Optimum Angle Diversity Receivers for Indoor Single User MIMO Visible Light Communication Systems

Abdelkader A. Matrawy[1], Mohamed A. El-Shimy[1], Mohamed R. M. Rizk[2], and Ziad A. El-Sahn[1]
[1]*Photonics Group, Electrical Engineering Department, Alexandria University, Alexandria 21544, Egypt.*
[2]*Electrical Engineering Department, Alexandria University, Alexandria 21544, Egypt.*
ziad.elsahn@alexu.edu.eg

Abstract: We propose a novel technique for single user MIMO-OFDM indoor visible light communication systems that optimizes the orientation angle of each photodetector in the receiver. Numerical results show that our technique outperforms conventional orientation method.

OCIS codes: (060.4510) Optical communications; (060.2630) Frequency modulation

1. Introduction

A growing research area in a wireless communication technology is to use the visible light emitting diode (LED) lamps for both illumination and data transmission. Visible-light communication (VLC) offers some unique features different from the conventional radio-frequency (RF) communication [1]. For indoor VLC systems, commonly multiple LED transmitters are used for illumination which enables the use of spatial diversity techniques to improve the system performance. Among diversity methods, multiple input and multiple output (MIMO) using orthogonal frequency-division multiplexing (OFDM) has been reported in [2, 3] and has shown to be an efficient technique to increase the transmission capacity of the VLC system. In [4], a Gigabit/s transmission was reported using MIMO OFDM VLC system and a tilting technique has been applied to optimize the orientation angle of the receiver module.

In this paper, we propose a novel technique for single user MIMO-OFDM VLC systems that optimizes the orientation angle (polar angle, and azimuthal angle) of each tilted photodetector (PD) in the receiver module. We consider a receiver module of 4 closely spaced PDs which have a highly correlated channel gain matrix. The receiver module performs our technique separately on each PD to reduce this high correlation and thus an improvement in the system's bit error rate (BER) performance.

2. Proposed system model

In this section, we consider an indoor MIMO-OFDM VLC system with N_T LED transmitters and N_R PD receivers. The system block diagram is shown in Fig. 1 which considers the use of singular value decomposition (SVD) and the LED nonlinearity (refer to [5] for further details). Let $X_i(k)$ denote the transmitted signal on the *k*-th subcarrier at the *i*-th LED, $Y_j(k)$ denote the received signal on the *k*-th subcarrier at the *j*-th PD, and $N_j(k)$ denote the sum of received thermal noise and ambient shot light noise on the *k*-th subcarrier at the *j*-th PD with zero mean and variance defined as in [1]. Then, $Y_j(k)$ can be written as

$$Y_j(k) = \sum_{i=1}^{N_T} H_{ji}(k) X_i(k) + N_j(k)\,, \tag{1}$$

where $H_{ji}(k)$ is the frequency domain channel response from the *i*-th LED to the *j*-th PD on the *k*-th subcarrier. In this paper, we consider only line of sight (LOS) paths between LED and PD because of negligable path delay differences between LEDs and PDs, i.e., $H_{ji}(k) = H_{ji}$, where H_{ji} is defined in [6] by:

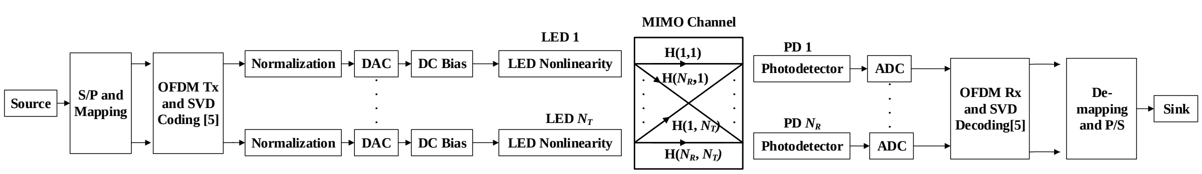


Fig.1. Generic indoor MIMO OFDM VLC system (ADC: analog to digital converter, DAC: digital to analog converter, P/S: parallel to serial, S/P: serial to parallel, SVD: singular value decomposition [5]).

$$H_{ji} = \begin{cases} \frac{(m+1)A_{pd}}{2\pi d_{ji}^2} cos^m(\emptyset_{ji}) \cos(\Psi_{ji}) & \Psi_{ji} \leq FOV \\ 0 & \Psi_{ji} > FOV \end{cases}. \quad (2)$$

Here, $\emptyset_{ji}$ is the angle of emergence with respect to the i-th LED and the normal at the source, A is the effective area of the PD, d_{ji} is the distance between the i-th LED and the j-th PD as shown in Fig. 2(a), FOV is the field of view of the PD, m is the Lambert's mode number defined in [6], and Ψ_{ji} is the angle of incidence on the j-th PD. We can derive an expression for $\cos(\Psi_{ji})$ using dot product [7]:

$$\cos(\Psi_{ji}) = \frac{\bar{u} \cdot \bar{v}}{\|\bar{u}\| \, \|\bar{v}\|} = \cos(\alpha_j - \vartheta_{ji}) \sin(\beta_j) + \cos(\emptyset_{ji}) \cos(\beta_j), \quad (3)$$

where $\bar{u}$, and $\bar{v}$ are two unit vectors as illustrated in Fig. 2(a), and ϑ_{ji} is the angle between the projection of d_{ji} on the x-y plane and the x-axis as illustrated in the same figure.

Due to closely spaced PDs in an indoor MIMO VLC receiver, the channel gain matrix is highly correlated and thus the system performance is affected. The main reason for this high correlation is the presence of cross channel gains (CCGs) H_{ji}, where $i \neq j$, and in order to reduce this correlation, PD is oriented to different polar and azimuthal angles. Fig. 2(a) explains the orientation angles of a particular PD where β is the polar angle and α is the azimuthal angle on the x-y plane (α, β). Our proposed technique is based on determining the optimum orientation angle (α_{opt}, β_{opt}) for each PD that minimizes the CCGs for that PD, while maintaining the LOS channel gain (LOSCG) $H_{ji} > 0$, where $i = j$. i.e. that guarantees the existence of a direct path between the i-th LED and the j-th PD.

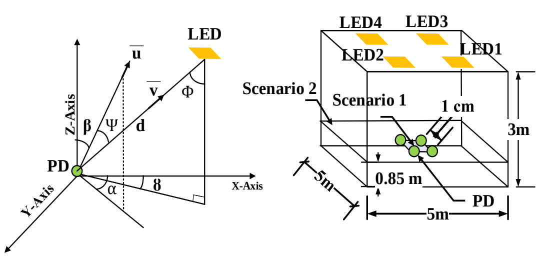
First, the receiver determines its location in the room by using one of the localization algorithms as the one explained in [8], then it uses these coordinates to calculate $\emptyset_{ji}$, and ϑ_{ji}. After that, it uses expression (3) to determine all possible pairs of (α_j,β_j) for the j-th PD that make $\Psi_{ji} \leq FOV$, where $i = j$, to ensure that the LOSCG > 0. Finally, the receiver selects the optimum pair ($\alpha_{opt\text{-}j}$,$\beta_{opt\text{-}j}$) from the pairs previously determined that minimize the summation of the CCGs for the j-th PD, such that:

$$sum_j = \sum_{i=1}^{N_T} H_{ji} \qquad i \neq j. \quad (4)$$

(e.g., for PD_1, the receiver gets all pairs of (α_1,β_1) that make $H_{11} > 0$, after that, from these pairs it selects the optimum pair ($\alpha_{opt\text{-}1}$,$\beta_{opt\text{-}1}$) that minimize sum_1, where $sum_1 = H_{12} + H_{13} + H_{14} + \ldots + H_{1i}$).

3. Simulation results

The proposed indoor 4×4 MIMO-OFDM VLC system is implemented in a typical 5m × 5m × 3m room as shown in Fig. 2(b). The receiver is 85 cm high from the ground, and the distance between each PD is 1 cm. The simulation parameters are set as follows: the IFFT/FFT size is 128, LED bias voltage is set at 3.2 V, $\emptyset_{1/2} = 60^o$, the responsivity of PD is 0.53 A/W, the effective area of the PD (A) is 1 cm^2, and FOV of all PDs is 60^o. Binary phase shift keying modulation is used and a conventional zero-forcing (ZF) detection scheme is utilized to recover detected signal. We assume two receiver distribution scenarios (Sc.1, and Sc.2), one at the center of the room and the other at the corner as marked in Fig. 2(b). The locations of LEDs and PDs of the two scenarios are given in Fig. 2(c).



(a) (b)

LED Number	Location (meter)
LED1	(3.5,3.5,3)
LED2	(1.5,3.5,3)
LED3	(3.5,1.5,3)
LED4	(1.5,1.5,3)

PD Number	Location (meter)	
	Scenario 1	Scenario 2
PD1	(2.55,2.55,0.85)	(0.5,0.5,0.85)
PD2	(2.54,2.55,0.85)	(0.49,0.5,0.85)
PD3	(2.55,2.54,0.85)	(0.5,0.49,0.85)
PD4	(2.54,2.54,0.85)	(0.49,0.4,0.85)

(c)

Fig. 2. (a) definition of the orientation angles (α, β), (b) Geometric set-up of the considered 4×4 indoor VLC system, the receiver is 85 cm high from the ground, and the distance between each PD is 1 cm, (c) locations of LEDs and PDs in the two scenarios.

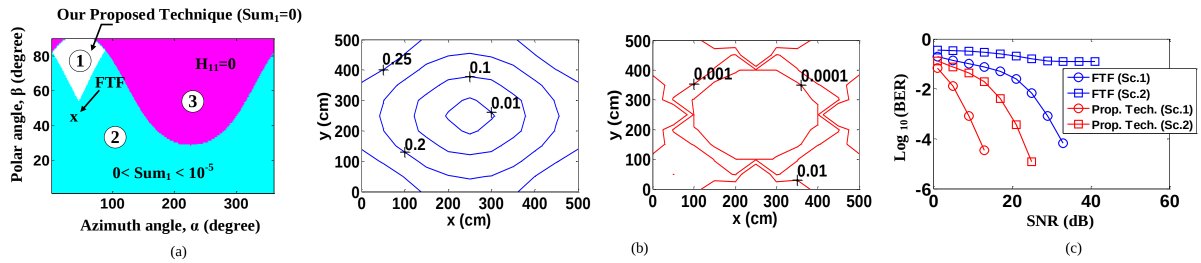


Fig. 3. (a) contour plot of sum_1 which is the summation of cross channel gains (CCGs) of PD_1 ($H_{12}+H_{13}+H_{14}$) in case of Scenario 1 (Sc.1). This is done by varying the orientation angles of PD1 ($0^o \leq \beta_1 \leq 90^o$, $0^o \leq \alpha_1 \leq 360^o$) while fixing the other 3 PDs, FTF is the face to face method (conventional method) [5] i.e., $\alpha = \delta^o$, and $\beta = \emptyset^o$, (b) contour plot of BER for the whole room at SNR = 15 dB in case of FTF method (left figure), and our proposed technique (right figure), (c) BER versus SNR plot comparing between FTF and our proposed technique (Prop. Tech.) for the two scenarios (Sc.1, and Sc.2).

Fig. 3(a) shows a contour plot of sum_1 (e.g., $H_{12}+H_{13}+H_{14}$) for different pairs of (α_1,β_1) for PD_1 where $0^o \leq \beta \leq 90^o$, and $0^o \leq \alpha \leq 360^o$ in case of Sc.1, while setting the orientation angles of the other 3 PDs at a fixed value. We have 3 regions: region 1 of $sum_1 = 0$, region 2 of $0 < sum_1 < 10^{-5}$, and region 3. Regardless of the value of sum_1 in region 3, its LOSCG $H_{11} = 0$ ($\Psi_{11} > FOV$) which means there is no a direct path between PD_1 and LED_1, so we should not choose any (α_1,β_1) pair from this region. Region 1 is our proposed technique that provides a very low CCGs (zero in our example) and as a consequence, an improved BER performance. While the conventional method [5] which is the face-to-face method (FTF) in which the PD is oriented such that its normal lies in the line of sight of the LED, i.e., $\alpha = \delta^o$, and $\beta = \emptyset^o$, is located in region 2 which has a higher CCGs compared to our technique. Fig. 3(b) shows a contour plot of BER analysis at SNR=15dB in case of FTF (left figure), and our proposed technique (right figure). We can see in case of FTF, the minimum required BER (10^{-3}) cannot be obtained at this SNR at any point in the room, while our proposed technique provides a BER less than 10^{-4} at a large coverage area especially at the center of the room. Fig. 3(c) plots a BER versus SNR to compare between our proposed technique and FTF method in the two scenarios (Sc.1, and Sc.2), our technique obviously outperforms the FTF method in the two scenarios, about 20 dB better than FTF at BER = 10^{-3}.

4. Conclusion

We evaluate for the first time to our knowledge a novel angle diversity technique for indoor single-user VLC system which optimizes the orientation angle of each photodetector in the receiver. The system consists of a multiple input and multiple output channel using orthogonal frequency division multiplexing. Numerical results for a 4x4 MIMO OFDM VLC system show that the proposed diversity technique outperforms the conventional orientation method (face-to-face method). In particular case where the receiver is at the center of the room, a gain of 20 dB in signal to noise ratio is achieved at a bit error rate of 10^{-3}.

5. References

[1] T. Komine, M. Nakagawa, "Fundamental analysis for visible light communications using LED lights," *IEEE transactions on Consumer Electronics*, Vol. 50, no. 1, pp. 100-107 (2004).

[2] T. Fath and H. Haas, “Performance comparison of MIMO techniques for optical wireless communications in indoor environments,” *IEEE Trans.on Commun*., vol. 61, no. 2, pp. 733-742 (2013).

[3] R. Mesleh, H. Elgala, and H. Haas, “On the performance of different OFDM based optical wireless communication systems,” *J. Opt. Commun. Netw.*, vol. 3, no. 8, pp. 1943-0620 (2011).

[4] A. H. Azhar, T. Tran, and D. O’Brien, “A gigabit/s indoor wireless transmission using MIMO-OFDM visible-light communications,” *IEEE Photon. Technol. Lett.,* vol. 25, no. 2, pp. 171-174 (2013).

[5] Yang Hong, Tesi Wu, and Lian-Kuan Chen, “On the performance of adaptive MIMO-OFDM indoor visible light communications,” *IEEE Photonics Technology Letters,* vol. 28, no. 8, pp. 907-910 (2016).

[6] J. Barry, J. Kahn, W. Krause, E. Lee, and D. Messerschmitt, “Simulation of multipath impulse response for indoor wireless optical channels,” *IEEE J. Sel. Areas in Commun*., vol. 11, no. 3, pp. 367-379 (1993).

[7] Y. Hong, J. Chen, and C. Yu, “Performance improvement of the pre-coded multi-user MIMO indoor visible light communication system,” *in Proc. CSNDSP*, Manchester, UK, pp. 314-318 (2014).

[8] Y. S. Eroglu, I. Guvenc, N. Pala, and M. Yuksel, “AOA-based localization and tracking in multi-element VLC systems,” *in Proc. IEEE Wireless and Microwave Technology Coneference (WAMICON),* Coconut Beach, FL, pp. 1-5 (2015).