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A Multiple Input-Multiple Output Visible Light Communication System Design Based on Optical Orthogonal Codes

Mohamed Shehata[1], Mohamed Sameh Said[1], and Hassan Mostafa[1,2]
[1]Electronics and Electrical Communications Engineering Department, Cairo University, Giza 12613, Egypt
[2]Nanotechnolgy Department at Zewail City of Science and Technology, Giza, Egypt

***Abstract*—In this work, a design for a multiple input-multiple output (MIMO) visible light communication (VLC) system is proposed, based on the optical code division multiple access (OCDMA) technique. The proposed design possess the capability of operating in the low signal-to-noise (SNR) regime, due to the multiplexing gain obtained from the MIMO technique and the processing gain obtained from the OCDMA technique. Simulation results show that, the proposed system is capable of achieving the forward error correction (FEC) bit error rate (BER) limit of 10^{-3}, while operating at SNR values as low as -1 dB. Accordingly, the reported design is recommended for VLC systems that employ very low sensitivity optical photo-detectors.**

***Index Terms*—Free space optics (FSO), multiple input-multiple output (MIMO), visible light communications (VLC).**

I. INTRODUCTION

The increasing demands for high-speed wireless services by terminal users has motivated making use of the numerous advantages offered by optical access technologies. Visible light communications (VLC) is considered a promising solution as it combines the advantages by these technologies to the wireless connectivity offered by the conventional wireless services. Conceptually, in VLC communications, the downlink relies on using the conventional light sources, such as room light emitting diode (LED) lamps, to wirelessly deliver cover the terminal users in in-door units. Accordingly, the VLC receiver architectures are extremely simple and easy to integrate to many of the nowadays available equipment, such as cellular phones, router, laptops...etc. Since VLC wireless services are provided by conventional lighting systems, such as LED lamps, these systems are subject to the coverage and the mobility problems associated with wireless access points. For instance, while the inter-cell interference problem dominates tends to deteriorate the performance of a base-station-to user equipment link in cellular communications, the inter-beam interference (IBI) among several lighting sources that co-exist in the same room introduces similar effects. Therefore, throughout the literature, several VLC receiver structures, such as the angle diversity receivers (e.g., [1]-[4]), have been reported to overcome these propagation impairments. Similarly, this work presents a proposed a MIMO-VLC system that mitigates the IBI by using optical orthogonal codes (OOCs).

The rest of the paper is organized as follows. Section II describes the system block diagram along with the analytical system model. The analytical characterization of the VLC-MIMO as well as the single mode fiber (SMF) channel are presented in Section II. Numerical simulations are conducted in Section 4 in order to evaluate the BER of the VLC-MIMO system performance. Finally, Section 5 concludes the whole paper.

II. MIMO VLC SYSTEM MODEL

A. Geo-Optical System Model

Fig. 1 illustrates the geometrical TX-RX configuration of this system. The proposed VLC-MIMO system consists of a TX array of N_t LED lamps and an RX array of N_t photo-detectors (PDs). The entire system is deployed in an $L_x \times L_y \times L_z m^3$ room. The centers of the TX-LED array and the RX-PD array are assumed to be initially co-located with the center of the room. The whole TX LED array is elevated at h_t m off the ground. The whole RX PD array is elevated at h_r m off the ground. The propagation of the optical signal from the i^{th} LED to the j^{th} PD is decomposed to two scenarios; a line-of-sight (LoS) and a non-line-of-sight (NLoS). The LoS component of the propagating optical signal is a result of the light ray that is collinear with the TX, whereas the NLoS component is a result of the reflections off the surfaces of the room walls. Most often, the LoS-to-NLoS power ratio is larger than 10 dB. Accordingly, throughout the following analysis, only LoS optical propagation is considered. In this case, the time-domain response of the MIMO-VLC channel is best described by an $N_r \times N_t$ matrix $\mathbf{H}$. The value of the general entry $h_{ij} = (\mathbf{H})_{ij} \in \mathbf{R}^+$ describes the line-of-sight (LoS) response of the link between the output of the i^{th} TX LED and the input of the j^{th} RX PD.

B. The MIMO-VLC Communications Chain

Fig. 2 illustrates a block diagram representation for the proposed VLC-MIMO system. As depicted in this figure, the entire system is driven by a single data source that emits a random binary-valued information sequence at at signalling rate of R_b bps. The emitted binary information stream is split into an N_t parallel streams of R_b/N_t bps each via an $N_t \times 1$ serial to parallel (S/P) converter. Each of the split information streams is applied to a spreader, where a unique OOC pattern, denoted by $\psi_i(t)$, is multiplied by each bit in this stream. The i^{th} OOC dedicated to its corresponding information stream is given by:

$$\psi_i(t) = \sum_{q=0}^{N_c-1} \phi_{m,q} w(t - qT_c) \tag{1}$$

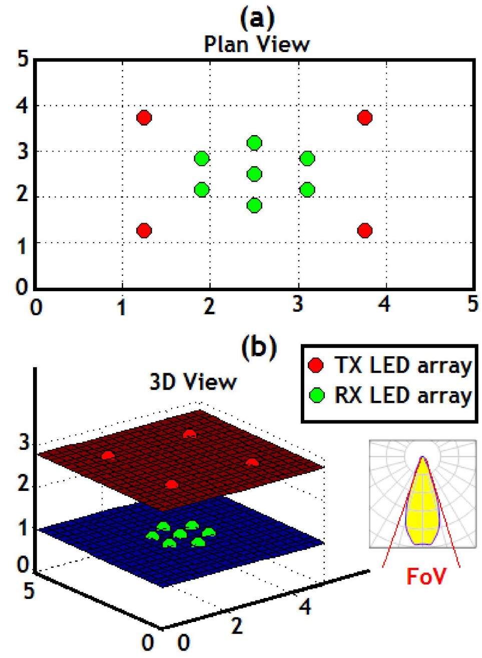

Fig. 1. Geometrical configuration of the TX LED array and the RX PD array as seen from (a): a top view and (b); a 3D view. FoV: Field of view angle of an LED.

where q is the chip index, $\phi_{m,q} \in \{0,1\}$ is the amplitude of q^{th} chip and $w(t)$ is an amplitude normalized optical encoding waveform. This waveform is selected from an orthonormal distinct code set $\{\psi_1(t), \psi_2(t), ..., \psi_{N_t}(t)\}$ and is dedicated to each of the N_t information streams, once an information bit is received from the relevant port. Many possible spreading codes, having different correlation properties, are candidates for VLC systems as the IEEE standard has not yet determined the proper core system [5]. The conventional classical spreading codes, such as the maximal-length codes and the Walsh codes, show poor autocorrelation and cross correlation properties. On the other hand, OOCs are characterized by being optimal in terms of the auto-correlation and cross-correlation properties. In particular, OOCs are characterized by being perfectly orthogonal up to four different codes.

The uniqueness of each OOC assigned to each branch is distinguished by the positions of the 1's chips within this OOC. The process of encoding an information bit by an OOC is performed by gating the OOC with each bit. The OOC encoded bits are modulated using an optically compatible modulation format. It should be highlighted that, in contrast to what is widely used in wireless communications, as would normally be preferred, quadrature-based modulation schemes are not applicable to VLC systems. Quadrature modulation requires complex-valued baseband signal processing. This leaves the possibility of using either the *M*-ary pulse amplitude modulation (*M*-PAM) schemes and/or, because of the pulsed nature of digital optical signals, the *M*-ary pulse position modulation (*M*-PPM). However, color shift keying (CSK) as recommended by the IEEE standard on VLC communications [5]. For simplicity, in this work, a non-return to zero (NRZ) format of the On-Off keying (OOK) modulation scheme is assumed. Each of the modulated signals is then forwarded to an LED in the N_t TX LED array after being conditioned by the proper driving interface circuitry.

The optical signal emitted by the i^{th} TX LED, denoted by $s_i(t)$, is propagated over the MIMO-VLC channel and is mathematically expressed as follows:

$$s_i(t) = \sqrt{E_b} \sum_{k=-\infty}^{+\infty} \sum_{q=0}^{N_c-1} b_{i,k} \phi_{i,q} w(t - qT_c - kT_b) \tag{2}$$

where $b_{i,k} \in \{0,1\}$ is the k^{th} bit, emitted by the i^{th} TX LED to the MIMO-VLC channel. It should be highlighted that, perfect TX-RX synchronization is assumed on both the bit level and the chip level of the propagating OOC encoded signal. The receiver part of the proposed MIMO-VLC system design consists of N_r RX photo-detectors (PDs). At the receiver side, the IBI signal and the superimposed AWGN sums up at the input of each of PD.

$$\begin{aligned} r_j(t) &= \sqrt{E_b} \sum_{k=-\infty}^{+\infty} \sum_{i=1}^{N_t} \sum_{q=0}^{N_c-1} h_{ij} b_{j,m} \phi_{m,q} w(t - qT_c - jT_b) \\ &+ n_j(t) \end{aligned} \tag{3}$$

where $n_j(t)$ is an additive white Gaussian noise (AWGN) process. The photodetected signal is then applied to a correlator after being multiplied by a scaled optical replica of $\psi_m(t)$ and the product is integrated over the entire bit duration. The result of integration at the correlator output is sampled and dumped every T_b seconds and is expressed as follows:

$$z_{j,m} = \left(G h_{ij} \sqrt{E_b} \Re \right) \int_{kT_b}^{(k+1)T_b} r_j(t) \psi_i(t - kT_b) dt \tag{4}$$

where $z_{j,k}$ is the sampled output of the j^{th} correlator, $\Re$ is the responsivity of the PD and G denotes the gain of the active OpAmp integrator. To simplify the analysis, it is assumed that $G h_{ij} \Re = 1$. The binary value of $b_{i,k}$ is estimated from the samples $z_{j,k}$ by the decision threshold as follows:

$$\widehat{b}_{i,k} = \frac{1}{2} \left(\text{sign}(z_{j,k} - z_{Th}) + 1 \right) \tag{5}$$

where sign(.) is the conventional signum function, defined as sign(x)= 1; $x \geq 0$, sign(x)= -1; $x < 0$ and z_{Th} is a fixed threshold voltage level.

III. SIMULATION RESULTS AND ANALYSIS

This section is devoted to evaluate the performance of the proposed MIMO-VLC system with the BER as the performance metric of interest. Throughout the simulations, a 4×7 TX-RX configuration is considered. At the transmitter side, the four LED sources are located around the circumference of a circle of 0.5 m radius at angles of $45^o, 135^o, 225^o$ and

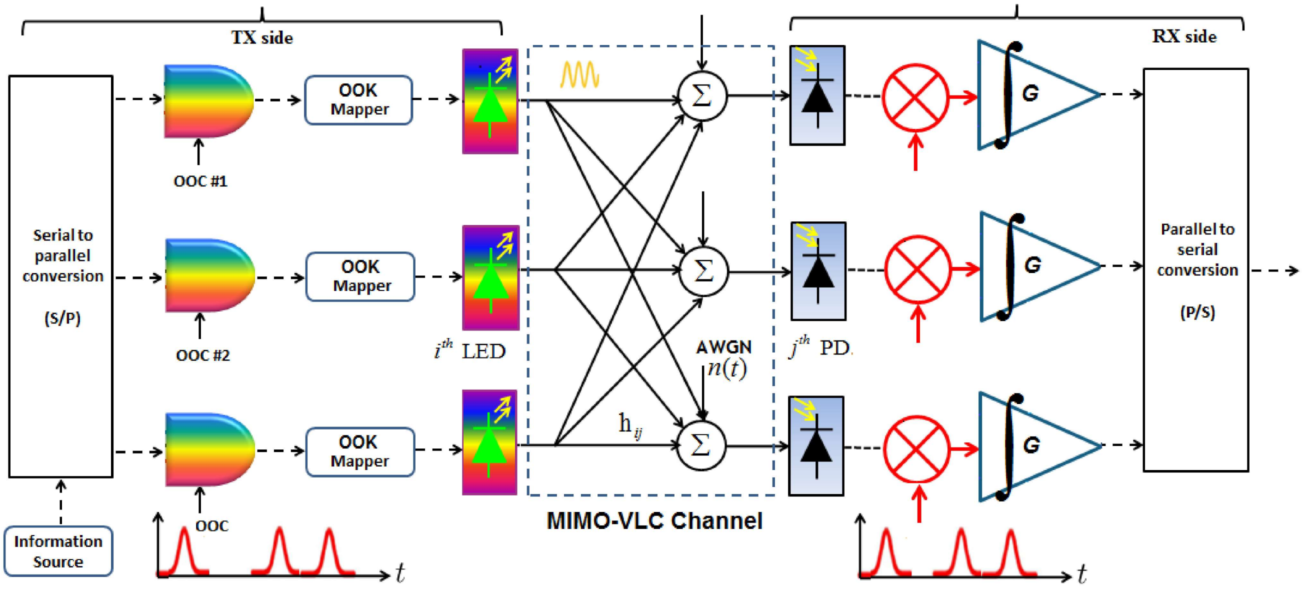

Fig. 2. Block diagram of the MIMO-VLC system model. Solid lines represent optical paths, while dashed lines represent electrical paths.

315^o, while, at the receiver side, six PDs are arranged around the circumference of a circle that has a radius of 5 cm. The seventh PD is located at the center of this circle. The OOcs assigned to each of the LEDs at the transmitter side are given by $C_1 = \{1, 2, 16, 106\}, C_2 = \{1, 3, 59, 143\}, C_3 = \{1, 4, 42, 65\}, C_4 = \{1, 5, 18, 107\}$. The waveforms of the OOCs are plotted in Fig. 3. As clear in the figure, the OOCs have no common chips positions, except for the first chip. This ensures the absence of inter-channel interference among the four branches of the MIMO-VLC system at each PD. The FoV angles for the LEDs and the PDs are assumed to be 120^o as seen from both the side and the plan views. The simulations start by calculating the channel matrix $\mathbf{H}$ using the DIALux Light 4.14 software tool. The dimensions of the room in which the system is deployed is assumed to be $L_x = 4$ m, $L_y = 5$ m and $L_z = 3$ m. Four QT12-50W lamp TX array and the PD RX array are assumed to be located at $h_t = 2.8$ m and $h_r = 1$ m above the ground, respectively. The reflection coefficients of the ceiling, walls and the ground are given by 0.7, 0.5 and 0.2, respectively. The $\mathbf{H}$ matrix is given by the illumination matrix, obtained from DIALux Light 4.14, normalized to the maximum illumination value allover the room size. Fig. 4 demonstrates the 2D distribution of the illumination matrix throughout the considered area. Initially, the center of the PD array, denoted by (x_R, y_R), is assumed to be co-located at the center point of the room.

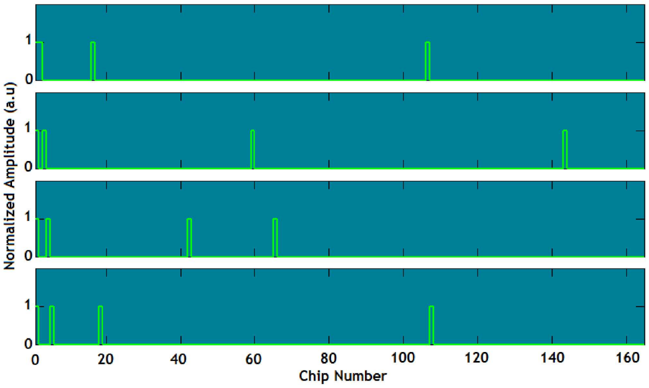

Fig. 3. Simulated waveforms of the OOCs assigned to the TX LED array.

The BER versus the SNR per bit (i.e., E_b/N_o) performance of the proposed system is calculated at six different locations off the center point of the room, namely at $x_R = \{0.25, 0.5, 0.75\}L_x$, while $y_R = 0$ and also at $y_R = \{0.25, 0.5, 0.75\}L_y$, while $x_R = 0$. A Monte-Carlo simulation approach is followed to evaluate the end-to-end BER performance by transmitting a number of 10^4 data packets over the semi-deterministic MIMO channel, calculating the conditional BER on a bit by bit basis and averaging the conditional BER over the number of realizations as follows:

$$P_e = P\left(\widehat{b}_{i,k} \neq b_{i,k}\right) \approx K^{-1}\sum_{k=1}^{K}\left(\widehat{b}_{i,k} \neq b_{i,k}\right)K; K \gg \quad (6)$$

where K is the number of iterations. Figs. 5 (a) and (b) plots the average BER performance for the proposed MIMO-VLC system, calculated at 12 different receiver locations around the room center point, without and with including the central PD, respectively. Six of these different locations are off the center point along the x axis, while the other six positions are located off the center point along the y axis.

Overall, it is clear from both figures that, the BER always attains its minimum at $(x_R = 0, y_R = 0)$. For $(x_R = \pm 0.5, x_R = \pm 0.75, |y_R = 0)$ and $(y_R = \pm 0.5, y_R = \pm 0.75, |x_R = 0)$, a slight degradation is observed in the BER performance, regardless of the value of E_b/N_o and the

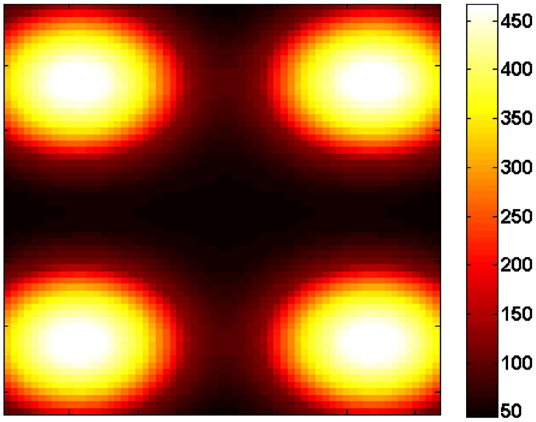

Fig. 4. Light intensity coverage map of the TX-LED array.

existence of the central PD. The proposed system is capable of achieving the forward error correction (FEC) BER limit of 10^{-3}, while operating at SNR values as low as 3 dB and -1 dB, without and with the central PD at the receiver side, respectively. The main reason behind the BER degradation at points other than $(x_R = 0, y_R = 0)$ is the near-far effect of the peripheral PDs relative to the center of the TX LED array.

IV. CONCLUSION

In this paper, a wireless optical system for indoor visible light communication systems is proposed, based on combining the multiple input-multiple output and the optical code division multiplexing techniques. The bit error rate performance of the proposed system is evaluated through extensive simulations. Simulation results show that, the proposed system achieves a high signal-to-noise ratio gain as a result of combining both techniques. The obtained results recommend the proposed design for operating at fairly low signal-to-noise ratio values and/or low receiver sensitivities.

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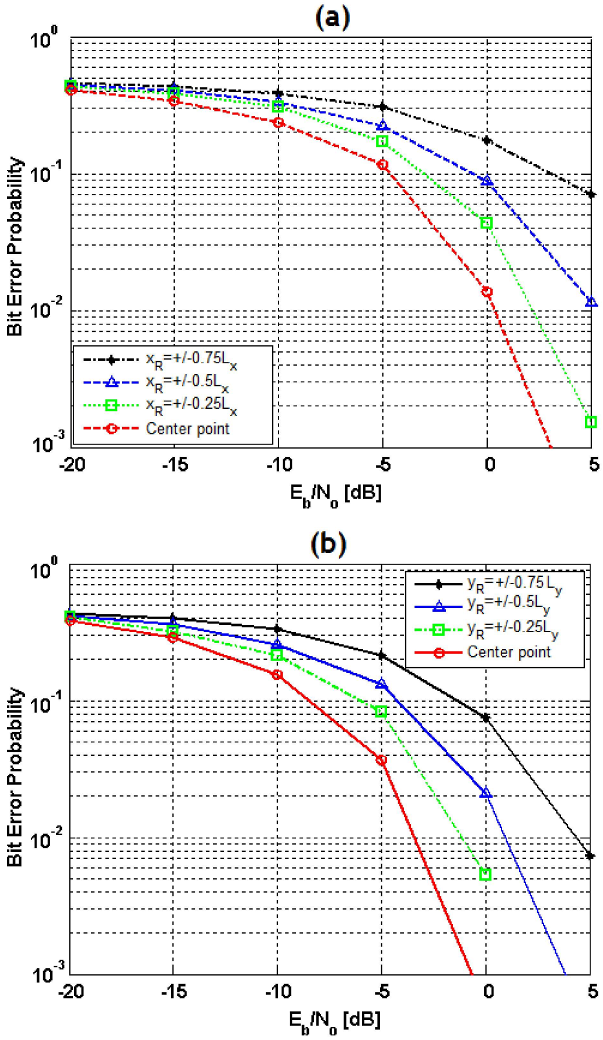

Fig. 5. The BER versus E_b/N_o performance of the proposed MIMO-VLC system, calculated at three different locations with respect to the center point along the x axis and the y axis (a): without including the central PD and (b): with including the central PD.

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