MIMO to Enhance the Performance of VLC Systems

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Abstract: In general, visible light communication (VLC) systems run at low data rates. By introducing multiple input and multiple output (MIMO) techniques, service at enhanced data rates can be viable for VLC systems. This work proposes MIMO technique to attain VLC system with high data rates. To attain MIMO method this system includes a number of photodiodes with a narrow field of view (FOV), which highlights the benefit of using MIMO technology in improving the data rate. The results show that using MIMO technique leads to enhance the VLC system when it is compared with the traditional system (without using MIMO). The results show that an improvement in the signal-to-noise ratio (SNR) level, which is the most attempt to determine communication quality, increasing the channel bandwidth and reducing the delay spread are achieved when MIMO technique is used.

1. Introduction

Visible light communication (VLC) utilizes the spectrum of light from 390 nm to 700 nm as a data communication medium. Light emitting diodes (LEDs) are used in VLC systems for communication along with illumination purposes [1]. Many applications, such as smart lighting, indoor communication, communication from vehicle to vehicle (V2V) and from vehicle to infrastructure (V2I), have been developed. Some studies often combine VLC with other strategies for communication. To increase the system bandwidth of conventional WiFi, WiFi-VLC hybrid indoor communication systems were proposed in [2]. VLC may be used as an alternative option because of the limitation of radio frequency (RF) in some locations, such as hospitals, ships, gas stations, etc. The demand for high-speed and ubiquitous wireless broadband connectivity has stimulated a massive increase in mobile data traffic. In combination with the worldwide adoption of social media and advanced multimedia applications, the growing number of mobile devices in various form factors and capabilities are the key contributors to this phenomenal growth. It proposed an optical wireless communication system that uses white lights for wireless indoor networks [3],[4]. A VLC system is the ideal choice for optical MIMO in respect of parallel transmission, as multiple LED lights are utilized for lighting and can transmit various data streams to optimize the throughput of each single LED [5],[6]. At the same time, there is a need for an array of photodiodes on the receiver side, and this configuration allows security, connection range and different distributors improvements, while the power needed is unchanged [7]. The existence of a large number of low bandwidths LEDs, makes MIMO techniques an appealing choice to achieve high data rates, and this paper explores the potential of this technique. MIMO is widely utilized in radio communications [8], where channels that are
decorrelated around between are produced by dispersion and interference. This enables MIMO streams to provide greater capability than the counterparts of the single input single output (SISO), which provided a set total transmission power level. For short range systems the MIMO approach in indoor systems modeling is shown and the potential of the MIMO systems has been studied and a low-speed demonstration has been published [9], [10]. Working on space-time codes for MIMO is detailed in [11]. In this work the focus has been on the parallel data transfer by applying the MIMO technology approach. In the advanced generations of communication networks, MIMO technology has become attractive and more common in an increase a data rate. In this paper, the MIMO technique is suggested to increase the overall performance of the system. A significant improvement is being accomplished in SNR using the MIMO technique at high data rates. This significant enhancement in the SNR rate is attributed to the potential of the receiver to gather the VLC signal with reduced ISI using several photodiodes (PDs) due to its narrow FOV. However, due to the use of multiple receiving components, the MIMO technique has several drawbacks, including high cost and complexity compared with a traditional VLC system. As the increase in the elements or components of any system leads to its complexity. Thus, in this paper to keep the complexity at an acceptable level we used 4 x 4 MIMO VLC system, which leads to enhance the performance of VLC system. In this paper, the VLC non-return zero on-off keying (NRZ OOK) method is modeled and simulated by using white LEDs as transmitters. The VLC system simulation is performed using Matlab software. The section is organized as follows into parts. Section 2 gives the system set-up. Section 3 shows the simulation results. The conclusions are given in section 4.

2. INDOOR VLC GEOMETRICAL MODEL
In terms of some numerical analyses, we will address the potential implementation of the proposed system. In this work, an unfurnished environment was assumed to investigate our system, which was utilized in [4]. The room’s size is 5m x 5m x 3m as shown in Figure 1. The room's lighting was provided by four lighting units which were used to attain an illumination level of 300lx to confirm that ISO and European standards [4]. The LEDs were placed at a distance of 2.5 m from the floor. The height of the receiver plane where the transceivers related with the user device were located at 0.85 m above the floor. In each light unit, there were (60 x 60) 3600 LEDs. The distance between each two adjacent LEDs was 1 cm. The half angle at half power of each LED chip is 70°, the center light intensity of an LED chips 0.73 cd. The optical power transmitted by an LED chip is 20 mW [4].

![Figure 1. Room configuration.](image-url)
Reflections back to the second order was well-thought-out of this work. To model the reflection similar to that used in [12] and [13], we used ray tracing. The room is divided into many small areas for ray tracing and each area represents a second transmitter [14]. Each small area is 3.9 cm² in size, with a coefficient of reflection of 0.8 [4].

To depict the benefit of using MIMO, we compared our system with the traditional VLC system (without MIMO). Thus, two types of optical receiver have been used, the first being a single photodiode (PD) receiver with a wide FOV and a photo sensitive area of 1 mm², which was utilized with the traditional system. We assume small area of the photodetector, so the optical receiver can work at high data rates. The relationship between the area of the photodetector and the bandwidth can be found in [6]. For the MIMO system, we utilized a matrix of PDs, which consists of four PDs with FOV of 50° in order to highlight the benefit of using MIMO technology in improving the system performance and thus improving the data rate, which is the main objective of this research.

Parameters were utilized in simulation are shown in Table I. Gfeller and Bapst [14] investigated the reflection coefficients of a variety of popular indoor materials. The reflection coefficients were found to range from 0.4 to 0.9. They also discovered that an ideal Lambertian pattern accurately approximated the power reflected by elements on the walls or ceiling. Thus, the reflection elements on the walls are viewed as a small transmitter in this paper, transmitting an attenuated version of the signals received from its center in a Lambertian pattern. In [4], authors investigated that the rate of reflected light is sufficiently low as compared to directed light. As a result, in VLC, the effect of directed light is significant, and it has a significant impact on system performance. For the sake of system analysis, we consider until the first reflection in this paper and neglecting higher reflection ranks from first reflection such as second reflection and beyond due to their very low impact on the system.

| Parameters                      | Values                          |
|---------------------------------|---------------------------------|
| Room Size                       | 5.0 x 5.0 x 3.0 m³              |
| TX Location                     | TX1(1.25m,1.25m,3m)             |
|                                 | TX2(3.75m,1.25m,3m)             |
|                                 | TX3(1.25m,3.75m,3m)             |
|                                 | TX4(3.75m,3.75m,3m)             |
| Transmitted optical power       | 20 mW                           |
| Semi angle at half power        | 70°                             |
| The LED number                  | 3600 (60 x 60)                  |
| LED light size                  | 0.01 m                          |
| Physical detector area of a PD  | 1.0 mm²                         |
| Gain of an optical filter       | 1.0                             |
| Lens refractive index at a PD   | 1.5                             |
| Background light current        | 5100 µA                         |
| Noise bandwidth factors         | 0.562                           |
| PD responsivity                | 0.54 A/W                        |
| Noise current density           | 2.7 pA/√HZ                      |

3. Results of Simulation
In the presence of propagation scattering and mobility, we assessed the results of the designed systems (MIMO-VLC system and traditional system) using a wide FOV receiver and a matrix of PDs receivers in an empty room. In eight separate places, the proposed structures were tested as the receivers traveled along the y-axis. On the basis of impulse response, delay spread, 3 dB channel BW, path loss
and SNR rate, the results are described. The results for x = 3 and x = 4 are identical, depending on the similarity of the room, to the findings for x = 1 and x = 2 respectively, so only the results for x = 1 m and x = 2 m can be seen along the y-axis.

3.1. Analysis of Impulse Response

Figure 2 illustrates the impulse responses of the two systems (traditional VLC and MIMO-VLC systems). While the receivers were placed at the center, the impulse responses were obtained. It can be noticed that when the receiver is located in the center, the impulse response of each transmitter in the MIMO-VLC system is the same. This is due to the distances between the four LED lights (transmitters) and the receiver are equal. As it is seen in Figure 2(b), the impulse response of the MIMO system outperforms the traditional system in terms of signal distribution. The traditional system’s impulse response (Figure 2(a)) involves several peaks relating to various process LOS components that arrive from various LEDs. The traditional system’s impulse response also demonstrates that the component of LOS and first order reflection have a significant effect on the signal, as these components allow the signal to scatter over a wide temporal range due to the wide FOV of this receiver.

![Figure 2](image)

Figure 2. Impulse response of the two systems at room center (x=2.5m, y=2.5m, z =0.85m).
(a) traditional VLC system and (b) MIMO system.

3.2. Analysis of Delay Spread

The delay spread (D) offers a reasonable estimate of the susceptibility of the channel inter-symbol interference. The delay spread is given as [1]:

$$D_{rms} = (\mu^2 + (\mu)^2)^{1/2}$$

(1)

The mean excess delay ($\mu$) is defined as:

$$\mu = \frac{\sum_{i=1}^{M} P_{d,i} t_{d,i} \sum_{j=1}^{N} P_{ref,j} t_{ref,j}}{P_{RT}}$$

(2)

and

$$\mu^2 = \frac{\sum_{i=1}^{M} P_{d,i} t_{d,i}^2 \sum_{j=1}^{N} P_{ref,j} t_{ref,j}^2}{P_{RT}}$$

(3)

M and N are defined here by the number of direct paths from LEDs to a given receiver and reflection paths towards the same receiver, $t_{d,i}$ represents the time taken for a signal when travelling in a direct path from a transmitter to a receiver, $t_{ref,j}$ represents the time taken for a signal when travelling in a reflection path from a transmitter to a receiver, $P_{d,i}$ is the optical power received from the
ithtransmitter's direct path, and $P_{\text{ref},j}$ is the optical power obtained from the $j$th surface element's reflected path. Due to LOS and NLOS components, $P_{\text{RT}}$ is the total optical power obtained and is given as [1]:

$$P_{\text{RT}} = \sum_{i=1}^{M} P_{\text{dir},i} + \sum_{j=1}^{N} P_{\text{ref},j}$$ (4)

The delay spread linked to the two systems (traditional VLC system and MIMO system) is presented in Figure 3 while the optical receiver was walked on $x = 1$ m and $x = 2$ m. To receive and track each incoming signal from each transmitter separately, either directly or reflections from walls, a simulation was performed. For each transmitter, the difference in results is due to the fact that the FOV of the receiver permitted the receiver to receive a limited range of signals, which reduce the delay spread. Thus, in using the MIMO-VLC system instead of the traditional VLC, it offered great flexibility. In general, the results indicate that the delay spread of the MIMO system is lower compared to that of the wide FOV system. Therefore, it leads to an improvement in the performance of the system. This improvement is due to the limited range of signals received by the MIMO receiver that includes number of photodiodes have a lower FOV compare with the wide FOV. In traditional system, the highest delay spread is observed when the receiver is configured under one of the four transmitters (at position $x= 1$ and $y= 1, 4$), which are the worst points for delay spread, impacting the system's performance. This is a consequence of the signals arriving from other transmitters that reach the receiver for a longer time and a greater distance after traveling from the three other LED light units. While the lowest level of delay spread can be observed when the receiver is away from a certain distance from the lighting units, thus the distances traveled by the signal are reduced. For example, this consequence can be observed when the receiver is positioned in places $(x= 1)$ and $(y = 2, 3)$ where the delay spread level is observed and normalized at a certain level.

Figure 3. Delay spread of the two systems when the optical receiver was moved (a) along $x = 1$ m and (b) along $x = 2$ m.

3.3. Analysis of 3 dB Channel Bandwidth

The 3-dB channel BW estimates the amount of data rate which the indoor channel of the VLC systems can support. The channel bandwidth can be expressed as [1]:

$$B = 1/5D_{\text{rms}}$$ (5)

$D_{\text{rms}}$ represents a delay spread defined in Equation (1). The 3 dB channel BW achieved by the two different systems is demonstrated in Figure 4. The results indicate that the MIMO-VLC system has a higher bandwidth relative to the traditional VLC system. The minimum communication channel bandwidth of the traditional system was 46 MHz at $x = 1$ m and $y = 1$ m. The results show that the
usage of the MIMO system at each position contributes to an improvement in the 3-dB channel bandwidth, which leads to a high data rate enabled by the channel.

![Figure 4](image_url)

**Figure 4.** 3 dB channel BW of the wide FOV and MIMO-VLC systems when the receiver was moved: (a) along the y-axis and x=1, (b) along the y-axis and x=2.

### 3.4. Analysis of Path Loss

The path loss ($PL$) is identified as [7]:

$$PL = -10 \log_{10}(P_T)$$

($P_T$) indicates the total power received by the receiver. The communication system path loss associated with the two systems is presented in Figure 5. With regard to the traditional VLC system, the results showed the stability of its level at close values at all locations. As in the traditional VLC system, the wide FOV was used and this enables it to receive a large range of signals, including unwanted signals resulting from reflections and ambient lights, as well as the effect of ISI, that does have a significant effect on the performance of the system. As far as the MIMO-VLC system is concerned, the results showed clear variations in the level of path loss at each location where the receiver is located. This variation is also due to the use of multiple photodiodes with a lower FOV than the wide FOV system, enabling a limited range of signals to be obtained.

![Figure 5](image_url)

**Figure 5.** Path Loss of the two systems when the optical receiver was moved (a) along the y-axis and x=1, (b) along the y-axis and x=2.
3.5. Analysis of SNR

The SNR correlated with the obtained signal can be determined by considering $P_{s1}$ and $P_{s0}$ in On-Off Keying (OOK), where $P_{s1}$ represents power of logic 1 and $P_{s0}$ represents logic 0. The SNR is given as [15]:

$$SNR = \left( \frac{R(P_{s1} - P_{s0})}{\sigma_t} \right)^2$$

(7)

here $\sigma_t$ represents standard deviation of the total noise. The total noise contains the shot noise, thermal noise and signal-dependent noise. $R$ is the responsivity of the PD. The $\sigma_t$ can be evaluated as [16]:

$$\sigma_t = (\sigma_{shot}^2 + \sigma_{preamplifier}^2 + \sigma_{signal}^2)^{1/2}$$

(8)

here $\sigma_{shot}^2$ represents the component of the background shot noise, the component of the preamplifier noise is $\sigma_{preamplifier}^2$ and the shot noise associated with the received signal is $\sigma_{signal}^2$. When working at 500 Mb/s, the SNR of the two systems (traditional and MIMO-VLC systems) can be seen in Figure 6. Using a MIMO-VLC system, a significant enhancement in the SNR rate was accomplished at 500 Mb/s. Moreover, it can be shown accurately that the MIMO VLC systems outperform the traditional VLC system. This is due to the reduction of the reflection element's impact through the use of a MIMO-VLC receiver that includes a number of narrow FOV (FOV=50°) photodiodes. To receive the appropriate signals and block the unwanted signals, the MIMO technology was used, which led to enhancing the SNR and performance of the system. A higher SNR gives our proposed system enough flexibility to significantly improve the data rate compared with the traditional system. It should be indicated that the MIMO-VLC system achieves around 12 dB SNR improvement across the traditional VLC system at the positions $(1m, 1m, 0.85m)$ and $(1m, 4m, 0.85m)$, which is the worst communication path for the MIMO-VLC system at $x=1m$.

![Figure 6](image-url)

**Figure 6.** SNR of the two systems when the optical receiver was moved along (a) the y-axis and x=1 and (b) the y-axis and x=2

4. Conclusion

We introduced and developed high data rate single-user MIMO-VLC system in this paper and compare it with traditional VLC system. Analysis of delay spread, 3 dB channel BW and path loss demonstrated the effect of each transmitter on the signal received by the receiver when using the MIMO-VLC system. There are several different paths for these signals. The production of ISI was induced by multiple signal propagation, which clearly affects the system's performance. In the traditional system, the effect of ISI appears strongly, so it has been suggested to use the MIMO-VLC system to mitigate its effect. Compared to the traditional system, our proposed system helped raise and increase the SNR by about 12 dB in the worst communication path of the MIMO-VLC system. Improved SNR enhances the performance of the system and allows the system more flexibility to significantly improve the data rate. In general, all the results obtained showed an improvement in the
system’s performance compared to the traditional VLC system. In addition, the parallel transmission of data added to the system flexibility in increasing the data rate. The SNR levels show the perfect comparison between the two systems because it represents the most important factor in determining the quality of communications.

5. References

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