T_s] respectively assume the forms,

$$\begin{aligned} y_{1[0,T_s]} &= 2P_t^2 R [h_{11}s_1x + h_{21}s_2x + h_{31}s_3x + h_{41}s_4x + n_1] \\ y_{1[T_s,2T_s]} &= 2P_t^2 R [h_{11}s_2x - h_{21}s_1^*x + h_{31}s_4^*x - h_{41}s_3^*x + n_2] \\ y_{1[2T_s,3T_s]} &= 2P_t^2 R [h_{11}s_3x - h_{21}s_4x - h_{31}s_1x + h_{41}s_2x + n_3] \\ y_{1[3T_s,4T_s]} &= 2P_t^2 R [h_{11}s_4x + h_{21}s_3^*x - h_{31}s_2x - h_{41}s_1^*x + n_4] \end{aligned} \quad (12)$$

Similarly, The received signals on the (PD2) at the time periods [0, T_s], [T_s, 2T_s], [2T_s, 3T_s] and [3T_s, 4T_s] respectively assume the forms,

$$\begin{aligned} y_{1[0,T_s]} &= 2P_t^2 R [h_{12}s_1x + h_{22}s_2x + h_{32}s_3x + h_{42}s_4x + n_1] \\ y_{1[T_s,2T_s]} &= 2P_t^2 R [h_{12}s_2x - h_{22}s_1^*x + h_{32}s_4^*x - h_{42}s_3^*x + n_2] \\ y_{1[2T_s,3T_s]} &= 2P_t^2 R [h_{12}s_3x - h_{22}s_4x - h_{32}s_1x + h_{42}s_2x + n_3] \\ y_{1[3T_s,4T_s]} &= 2P_t^2 R [h_{12}s_4x + h_{22}s_3^*x - h_{32}s_2x - h_{42}s_1^*x + n_4] \end{aligned} \quad (13)$$

The received signals on the (PD3) at the time periods [0, T_s], [T_s, 2T_s], [2T_s, 3T_s] and [3T_s, 4T_s] respectively assume the forms,

$$\begin{aligned} y_{1[0,T_s]} &= 2P_t^2 R [h_{13}s_1x + h_{23}s_2x + h_{33}s_3x + h_{43}s_4x + n_1] \\ y_{1[2T_s,3T_s]} &= 2P_t^2 R [h_{13}s_2x - h_{23}s_1^*x + h_{33}s_4^*x - h_{43}s_3^*x + n_2] \\ y_{1[2T_s,3T_s]} &= 2P_t^2 R [h_{13}s_3x - h_{23}s_4x - h_{33}s_1x + h_{43}s_2x + n_3] \\ y_{1[3T_s,4T_s]} &= 2P_t^2 R [h_{13}s_4x + h_{23}s_3^*x - h_{33}s_2x - h_{43}s_1^*x + n_4] \end{aligned} \quad (14)$$

The received signals on the (PD4) at the time periods [0, T_s], [T_s, 2T_s], [2T_s, 3T_s] and [3T_s, 4T_s] respectively assume the forms,

$$\begin{aligned} y_{1[0,T_s]} &= 2P_t^2 R [h_{14}s_1x + h_{24}s_2x + h_{34}s_3x + h_{44}s_4x + n_1] \\ y_{1[2T_s,3T_s]} &= 2P_t^2 R [h_{14}s_2x - h_{24}s_1^*x + h_{34}s_4^*x - h_{44}s_3^*x + n_2] \\ y_{1[2T_s,3T_s]} &= 2P_t^2 R [h_{14}s_3x - h_{24}s_4x - h_{34}s_1x + h_{44}s_2x + n_3] \\ y_{1[3T_s,4T_s]} &= 2P_t^2 R [h_{14}s_4x + h_{24}s_3^*x - h_{34}s_2x - h_{44}s_1^*x + n_4] \end{aligned} \quad (15)$$

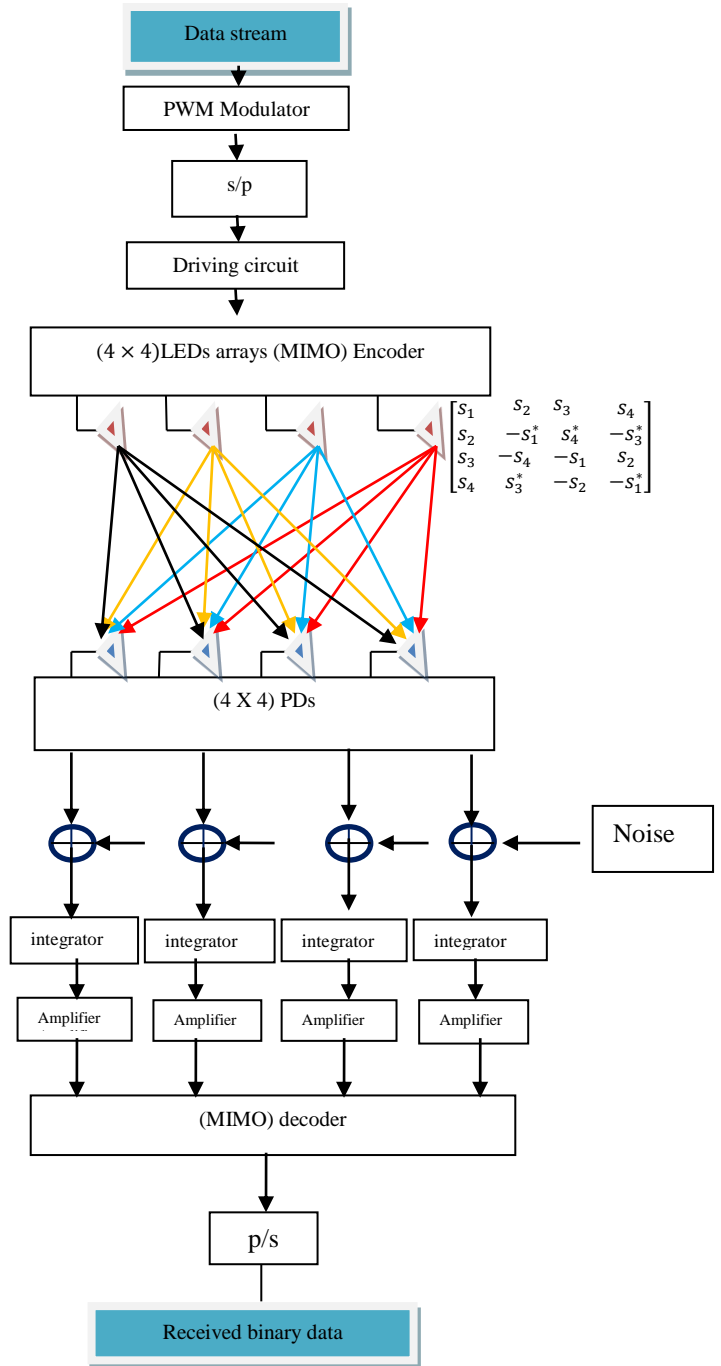


Fig. 3. Block diagram of VLC-MIMO system

where R is the photodetector responsivity and n is the additive white Gaussian noise with zero mean and variance σ_n^2 .

3-3-VLC-MIMO System Design

Many researchers have utilized SISO systems in VLC. A major problem with single emitter (LED) and single receiver (photodetector) is the limitation in link range as well as the data throughput.

To increase the reliability of VLC system, multiple input (LEDs) and multiple output (photodetectors) has been proposed offering enhanced range link and data throughput. Fig. 4 shows typical indoor illumination installing MIMO system.

It consists of TX side and RX side. The TX side is setting up in the room ceiling of 3-m altitude above ground like a spot light of 16 white power LEDs.

RX modules could be in any part of the received light spot zone.

The proposed low level of TX-RX modules of 4x4 MIMO systems is shown in Fig. 5.

The system simply consists of 16 power LEDs of 1watt each grouped in 4 groups of 4 LEDs. Each group represents TX module. Each module takes data from TX Arduino (UNO) pins.

The TX Arduino works as data generator in form of 4 metrics as S_1, S_1^*, S_2 and S_2^* . The S_1, S_1^*, S_2 and S_2^* data elements represented by Arduino pins as pins 7, 8, 12 and pin 13 respectively. These data transmitted using white light by modulate LEDs intensities using PWM modulation.

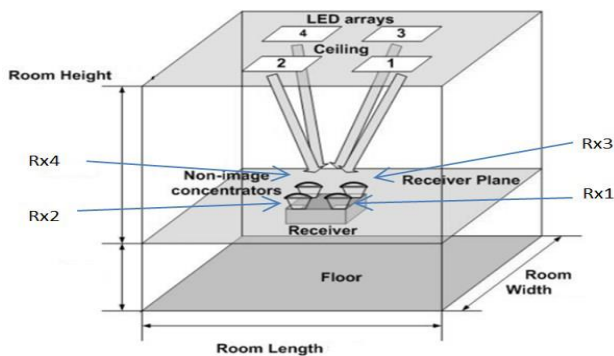


Fig. 4 typical indoor illumination

The RX side consists of 4 RX module, each module simply formed by a photo transistor as photo sensor, PWM demodulator (integrator) and amplifier.

The received signals y_1, y_2, y_3 and y_4 from RX modules is provided to Arduino analogue pins as A_0, A_1, A_2 and A_3

respectively. The Arduino follow the MIMO received algorithm to construct the transmitted data.

3-3-1-TX Module

Fig. 6 shows the TX module, simply consists of LM555 timer IC Q1 as driver and 4 power LEDs. The LEDs work as TX source and spot light.

LM555 IC works as PWM with frequency around 2.5 KHz, the output of the LM555 control the base current of Q1 power transistor which works always to give bias to the 4 LEDs using R1 resistor and the modulation signal is provided to pin 5 of the IC from pin13.

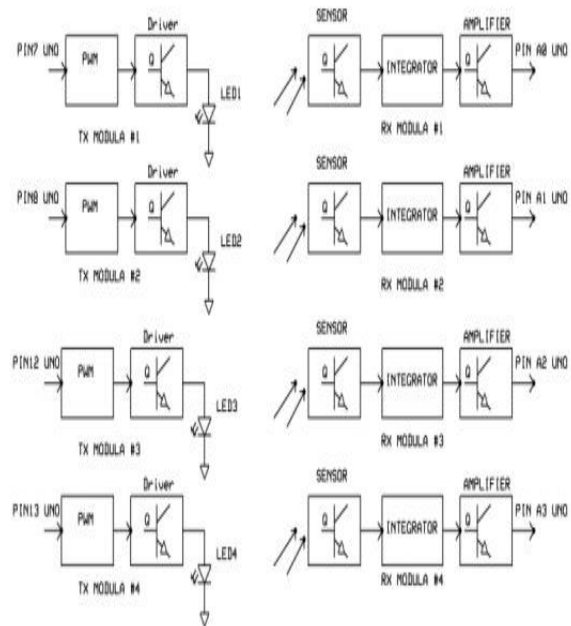


Fig. 5. The low level circuit of TX-RX modules of 4x4 MIMO systems

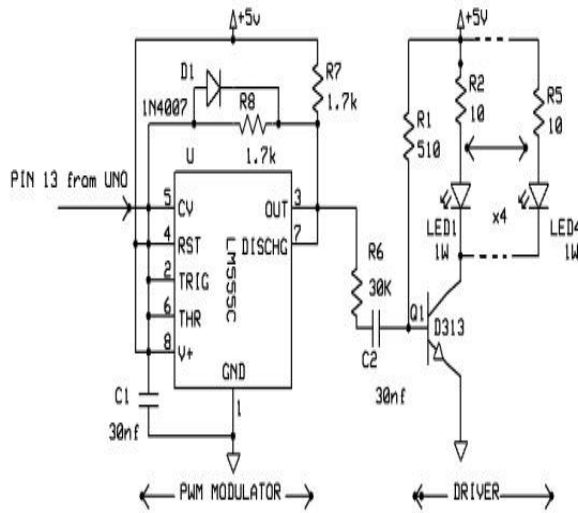


Fig. 6. The transmitter module

3-3-2-RX Module

Fig. 7 shows the RX module, simply constructed from photo sensor like 3DU33 photo transistor, 3 poles passive LPF and 2 stage amplifiers formed by Q2 and Q3.

As mentioned earlier, to get higher power densities the RX module must be near the center zone of the received spotted light as presented in Fig. 8, which shows the received test signal of 2.5KHz received for maximum amplitude when the RX module is located near spotted received zone.

If the frequency of the signal is increased, the received signal will be suffered from distortion because of slow time response of the photo sensor. The output of the RX modules lunched to RX Arduino to construct the transmitted data. The proposed VLC circuits implemented MIMO system is set out in Fig. 9.

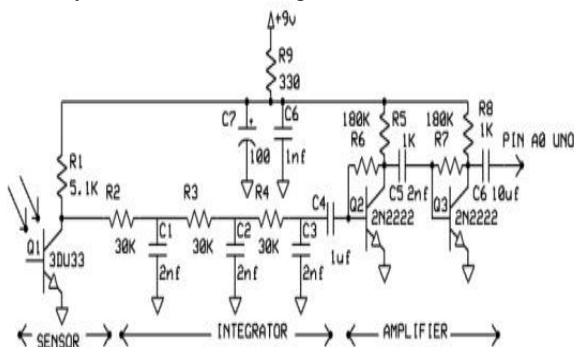


Fig. 7. The receiver module

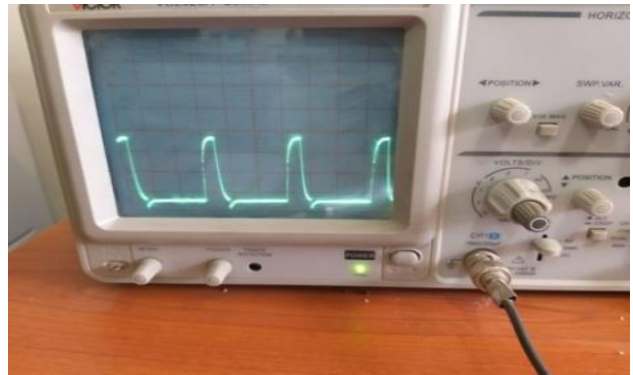


Fig. 8. The received test signal

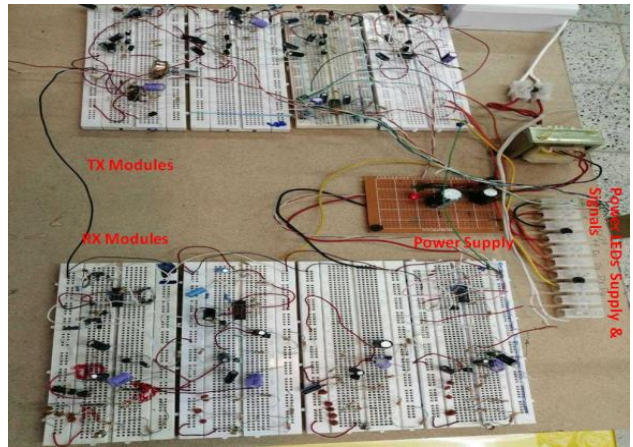


Fig. 9. The proposed VLC system circuits

4- Evaluations

In order to access VLC based MIMO channel, a power distribution of VLC based SISO channel under the specified specifications has been measured.

Table (2) illustrates some of the main parameters of the VLC link.

Table (2) system Parameter of the proposed VLC-MIMO link

Parameters	Value
size of room	3*3*5 m ³
reflection coefficient	0.7
transmitted power	20mW
field of view (FOV)	70 ⁰
Number of LEDs per array	4x4 (16)
Responsivity	0.2

In the case of SISO system considering LOS propagation environment without reflection, the distribution of the optical power is shown in Fig. 10.

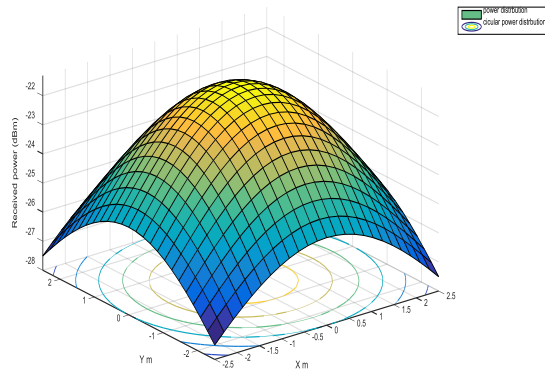


Fig. 10. The optical power distribution of VLC-SISO LOS without reflection.

It can be seen that the optical power is mostly uniform distributed at the center with maximum power at -23.5 dB and minimum at -27.5 dB. Other considering that LOS and NLOS propagation environment where in addition to direct light path, the reflected light from the walls are taken in conseraction.

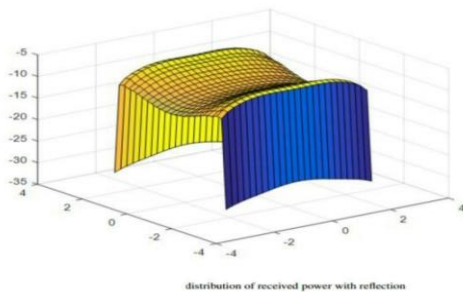


Fig. 11. The optical power distribution of VLC-SISO LOS with reflection.

It can be seen from Fig. 11 that the received optical power distributed non-uniformly due to reflections of light from walls.

As shown in Fig. 12. diverse the sources and detectors at transmitter and receiver respectively reported significantly more distributed for optical power in all directions of the room leading to increasing capacity.

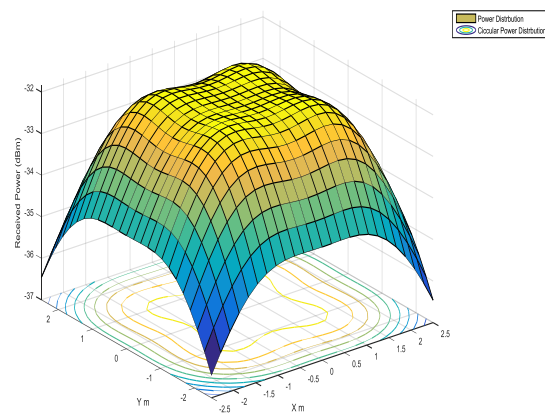


Fig. 12. The optical power distribution of VLC-MIMO reflection

Fig. 13 compares the BER performance against SINR for SISO and MIMO communication systems of LOS propagation mode using OOK modulation scheme. It can be seen that the performance of 4×4 MIMO implemented VLC system has a superior performance as compared to SISO implemented VLC system.

This is due to the ability of MIMO. In Fig. 14, the comparison between the BER performance have been done between SISO and 4×4 MIMO but for NLOS propagation mode for the parameters shown in table (3). 4×4 MIMO implemented VLC system perform better than SISO system. This is due to the ability of MIMO to combat the multipath fading and improve the data rate.

Comparison of the findings with those of other studies confirms that the 4×4 MIMO reported significantly decreased BER performance for NLOS as compared to LOS scenarios.

This is due to decreasing in the power received when the detector is not within the LOS with LEDs. These results reflect those of [14] who also found that the performance of 4×4 MIMO is better than single LED and single PD. These results are consistent with data obtained in [17] that achieves 18 dB in the case of LOS and 22 dB in the case of NLOS at a BER of 10^{-5} .

However, if VLC implemented, MIMO outperforms the SISO at the expensive of more complexity, but in our work, we implemented the VLC-MIMO system with less complexity as explained in section 3.3 as compared to the above study.

The present study was designed to reduce the complexity of the electronic circuit as compared to the circuits designed in the literature. The present implementation is significant in at least two major respects: firstly, the electronic circuit implemented using inexpensive electronic components and available in the markets.

Secondly, the design of the electronic circuit achieved in a simple modality and uncomplicated mathematical

relations. So, to avoid the use of system integration in the circuit design which is limited, we used the Arduino microcontroller which is open source electronic platform, reprogrammable and inexpensive. However, our design may be considering a real VLC-MIMO communication system.

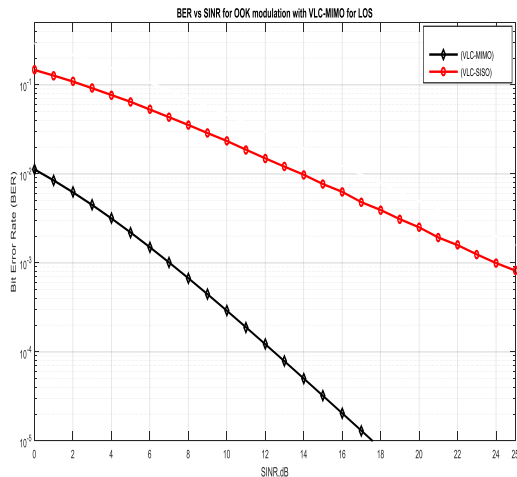


Fig. 13. BER vs. SINR for LOS propagation mode

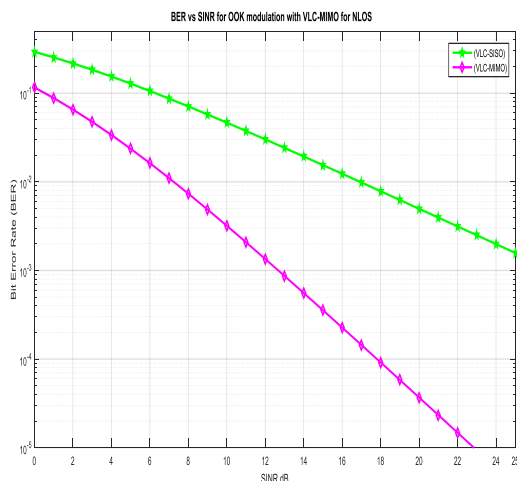


Fig. 14. BER vs. SINR for NLOS propagation mode

5- Conclusions and Future Works

The present work was designed to provide high data rate for VLC by exploiting the benefits of using multiple sources at emitter and multiple detectors at receiver. The most obvious finding to emerge from this study is that the power is distributed uniformly for entire room using array of 4×4 MIMO as compared to SISO systems due to

compact the multipath effect and reduces interference of unwanted signals reflected from walls and ceil. The proposed system is designed practically using inexpensive electronic circuits for both emitter and destination.

In general, therefore, it seems that increasing the number of LEDs as well as PDs for the VLC systems may improve the power distribution and leading to increase the data rate. The question raised by this study is how the BER can be improved with increasing the number of LEDs and PDs? The study should be repeated using suitable error correction codes such as LDPC code and LT code.

Acknowledgment

This work is partially supported by the Information and Communication Engineering Department at AlKhwarizmi College of Engineering-University of Baghdad.

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