A Novel Mirror-Aided Non-imaging Receiver for Indoor 2×2 MIMO Visible Light Communication Systems

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Abstract—Indoor visible light communication (VLC) systems are now possible because of advances in light emitting diode and laser diode technologies. These lighting technologies provide the foundation for multiple-input multiple-output (MIMO) data transmission through visible light. However, the channel matrix can be strongly correlated in indoor MIMO-VLC systems, preventing parallel data streams from being decoded. Here, in 2×2 MIMO-VLC systems, we describe a mirror diversity receiver (MDR) design that reduces the channel correlation by both blocking the reception of light from one specific direction and improving the channel gain from light from another direction by utilizing a double-sided mirror deployed between the receiver's photodetectors. We report on the channel capacity of the MDR system and the optimal height of its mirrors in terms of maximum channel capacity. We also derived analytic results on the effect of rotation on MDR's performance. Based on numerical and experimental results, we show that the double-sided mirror has both constructive and destructive effects on the channel matrix. Our design can be used with previously described non-imaging systems to improve the performance of indoor VLC systems.

Index Terms—Visible light communication, multiple-input multiple-output, non-imaging receiver design.

I. INTRODUCTION

Advances in the development and fabrication of light emitting diodes (LED) and laser diodes (LD) have made these technologies inexpensive, efficient and ubiquitous [3]. Their ubiquity makes the development of indoor visible light communication (VLC) systems possible. Indoor LED and LD lighting systems are characterized by multiple light sources embedded in ceilings. This configuration can be exploited in multiple-input multiple-output (MIMO) VLC systems. Such systems have the potential to achieve high data rates via the transmission of different data streams from different LED or LD sources [4]. Indeed, experiments have shown that indoor MIMO-VLC systems can transmit Gigabits of data [5]–[8]. Despite the speed of data transmission, using a spatial-

multiplexing MIMO scheme with indoor VLC intensity channels based on line-of-sight (LoS) links remains a challenge because of the resulting highly correlated channel matrix, preventing the received signals from being decoded in parallel by the receiver.

To compensate for channel correlation and to improve system performance, several advanced transmission schemes have been proposed. A system based on per-antenna rate control (PARC) was proposed to increase the transmission rate by adjusting the data rate at each antenna according to the condition of the channel [9]. A joint space-amplitude constellation that minimized the average optical power with a fixed Euclidean distance was designed to obtain a suitable intensity-modulated VLC system [10]. A space-time block coding was adopted to improve the transmission rate at low bit error rate (BER) and to stress the trade-off between them [11]. Transmit precoding and power allocation were used to improve system performance by pre-processing the data streams to match optical power and non-negativity constraints [12]–[15]. Although these proposed techniques improve transmission rates, they do not directly impact channel correlation.

Various advanced receiver structures have been proposed to reduce the channel correlation. One proposed structure is to incorporate convex, hemispherical or fisheye lenses into the receiver's design [8], [16], [17]. The lens would allow the optical intensity signals to be projected onto the photodetector (PD) array of the receiver, resulting in partial and completely separated light images and a well-conditioned (uncorrelated) channel matrix. Although the imaging receiver leads to the performance improvement in spatial multiplexing MIMO-VLC systems, there exist some disadvantages and limitations to implement. In [4] and [7], the thin-lens imaging receiver provides the well-conditioned channel matrix but results in the limited field-of-view (FoV). Convex-lens imaging receiver was demonstrated at high speed transmission [8] but leads to the small FoV and poor quality imaging at the receiver plane. Hemispherical-lens and fisheye-lens imaging receivers with larger FoV were proposed in [16], [17] but result in a bulky design.

To compensate for the drawbacks of imaging receiver such as the limited FoV, increased receiver size, and the additional optics, a non-imaging receiver that does not include a lens was proposed at the expense of performance. The non-imaging receiver is relatively simple and compact to implement in comparison with the imaging receiver. A line-blocked receiver

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(LBR) is a simple and efficient non-imaging receiver design that reduces the correlation by blocking the link from the light source (LED or LD) to a PD [18]. Such a design would, however, be difficult to implement practically because of the users mobility and location. Another simple method is the spatially separated receiver (SSR), which reduces channel correlation by making the distances between PDs greater [18]. This method is practical to implement; however, it leads to larger receiver sizes with limited performance enhancement. Receivers that reduce channel gains from specific directions have also been proposed to reduce channel correlation [9], [19]–[21]. An angle diversity receiver (ADR) was proposed to vary the orientation angles of PDs so that the incident light from a specific direction does not reach the receiver or is directed out of the receivers FoV [19]. The prism array receiver (PAR) described in [20] deploys a prism on the top of each PD to orient the direction of the received light. Light from a specific direction passes through the prism and reaches the PD; light from other directions is blocked by the prism. PDs with different FoVs that can separate light from various channels are proposed in [21].

Most of these non-imaging MIMO-VLC receivers, except for SSR, were designed to destroy channel gains from specific LED-to-PD links to reduce channel correlation. In other words, these receivers achieve spatial directivity for each PD through destruction of the reception of the intensity signals in a specific direction. In [1], [2], we proposed a new receiver design that, like the earlier designs, exploits the destructive effect on the directivity at the receiver; unlike the earlier designs, our design exploits a constructive effect as well. In our mirror diversity receiver (MDR) design, we utilize double-sided mirrors between the PDs that both destructively reduce channel gains from a specific direction by blocking the light and constructively increase the channel gain from another direction by receiving the reflected light at the PD. Here, we analyze the performance of a 2×2 MIMO-VLC system in a two-dimensional geometric model to verify its superiority over the previously reported non-imaging receivers in terms of capacity. We derive the optimization problem with respect to the height of the mirrors to maximize channel capacity. In addition, we extend the work to more general scenario that the receiver is arbitrary rotated. We analyze the channel gains of a rotated MDR to test how different positions of the receiver effect our MDR system. Finally, we consider how our MDR system can be extended to work in a general MIMO-VLC system and how it can be used in other non-imaging receivers.

The remainder of this paper is organized as follows. Section II introduces a model of a two-dimensional 2×2 MIMO-VLC. We describe our proposed MDR in detail in Section III and analyze its performance in Section IV. We provide numerical and experimental results in Sections V and VI, respectively, to validate the superiority of our proposed system. Finally, we provide a summary of our results and a discussion of future direction of this work in Section VII.

II. SYSTEM MODEL

In this paper, we consider an optical wireless communication MIMO system with two LEDs at transmitters and the

TABLE I
DEFINITION OF NOTATIONS CHARACTERIZING THE SYSTEM MODEL IN FIG. 1

Definition	Notation
Locations of LED i	$\mathbf{x}_i$
Location of the receiver	$\mathbf{x}_r$
Transmission distance from LED i to PD j	d_{ji}
Incident vector of light irradiation in center	$\mathbf{t}_i$
Incident vector of light from LED i to PD j	$\mathbf{d}_{ji}$
Incident vector of oriented angle in PD j	$\mathbf{r}_j$
Incident angle of light at LED i to the receiver	α_{ji}
Incident angle of light at PD j from LED i	β_{ji}
Length of one side of a PD in the shape of a square	d_p
Height of a double-sided mirror	h_M
Incident angle of light into the mirror	β_{Mj}
Incident angle of reflected light into PD j	β_{jj}
Max. length that the reflected (shaded) light can reach	d_{ji}

proposed receiver equipped with two PDs (Fig. 1).¹ We utilize an intensity modulation and direct detection (IM-DD) scheme for modulation and demodulation in this system. As shown in Fig. 1, the link between the LEDs and PDs are direct line-of-sight (LoS) link without reflections. For simplicity, we assume that transmitter-receiver pairs are aligned as two-dimensional cartesian coordinates, although we note that our proposed receiver can be easily extended to the three-dimensional space. Each LED is symmetrically located over the X -axis and at the same height in the Y -axis, i.e., the i -th LED is on the point $((3 - 2i)x_0, y_0)$, where $x_0 > 0$ and $y_0 > 0$. Each LED irradiates light in a Lambertian radiation pattern centered in the direction of unit vector $\mathbf{t}_i$. We assume that the receiver size is relatively small compared to the transmission distance and two PDs are co-located on the point $(x, 0)$; that is, the transmission distances and the irradiance angles between the i -th LED and both PDs are the same, i.e., $d_{1i} = d_{2i} = d_i$ and $\alpha_{1i} = \alpha_{2i} = \alpha_i$. We note that the j -th PD plane is oriented in the direction of unit vector $\mathbf{r}_j$.

Each electrical signal is modulated for the input of each LED, converted to intensity signal s_i for $i = 1, 2$. At the receiver, each PD directly detects electrical current signal y_j for $j = 1, 2$ proportionally to the intensity of the received signal. For the sake of simplicity, the received signal can be represented in vector space as

$$\mathbf{y} = \mathbf{H}\mathbf{s} + \mathbf{n}, \quad (1)$$

where $\mathbf{n} = [n_1 \ n_2]^T$ denotes independent and identically distributed (i.i.d.) additive white Gaussian noise (AWGN) vectors with zero mean and variance of $\sigma_{n_j}^2 = \frac{N_0}{2}$.² $\mathbf{H} \in \mathbb{R}^{2 \times 2}$ is the 2×2 channel matrix whose element h_{ji} represents the channel gain between the i -th LED and the j -th PD, which is given by [22]

$$h_{ji} = \frac{(m+1)A_{ji}}{2\pi d_{ji}^2} \cos^m \alpha_{ji} \cos^k \beta_{ji}, \quad |\alpha_{ji}| \leq \frac{\pi}{2}, |\beta_{ji}| \leq \frac{\text{FoV}}{2}. \quad (2)$$

Otherwise, $h_{ji} = 0$. Here, $\alpha_{ji}, \beta_{ji}, d_{ji}$ and A_{ji} are respectively the irradiance angle at the i -th LED to the receiver, the incident

¹We note that the frequently used parameters characterizing the system model are listed in Table I for better readability.

²We note that the shot and thermal noise in receiver electric domain are generally modeled as AWGN.

Fig. 1. System model of a 2-dimensional 2×2 OWC-MIMO link equipped with the proposed mirror diversity receiver; The geometry of transmitter-receiver pair (left), the structure of proposed MDR (top right), and the example for its reception of incident light from the 1st LED with $\mathbf{r}_j = [0 \ 1]^T$ (bottom right).

angle at the j -th PD from the i -th LED, the transmission distance between the i -th LED and the j -th PD and the active area of the j -th PD with respect to the i -th LED. Each angle can be computed as

$$\cos \alpha_{ji} = \mathbf{d}_{ji} \cdot \mathbf{t}_i \quad (3)$$

$$\cos \beta_{ji} = -\mathbf{d}_{ji} \cdot \mathbf{r}_j, \quad (4)$$

where $\mathbf{d}_{ji}$ denotes the direction vector from the i -th LED to the j -th PD, which is given by $\mathbf{d}_{ji} = \frac{[x-(3-2i)x_0 \ -y_0]^T}{d_{ji}}$. In (2), k denotes the FoV coefficient of the PD. The Lambertian emission order is given as

$$m = \frac{-\ln 2}{\ln(\cos \Phi_{1/2})}, \quad (5)$$

where $\Phi_{1/2}$ denotes the semi-angle at half-power of light emission in the LED. In a conventional non-imaging receiver using PDs with the same PD plane size, the active PD area for each channel element is the same as A . The high correlation between channel vectors with respect to the two LEDs prevents spatial multiplexing MIMO transmission and decoding in a conventional receiver. In the next section, we propose a new receiver structure to reduce the correlation by deploying a double-sided mirror between two PDs.

III. PROPOSED MIRROR DIVERSITY RECEIVER

The structure of the proposed MDR is shown in the upper right corner of Fig. 1. To obtain channel vectors with lower correlation, we deploy a double-sided mirror perpendicularly to the X -axis between the two PDs. While we use double-sided mirrors, any type of double-sided reflector could be used for the same purpose. Depending on the direction of the incident light, one of the PDs will receive greater light intensity due to the reflected light by the mirror. At the same time, any incident light from the other direction is blocked by the mirror. By doing so, each PD can exploit spatial directivity to separate the intensity signal from one LED from that from the other LED. For example, as shown in the bottom right of Fig. 1, the first PD gains more light intensity from the reflected

light from the mirror, while the second PD in the shaded plane does not receive light from the first LED due to blockage by the mirror. We can then compute the additional channel gain and the loss of channel gain due to the mirror to find the channel matrix at the proposed MDR. We analyze only the channel matrix in the range of $x \geq 0$ due to symmetry. We assume that the active area of the two PDs is in the shape of a square with the same area, $A = d_p^2$, where d_p is the length of one side. The height of the mirror is defined as h_M . Depending on the location of the LED relative to the location of the receiver, we know that the channel gain of each PD increases or decreases. By considering two scenarios with differing receiver locations, i.e., between the two LEDs, $0 \leq x < x_0$ or outside the two LEDs, $x \geq x_0$, we can calculate the channel matrix at the proposed MDR.

A. Scenario 1: $0 \leq x < x_0$

The received intensity through a direct LOS link without the mirror is obtained by (2). We focus on the amount of received intensity or loss of intensity due to the mirror. As shown in Fig. 1, in this scenario, the i -th PD can gather more reflected light from the i -th LED, while it loses some amount of intensity from the other LED due to blockage by the mirror. The increased and decreased amount of intensity is proportional to each PD's effective active area where the reflected light can be gathered or can be shaded by the mirror. To calculate the effective active area for receiving extra reflected light, we first calculate the incident angles of the light into the mirror and the reflected light into the PD plane, which are given by

$$\begin{aligned} \cos \beta_{Mj} &= -\mathbf{d}_{jj} \cdot [0 \ 1]^T \\ \cos \tilde{\beta}_{jj} &= -(\mathbf{T}_M \mathbf{d}_{jj}) \cdot \mathbf{r}_j, \end{aligned} \quad (6)$$

where $\mathbf{T}_M$ denotes the transformation matrix due to the mirror, which is given by $\mathbf{T}_M = \begin{bmatrix} -1 & 0 \\ 0 & 1 \end{bmatrix}$. As shown in the bottom right of Fig. 1, we define the effective maximum length as $\tilde{d}_{ji}$ in the PD plane, which is the length the reflected light can

reach in the case of $i = j$ or be blocked in the case of $i \neq j$. The effective maximum length can be computed by using the following trigonometric identities:

$$\tilde{d}_{ji} = \begin{cases} \min\left(\frac{h_M \sin \beta_{Mi}}{\cos \tilde{\beta}_{ii}}, d_p\right), & i = j \\ \min\left(\frac{h_M \sin \beta_{Mi}}{\cos \tilde{\beta}_{ji}}, d_p\right), & i \neq j. \end{cases}, \quad (7)$$

where we note that we use the identity of $\tilde{\beta}_{ji} = \beta_{ji}$ in case of $i \neq j$ for notational simplicity. Now, the effective active area where the reflected light is received or blocked can be calculated as $\tilde{A}_{ji} = \tilde{d}_{ji} d_p$. Therefore, the overall channel gain at the proposed MDR can be computed as (8) at the top of next page, where $\eta_M \in [0, 1]$ is the mirror's reflection coefficient, which is equal to one with a perfect mirror, and δ_k is the Dirac delta function, where $\delta_k = 1$ for $k = 0$ and $\delta_k = 0$ otherwise. We observe from (8) that the channel gains of the diagonal components in the channel matrix are increased compared with those in a conventional receiver, while those of off-diagonal components are reduced. This means that the two channel vectors for the first and second LEDs can be further uncorrelated by introducing our proposed MDR.

B. Scenario 2: $x \geq x_0$

It is clear to see that some of the intensity signals from both LEDs are blocked at the first PD due to the mirror, while the intensity signals reflected by the mirror can help increase the channel gain at the second PD. Similarly to the first scenario, we can calculate the channel gain given by (9) at the top of next page. When $j = 1$, the channel gain in the first row in the channel matrix is reduced compared with that in a conventional receiver. On the other hand, when $j = 2$, the channel gain in the second row in the channel matrix is increased.

C. Relation to Previous Receivers

We observe that some previous receiver structures are special cases of our proposed MDR by adjusting the system's parameters and by taking into consideration the calculation of the channel matrix. For example, the proposed MDR without a mirror ($h_M = 0$) is the same as some types of conventional receivers. In Table II, we summarize the relation between the type of receiver and the corresponding system parameters.

TABLE II
RELATION TO VARIOUS RECEIVERS

Type of Receivers	System Parameters	
	Height of mirror	Incident vector of PD
Conventional receiver	$h_m = 0$	$\mathbf{r}_j = [0 \ 1]^T, \forall j$
Pyramid ADR [19]	$h_M = 0$	$\mathbf{r}_j = \mathbf{T}_M \mathbf{r}_i$
Hemispheric ADR [19]	$h_M = 0$	$-\dagger$
Pure MDR	$h_M > 0$	$\mathbf{r}_j = [0 \ 1]^T, \forall j$
Combined MDR-ADR	$h_M > 0$	$-\dagger$

$\dagger$ Any unit vectors

The Table II shows that our proposed MDR can be used with previous non-imaging receivers³. In addition, unlike LBR or SSR, our proposed receiver is designed to handle challenging issues such as sensitivity to the receiver's mobility/location and limitation of receiver size even with spatially separated PDs.

IV. PERFORMANCE ANALYSIS OF THE MIRROR DIVERSITY RECEIVER

In this section, we analyze the performance of our proposed MDR to validate its superiority over other receivers. We set the incident vector of PD to $\mathbf{r}_j = [0 \ 1]^T$. With this assumption, we note that the following identities holds: $\beta_{Mj} = \tilde{\beta}_{jj} = \beta_{ij} \triangleq \beta_j$ for $i \neq j$. For simplicity, using $A_{ji} = A$, $d_{ii} = d_{ji} \triangleq d_i$, and $\alpha_{ii} = \alpha_{ji} \triangleq \alpha_i$, the channel gain in MDR can be computed as (10) at the top of next page, where $\tilde{d}_i = \min(h_M \tan \beta_i, d_p)$ can be easily computed by manipulating (7) and defining $\tilde{d}_{ii} = \tilde{d}_{ji} \triangleq \tilde{d}_i$. As can be observed in (10), the worst-case scenario is for the conventional receiver ($h_M = 0$) to use spatial-multiplexing MIMO. This is because the transmitted intensity signals from the first and the second LEDs are scaled signals that are perfectly overlapped in the same direction vector of $[1/\sqrt{2} \ 1/\sqrt{2}]^T$ and the receiver cannot decode two signals. For simplicity, let us define the indicator function to check if the incident angle of light falls into the range of the receiver's FoV, i.e.,

$$u_i = \begin{cases} 1, & \text{if } |\beta_i| \leq \frac{\text{FoV}}{2} \\ 0, & \text{if } |\beta_i| > \frac{\text{FoV}}{2} \end{cases}. \quad (11)$$

When $\xi_i \triangleq \frac{(m+1)}{2\pi d_i^2} \cos^m \alpha_i \cos^k \beta_i u_i$ and the element of the effective active area matrix $\tilde{\mathbf{A}}$ is

$$\tilde{A}_{ji} = \begin{cases} A + (-1)^{i+j} \eta_M^{\delta_j-i} d_p \tilde{d}_i, & \text{if } 0 \leq x < x_0 \\ A + (-1)^j \eta_M^{\delta_j-2} d_p \tilde{d}_i, & \text{if } x \geq x_0 \end{cases} \quad (12)$$

the channel matrix of the MDR can be represented as

$$\tilde{\mathbf{H}} = \tilde{\mathbf{A}} \text{diag}(\xi_1, \xi_2), \quad (13)$$

where $\text{diag}(\xi_1, \xi_2)$ denotes the diagonal matrix consisting of the elements ξ_1 and ξ_2 . For a conventional receiver with $h_M = 0$, the effective active-area matrix is $\tilde{\mathbf{A}} = \mathbf{A} \mathbf{1} \mathbf{1}^T$ and the rank of the channel matrix is $\text{rank}(\mathbf{H}) = \text{rank}(\mathbf{A} \mathbf{1} \mathbf{1}^T \text{diag}(\xi_1, \xi_2)) = 1$, where $\mathbf{1}$ is a column vector with all element values equal to one. Again, this shows proves that the conventional receiver cannot support multiplexing MIMO in this worst-case scenario. On the other hand, the channel matrix at the proposed MDR ($h_M > 0$) consists of the product of two rank-two matrices of $\tilde{\mathbf{A}}$ and $\text{diag}(\xi_1, \xi_2)$. This structure can support multiplexing MIMO.

A. Channel Capacity

We now consider the channel capacity of the MIMO system with the known channel state information (CSI) at the receiver only. When the electrical signal at the transmitter is

³We investigate the compatibility between our proposed receiver and angle diversity receiver [23].

$$\tilde{h}_{ji} = \begin{cases} h_{ji} + (-1)^{i+j} \eta_M^{\delta_{j-i}} \frac{(m+1)\tilde{A}_{ji}}{2\pi d_{ji}^2} \cos^m \alpha_{ji} \cos^k \tilde{\beta}_{ji}, & \text{if } |\alpha_{ji}| \leq \frac{\pi}{2}, |\beta_{ji}| \leq \frac{\text{FoV}}{2}, |\tilde{\beta}_{ji}| \leq \frac{\text{FoV}}{2} \\ h_{ji}, & \text{if } |\alpha_{ji}| \leq \frac{\pi}{2}, |\beta_{ji}| \leq \frac{\text{FoV}}{2}, |\tilde{\beta}_{ji}| > \frac{\text{FoV}}{2} \end{cases} \quad (8)$$

$$\tilde{h}_{ji} = \begin{cases} h_{ji} + (-1)^j \eta_M^{\delta_{j-2}} \frac{(m+1)\tilde{A}_{ji}}{2\pi d_{ji}^2} \cos^m \alpha_{ji} \cos^k \tilde{\beta}_{ji}, & \text{if } |\alpha_{ji}| \leq \frac{\pi}{2}, |\beta_{ji}| \leq \frac{\text{FoV}}{2}, |\tilde{\beta}_{ji}| \leq \frac{\text{FoV}}{2} \\ h_{ji}, & \text{if } |\alpha_{ji}| \leq \frac{\pi}{2}, |\beta_{ji}| \leq \frac{\text{FoV}}{2}, |\tilde{\beta}_{ji}| > \frac{\text{FoV}}{2} \end{cases}. \quad (9)$$

$$\tilde{h}_{ji} = \begin{cases} \frac{(m+1)}{2\pi d_{ji}^2} \cos^m \alpha_i \cos^k \beta_i \left(A + (-1)^{i+j} \eta_M^{\delta_{j-i}} d_p \tilde{d}_i \right), & \text{if } |\alpha_i| \leq \frac{\pi}{2}, |\beta_i| \leq \frac{\text{FoV}}{2}, 0 \leq x < x_0 \\ \frac{(m+1)}{2\pi d_{ji}^2} \cos^m \alpha_i \cos^k \beta_i \left(A + (-1)^j \eta_M^{\delta_{j-2}} d_p \tilde{d}_i \right), & \text{if } |\alpha_i| \leq \frac{\pi}{2}, |\beta_i| \leq \frac{\text{FoV}}{2}, x \geq x_0 \end{cases}, \quad (10)$$

constrained to $E[\|\mathbf{s}\|^2] = P$ and the power is equally allocated to each LED, the channel capacity can be computed as⁴

$$C = \frac{1}{2} \log_2 \det \left| \mathbf{I} + \rho \tilde{\mathbf{H}} \tilde{\mathbf{H}}^T \right|, \quad (14)$$

where $\rho \triangleq \frac{P}{N_0}$ is the average electrical signal-to-noise ratio (SNR) per LED. Using (13), (14) can be rewritten as

$$\begin{aligned} C &= \frac{1}{2} \log_2 \prod_{m=1}^2 (1 + \rho \lambda_m) \\ &= \frac{1}{2} \log_2 \left(1 + \rho \sum_{m=1}^2 \xi_i \tilde{A}_{ii} + \rho^2 \xi_1 \xi_2 (\tilde{A}_{11} \tilde{A}_{22} - \tilde{A}_{12} \tilde{A}_{21}) \right), \end{aligned} \quad (15)$$

where λ_m denotes the eigenvalues of the channel matrix $\tilde{\mathbf{H}} \tilde{\mathbf{H}}^T$.

B. Optimal Height of a Perfect Mirror

We note that the capacity depends on the height of mirror h_M and can be maximized with optimal h_M . For analysis, we assume a perfect mirror, i.e., $\eta_M = 1$ and find the optimal height of the perfect mirror as follows. (See the Appendix A for the proof.)

Theorem 1 (Optimal Height of Mirror): The channel capacity of 2×2 MIMO-VLC two-dimensional systems with MDR and a perfect mirror is maximized with the optimal height of mirror as follows. For $0 \leq x < x_0$,

$$h_M^* \geq \frac{d_p}{\tan \beta_1}. \quad (16)$$

For $x \geq x_0$,

$$\begin{cases} h_M^* \geq \frac{d_p}{\tan \beta_1}, & \text{if } \frac{2\rho A^2 \xi_2^2}{1+2\rho A^2 \xi_2^2} \leq \frac{1}{2} \left(1 + \frac{\tan \beta_1}{\tan \beta_2} \right) \\ h_M^* = \frac{d_p}{\tan \beta_2}, & \text{otherwise} \end{cases}. \quad (17)$$

For $0 \leq x < x_0$, the capacity is maximized when the non-diagonal elements in the channel matrix become zero. In other

⁴This is the capacity formula in the classical MIMO system. The upper and lower bounds of the channel capacity in an optical wireless intensity channel are obtained in [24, Eq. (7.43)]. We note that the above capacity formula is enough to verify the performance of various receivers because 1) it is used in the previous literature (See [19], [25] and references therein performance comparison and evaluation of the optical wireless intensity channel); and 2) it is in the same form as the achievable rate formula of constant power and continuous rate adaptation optical MIMO systems in [12, Eq. (24)-(25)] with the bit error rate (BER) requirement introduced.

Fig. 2. The rotated MDR in the top view in the direction of the Y-axis; an example of the projection of reflected light and shade of the mirror on the receiver plane for the light propagation from the second LED.

words, the capacity is maximized if the light radiated from the j -th LED is perfectly blocked at the i -th PD, while its reflected intensity signals are exploited to enhance the received power at the j -th PD, and vice versa. We also note that the minimum optimal height of the mirror is dependent on the incident angle of light from the first LED, β_1 , which varies in receiver position. At $x = 0$, β_1 is the largest in the range of $0 \leq x < x_0$ and optimal h_M can be minimized, which means that an optimal MDR can be implemented practically. On the other hand, when the receiver's position becomes close at $(x_0, 0)$, β_1 approaches zero and therefore the optimal h_M approaches infinity, which means that it is practically impossible to implement an optimal MDR due to the limitation of receiver size.

For $x \geq x_0$, the channel capacity under the optimal height of the mirror depends on the condition that is related to ρ , A and β_j for $j = 1, 2$. For the fixed transmitter/receiver position, when $h_M^* \geq \frac{d_p}{\tan \beta_1}$, the channel matrix is a rank-1 matrix, while the channel matrix with $h_M^* = \frac{d_p}{\tan \beta_2}$ is a rank-two matrix. Therefore, the transmission mode can be changed as follows.

Corollary 1.1: For a fixed transmitter and receiver position under $x \geq x_0$, the multiplexing scheme is the optimal transmission mode to achieve a channel capacity in a high SNR regime, while the beamforming scheme is the optimal one in a low SNR regime.

C. Rotation of the Receiver

The receiver is not always placed as shown in Fig. 1 where two PDs are placed in parallel on the X -coordinate. As shown in Fig. 2, we consider channel gains when the receiver is rotated in the direction orthogonal to the two-dimensional coordinate. Let us define $\beta_r \in [0, \pi/2]$ as the rotated angle at the X -axis. For example, with light transmitted from the second LED, the projected areas of the light reflected in the mirror and blocked by the mirror are rotated compared with the PD planes. The effective active area of the PD plane that is affected by the reflected light and the shade is different from (12) since it depends on the rotation angle. As the rotation angle increases, the intersection between the PD plane and the projected area of the reflected light or shade decreases. In Appendix B, we derive the effective active area for a rotated MDR and then the channel matrix can be represented as follows.

Theorem 2 (Channel Matrix of a Rotated MDR): The channel matrix of two-dimensional 2×2 MIMO-VLC systems with the MDR with a rotation angle β_r is given by

$$\tilde{\mathbf{H}} = \tilde{\mathbf{A}} \text{diag}(\xi_1, \xi_2) \quad (18)$$

where $\xi_i \triangleq \frac{(m+1)}{2\pi d_i^2} \cos^m \alpha_i \cos^k \beta_i u_i$, the element of the effective active-area matrix, $\tilde{\mathbf{A}}$, is represented as

$$\tilde{A}_{ji} = \begin{cases} A + (-1)^{i+j} \eta_M^{\delta_{j-i}} \tilde{d}_i \cos \beta_r \left(d_p - \frac{1}{2} \tilde{d}_i \sin \beta_r \right), & \text{if } 0 \leq x < x_0 \\ A + (-1)^j \eta_M^{\delta_{j-2}} \tilde{d}_i \cos \beta_r \left(d_p - \frac{1}{2} \tilde{d}_i \sin \beta_r \right), & \text{if } x \geq x_0 \end{cases} \quad (19)$$

and

$$\tilde{d}_i = \begin{cases} \min \left(h_M \tan \beta_i, \frac{d_p}{\cos \beta_r} \right), & \text{if } 0 \leq \beta_r \leq \frac{\pi}{4} \\ \min \left(h_M \tan \beta_i, \frac{d_p}{\sin \beta_r} \right), & \text{if } \frac{\pi}{4} < \beta_r \leq \frac{\pi}{2} \end{cases} \quad (20)$$

As β_r increases, we know that the effective active area of the PD plane becomes similar to that of the conventional receiver since the mirror becomes less efficient in providing the constructive and destructive effect. When $\beta_r = \pi/2$, the channel matrix of the rotated MDR is the same as the conventional receiver which means that deploying the mirror is useless in this case. We evaluate the performance of a rotated MDR depending on the rotation angle in the next section.

D. Delay Spread of Reflected Light

In this paper, we assume that the transmission distance of the reflected light via a mirror is the same as that of the LoS light since the receiver size is relatively small compared to the transmission distance and two PDs are co-located. It is valid to assume the same transmission distance but not always to assume the same transmission delay for the reflected and LoS lights. As the transmission symbol duration decreases, the delay spread due to the reflected lights is significant and it might lead to the inter-symbol interference. As can be seen in Fig. 1, the transmission delay induced by the reflected light is upper-bounded by $\tau_{ub} = d_p \sqrt{2}/c$, where c is the speed of light. For instance, let us assume $d_p = 1$ mm which we will

use for simulation in the next section. The upper-bound of transmission delay is $\tau_{ub} = 4.7$ ps which is nearly $1.6E^4$ times shorter than the transmission speed (12.5 Mb/s at transmission distance 2 m) of non-imaging MIMO-VLC systems recently demonstrated in [5] and nearly $8E^2$ times shorter than that (250 Mb/s at transmission distance 40 cm) in [6]. With this current stage of the state-of-the-art MIMO-VLC systems, our proposed MDR is not vulnerable to the inter-symbol interference due to the delay spread of the reflected light. However, the transmission speed is still increasing with the development of lighting devices supporting larger modulation bandwidth. For Giga-bits non-imaging MIMO-VLC system, we take into consideration applying optical orthogonal frequency division multiplexing (OFDM) [26], [27] or equalization methods [28]–[30] to suppress the inter-symbol interference.

V. NUMERICAL RESULTS

In our performance evaluation, we consider the system model in Fig. 1 by using the parameters given in Table III. We note that we utilize a mirror with fixed height, which is not optimal at each receiver position but is practical to implement adaptively with user mobility and location. In addition, except for the mirror's parameters, we use similar system parameters as used in the simulations in [18], [19].

For comparison, we consider other MIMO-VLC non-imaging receivers, i.e., the spatially-separated receiver (SSR), the line-blocked receiver (LBR), and the angle diversity receiver (ADR). Typical system parameters for LEDs and PDs are provided in Table III.

TABLE III
SYSTEM PARAMETERS FOR SIMULATION

	Parameters	Values
LED	Locations at $(\pm x_0, y_0)$	$(\pm 2, 3)^T$
	Direction vector of irradiation in center ($\mathbf{t}_i$)	$[0 \ -1]^T$
	Semi-angle at a half power ($\Phi_{1/2}$)	60°
	Lambertian emission order (m)	1
MDR	Location at $(x, 0)$	$0 \leq x \leq 4$
	Direction vector of PD orientation ($\mathbf{r}_j$)	$[0 \ 1]^T$
	Receiver field-of-view (FoV)	180°
	FoV coefficient (k)	1
	Active area of PD (A)	1 cm^2
	Length of one side at PD plane (d_p)	1 cm
	Height of mirror (h_M)	$1 \text{ cm}^\dagger$
	Reflection coefficient of mirror (η_M)	$0.8^\ddagger$

[†]The unit of distance is meter (m).

[‡]Unless otherwise stated.

The separation between two PDs in SSR is defined as $x_s = 10$ cm and we assume that two PDs at SSR are located at the points $(x \pm \frac{x_s}{2}, 0)$. For LBR, we assume that the specific links from the i -th LED to the j -th PD for $i \neq j$ are perfectly blocked to make the channel matrix uncorrelated. Thus, we assume that non-diagonal elements of the channel matrix at LBR are zero, i.e., $h_{ji} = 0$ for all $i \neq j$. We take into consideration two types of ADR with optimized and fixed elevation angle. ADR with optimal elevation angle requires the optimization to find the angle of the PDs orientation, which we numerically obtain to maximize the channel capacity for each

Fig. 3. Channel capacity as a function of the receivers position within $0 \leq x < x_0$ in SSR, LBR, ADR, and the proposed MDR for different SNRs.

receiver position. ADR with fixed elevation angle is practically used one [9], [19] that utilizes the fixed orientation angle of 44.7° which maximizes the channel capacity at center $x = 0$. We note that ADR means ADR with optimized elevation angle unless stated otherwise.

A. Channel Capacity vs. Receiver's Position

Fig. 3 and Fig. 4 illustrate the channel capacity of a 2×2 MIMO-VLC system with various receivers with respect to the receiver position at $0 \leq x < x_0$ and $x \geq x_0$ respectively for different SNRs. Due to the small size of the active PD area, the channel gains, $\tilde{h}_{ji}$ (or h_{ji}), in the system are around 60 dB, which means that ρ should be at least 120 dB for reasonable performance.⁵ Therefore, we consider three scenarios with $\rho = 120, 140$, and 160 dB. Fig. 3 shows that the proposed MDR outperforms the existing advanced receivers at all receiver positions and SNR of interest. We can see that the constructive effect on the channel gain by receiving the reflected light further improves the system's performance compared with other receivers that utilize only the destructive effect on the channel gain by blocking the link. For $\rho = 120$ dB (low received SNR), the performance gap among our proposed MDR and the other receivers is smaller than that in the high SNR regime with $\rho = 160$ dB. We also note that our proposed MDR provides better performance even though we do not use the mirror with the optimal height but with a fixed height.

In Fig. 4, we observe that our proposed MDR provides the gain in the wider range of receiver's position over other schemes as the SNR ρ decreases. This is because the channel gain is more dominant in performance than channel correlation for low SNR regime and our proposed MDR can obtain larger channel gain by receiving the reflected light in the mirror. In Figs. 4a and 4b, the ADR with optimal elevation angle

(a) At $\rho = 160$ dB

(b) At $\rho = 140$ dB

(c) At $\rho = 120$ dB

Fig. 4. Channel capacity at the receiver's position in $x \geq x_0$ in SSR, LBR, ADR, and the proposed MDR for different SNRs.

and LBR provide better performance as the receiver's position becomes far away from the center, while both receivers require the adaptive control unit to tilt the angle of orientation or to move the obstacle according to the receiver's position. We can see that our proposed MDR outperforms the practical ADR with fixed elevation angle regardless of SNR regime and receiver's position. This is because ADR with fixed elevation angle cannot adjust the orientation angle to provide less channel correlation or larger channel gain than our proposed MDR. We emphasize that the main difference between our proposed MDR and other existing receivers comes from the mirror itself which provides both additional channel gain or better channel correlation by reflecting/blocking light. Consequently, the proposed MDR is comparable with or better than the existing receivers regardless of receiver's position and SNR

⁵We note that this operating SNR range is almost the same as in [19], [20].

regime.

B. Channel Capacity vs. Height of Mirror

In Fig. 5, we present the channel capacity of the proposed MDR with respect to the height of a perfect mirror, h_M , at different receiver positions, $x = 1$ and $x = 3$. For the arbitrarily chosen SNRs, Fig. 5 verifies the validity of Theorem 1 in describing the optimal height of a perfect mirror. As proved in Appendix A, the channel capacity is discontinuous at two points, $h_M = \frac{d_p}{\tan \beta_2} = 6$ mm and $h_M = \frac{d_p}{\tan \beta_1} = 30$ mm because the discontinuity of $\tilde{d}_1$ and $\tilde{d}_2$ makes different functions for channel capacity in different ranges of $0 \leq h_M \leq \frac{d_p}{\tan \beta_2}$, $\frac{d_p}{\tan \beta_2} \leq h_M \leq \frac{d_p}{\tan \beta_1}$, and $h_M \geq \frac{d_p}{\tan \beta_1}$. For example of $x \geq x_0$ in Fig. 5a, the channel capacity is upper-bounded at the point $h_M = \frac{d_p}{\tan \beta_2} = 6$ mm for $0 \leq h_M \leq \frac{d_p}{\tan \beta_2}$ and convex-quadratic for $h_M \geq \frac{d_p}{\tan \beta_2} = 6$ mm as explained in Appendix A. It makes a peak point at $h_M = \frac{d_p}{\tan \beta_2} = 6$ mm and the optimal height of mirror can be determined depending on ρ affecting the capacity.

We note from Fig. 5a that there exists a trade-off between the system's performance and the implementation cost (height of mirror) when $x < x_0$. We also see in Fig. 5b that the optimal height of a perfect mirror in the high SNR regime at receiver position $x = 3$ is only 6 mm smaller than d_p and it also provides nearly 0.25 [bits/channel use] higher capacity performance at $x = 1$. This means that the proposed MDR can be compactly implemented as well as perform better. In order to confirm the beneficial region of the proposed MDR, we compare it with the ADR which offers the best performance among the existing schemes in Figs. 3 and 4. For both positions, the proposed MDR provides higher capacity excepting the region where the height of perfect mirror is smaller than nearly 4 mm. The region where the MDR is superior depends on the reflection coefficient of mirror. If the reflection coefficient η_M decreases, the difference between the two schemes will be reduced and the proposed MDR requires higher mirror to compensate for the reflection loss. However, although we here use $\eta = 0.8$ for a commercial mirror, a mirror with high reflection coating can have a reflection coefficient more than 0.99. Therefore, we still implement the compact MDR which is superior to other existing non-imaging receivers.

C. Channel Capacity vs. Rotation of Receiver

Fig. 6 depicts the channel capacity of the proposed MDR with respect to the rotation angle, β_r , at the receiver positions $x = 0$ to $x = 3$ for the given $\rho = 140$ dB. We first see that the points at $\beta_r = 0$ (the MDR with no rotation) are exactly the same as the ones in Figs. 3 and 4. As expected at all positions, the larger the rotation angle, the greater the channel capacity degradation. In particular, the channel capacity is drastically decreased at the symmetric position of $x = 0$ since the MDR provides the best performance at this position but the channel correlation becomes high and the channel gains from the two LEDs to the receiver are weaker than the strongest channel gains at the asymmetric positions. As the

(a) At $x = 1$

(b) At $x = 3$

Fig. 5. Example of optimization; channel capacity of the proposed MDR as a function of height of perfect mirror for different SNRs.

rotation angle increases, the correlation of the rotated MDR becomes high and the spatial multiplexing mode does not add benefit. For comparison with the existing advanced non-imaging receiver, we also present the simulation results on ADR. First, both receivers at the rotation angle $\beta_r = 90^\circ$ have the same capacity as the conventional receiver since there is no effect of mirror in MDR and the elevation angle of ADR is optimized to be zero to maximize the capacity. We can observe that the proposed MDR outperforms ADR over entire angle of rotation when the receiver is located close to the center ($x = 0$). On the other hand, as the receiver is positioned far away from the center, i.e., at $x = 2$ and $x = 3$, the MDR is not beneficial in the mid-range of rotation angle at $x = 2$ and worse than ADR at $x = 3$. As we mentioned earlier, we utilize ADR with elevation angle optimized for the receiver position and rotation angle. Assuming ADR with fixed elevation angle (44.5° optimized for $x = 0$ and $\beta_r = 0$) as in [19], we see

Fig. 6. Channel capacity of the proposed MDR as a function of rotation angle at the receiver positions, $x = 1$ to $x = 3$, for an electrical SNR of $\rho = 140$ dB.

Fig. 7. Channel capacity of the proposed MDR at the receiver positions in X - Z coordinate for an electrical SNR of $\rho = 140$ dB.

from Fig. 6 that the proposed MDR is comparable with ADR with fixed elevation angle at $x = 2$ and $x = 3$.

D. Channel Capacity in Three-dimensional Space

Based on the analysis on the channel gain and the effect of rotation, we can calculate the channel gain of proposed MDR in the three-dimensional space. This is because the link from one LED to the receiver can be viewed as one between one LED and receiver with any rotation in the two-dimensional space. For example, let us assume the receiver located in X - Z coordinate. The channel gains from LED 1 to MDR at $(x, z) = (1, 1)$ in X - Z coordinate is the same as those at $x = 2 - \sqrt{2}$ with $\beta_r = 45^\circ$ in 2-dimensional system model. In order to evaluate the channel capacity of the proposed MDR in X - Z coordinate, we assume that i) the receiver is located on the

(a) Rate difference between proposed MDR and ADR with optimal elevation angle

(b) Rate difference between proposed MDR and ADR with fixed elevation angle

Fig. 8. Difference of channel capacity between proposed MDR and ADR at the receiver's position in 2-dimensional X - Z coordinate for SNR $\rho = 140$ dB.

X - Z plane with the same height $y = 0$ and ii) the receiver can be uniformly rotated on the X - Z plane. Therefore, we average out the channel capacity over rotation angle β_r at each receiver position to compute the average channel capacity. Due to the symmetry of X - Z plane, we only show the results for a quadrant of X - Z plane.

Fig. 7 depicts the channel capacity of proposed MDR at the different receiver position in X - Z plane for an electrical SNR $\rho = 140$ dB. The proposed MDR has an elliptic contour where it provides the highest channel capacity at the center. The channel capacity decreases faster in the direction of Z -coordinate since the receiver becomes far away from both LEDs and the channel gains decreases more than in the direction of X -coordinate.

We present in Fig. 8 the difference of channel capacity between proposed MDR and ADR in X - Z coordinate. In

Fig. 9. Schematic of the experimental setup for a 2×2 multiplexing MIMO-VLC system in a two-dimensional geometric model.

Fig. 10. The experimental setup for a 2×2 multiplexing MIMO-VLC system in a two-dimensional geometric model. Each LD is located in the left corner and the proposed MDR is placed at the right of the middle; (a) LP450-SF15 LD, (b) S120VC PD, (c) two-sided mirror, (d) TC4005 LD controller, and (e) power meter.

both subfigures, the highest rate difference appears around $(x, z) = (0, 2)$. The lowest difference appears outside the LED position, i.e., $x \geq x_0$ and the rate gain is relatively small when $x \geq x_0$. More specifically in Fig. 8a, the ADR with optimal elevation angle outperforms the proposed MDR in some of the contour for $x \geq x_0$ since it can adaptively adjust the elevation angle suitable for the receiver's position. However, the proposed MDR still outperforms the MDR with optimal elevation angle for the majority of plane and the overall performance over X - Z coordinate is better. In Fig. 8b, the proposed MDR outperforms the MDR with fixed elevation angle for all the receiver positions of interest in X - Z coordinate.

VI. EXPERIMENTAL RESULTS

In this section, we provide experimental results to validate our proposed MDR in a 2×2 multiplexing MIMO-VLC system. A schematic and actual photograph of the experimental setup are shown in Figs. 9 and 10, respectively. Two

identical Thorlabs LP-450-SF15 blue laser diodes (LDs) were used as transmitters and placed at the positions equivalent to $(0.5, 1)$ and $(-0.5, 1)$ in a two-dimensional geometric model. The two LDs were controlled by a TC4005 Benchtop Laser Diode/TEC Controller. The light beam was well diffused to cover a wide area. It fell on the receiver to enable the MIMO system. Although we used LDs rather than LEDs to generate the diffused light beam, we note that the superiority of the proposed MDR can be verified in MIMO-VLC systems with any diffused lighting source. The receiver unit consisted of two Thorlabs S120VC silicon photodiode sensors with active areas of $9.7 \times 9.7 \text{ mm}^2$ and a two-sided plane aluminum glass mirror with an estimated average reflectance in excess of 90 % in the visible wavelength range. The mirror was made by sticking the back surfaces of two commercially available mirrors together. The receiver unit was located at two coordinate positions at $(0, 0)$ and $(0.5, 0)$ to evaluate the performance depending on the receivers position. The two PDs were separated by 5 cm for all receivers except for SSR, which had 10 cm separation. The system parameters for the experiment are listed in Table IV. No optics was used to collimate or focus the laser light. All measurements were made under ambient room illumination conditions.

TABLE IV
EXPERIMENTAL SYSTEM PARAMETERS

Parameters	Values
Location of LEDs at $(\pm x_0, y_0)$	$(\pm 0.5, 1)^{\dagger}$
Direction vector of irradiation in center ($\mathbf{t}_i$)	$\mathbf{t}_i = \mathbf{d}_{ji}$
Semi-angle at a half power ($\Phi_{1/2}$)	30°
Location of PDs at $(x, 0)$	$x = 0^{\dagger}$
Direction vector of PD orientation ($\mathbf{r}_j$)	$[0 \ 1]^T$
Receiver field-of-view (FoV)	180°
Active area of PD (A)	0.94 cm^2
Length of one side at PD plane (d_p)	0.94 cm
Height of mirror (h_M)	Optimal
Reflection coefficient of mirror (η_M)	0.9

† The unit of distance is a meter (m).

The average received power on each detector from each LD is given by $\mathbb{E}[y_{ji}] = P_{R_{ji}} = h_{ji}P_{T_j} + P_{bg_j}$, where $P_{R_{ji}}$, P_{T_j} , and P_{bg_j} denote the average received power, the transmit power, and the background noise power, respectively. Given the measured $P_{R_{ji}}$ and P_{bg_j} , the experimental channel matrix, $\mathbf{H}$, is calculated as

$$h_{ji} = \frac{P_{R_{ji}} - P_{bg_j}}{P_{T_j}}, \quad (21)$$

where we operate at $P_{T_j} = 0.919 \text{ mW}$ for each LD. Then, based on the channel matrix measurement, we evaluate the bit error rate (BER) performance when the M -ary pulse amplitude modulation (PAM) is utilized at the transmitter. The analytical BER of a 2×2 multiplexing MIMO-VLC can be approximated as [31]

$$\text{BER} \approx \frac{L-1}{L} \sum_{m=1}^2 Q \left(\sqrt{\frac{6\rho\lambda_m \log_2 L}{(L-1)}} \right), \quad (22)$$

where we define $Q(x) = \frac{1}{\sqrt{2\pi}} \int_x^\infty \exp(-t^2/2) dt$. Note that the channel matrices for other receivers, such as LBR, SSR,

Fig. 11. The bit error rate as a function of the electrical SNR per LED in SSR, LBR, ADR, and the proposed MDR at position $x = 0$.

and ADR, are also measured based on the same system parameters and their BERs are calculated.

Fig. 11 depicts the BER of several non-imaging receivers at position $x = 0$. In accordance with the simulation results in the previous section, we confirm that the proposed MDR outperforms the other receivers. We observe that the proposed MDR offers almost 4 to 5 dB SNR gain over LBR and ADR. We also observe that the mirror between the PDs completely blocks the light to be received at the PD beyond it. The SNR gain of the proposed MDR over that of LBR comes from the constructive effect of the mirror by improving the channel gain from the reception of reflected light. As shown in Fig. 11, SSR with SM is not suitable for ill-condition MIMO channel due to the high correlation and we also simulated the SSR with repetition coding (RC) and 16-ary PAM to satisfy the same spectral efficiency. It can be further improved but the proposed MDR still offer nearly 12 dB SNR gain over SSR with RC.

In Fig. 12, we present the BER of the receivers at position $x = 0.5$ where the receiver is located immediately at the same position of x_0 as the first LD. For ADR, we appropriately tilt the j -th PD plane to face the j -th LD to maximize the diagonal elements in the channel matrix.⁶ Practically, this requires an alignment system in relation to the receiver's position. With this setting, the ADR provides the best performance among the non-imaging receivers. At this position of $x = 0.5$, the channel gains from the first receiver to each photodetector are sufficiently large to provide the diversity gain of RC and the performance of SSR with RC are comparable to other schemes. To verify that the mirror can be combined with other receivers to provide better system performance, we deploy the mirror between two PDs with the same setting of the orientation angle of the PD plane as the ADR. As can be seen

⁶It is different from the simulation setting in which each PD has the same orientation angle.

Fig. 12. The bit error rate as a function of the electrical SNR per LED in SSR, LBR, ADR, the proposed MDR, and combined MDR-ADR at position $x = 0.5$.

in the figure, the mirror provides almost 1.5 dB additional SNR gain.

VII. CONCLUSIONS AND FUTURE WORKS

In this paper, we proposed a new non-imaging receiver structure utilizing a double-sided mirror to enhance system performance by interfering with the reception of the light from one specific direction as well as by enhancing the reception of light from another specific direction. Our proposed MDR can further provide lower channel correlation while enhancing the channel gain itself. We analyzed and verified our proposed MDR on a two-dimensional 2×2 MIMO-VLC system by comparing it with existing non-imaging receivers. Moreover, we found the optimal height of a perfect mirror by maximizing the channel capacity of a MIMO-VLC system utilizing our proposed MDR. The effect of rotation in the proposed MDR was analyzed and investigated. Although we consider a specific MIMO-VLC system in two-dimensional geometric model, we note that our numerical and experimental results prove that the proposed MDR is a promising technique to improve the system performance.

In order to generalize our proposed MDR with multiple PDs, we can arrange our proposed MDR isotropically to obtain directivity and then place the mirrors in the middle of multiple PDs. In Fig. 13, we show examples of the proposed MDR structure with four and six PDs. Figs. 13a and 13b show an extension to a two-dimensional MDR structure by using four PDs and installing the two-sided mirror on both coordinates. In Figs. 13c and 13d, we utilize the design of the receiver structure that provides directivity in [19], [20]. This receiver geometry allows us to easily generalize the receive's structure with an arbitrary number of PDs. We can install a one-side mirror inside each PD for directivity. As we highlighted earlier, the channel matrix of MIMO-VLC systems can be well-conditioned, while maintaining the channel gain thanks

Fig. 13. Generalization of the proposed MDR with multiple PDs. Hatching lines in the figure symbolize a mirror.

to the reception of reflected light from the mirror. This is a unique feature of mirror-aided receiver different from the existing non-imaging receiver. Moreover, the proposed concept of our receiver design can be easily combined with other well-known receivers, i.e., ADR. Therefore, we expect that our proposed mirror diversity receiver remains competitive in performance if we carefully deploy the mirror in suitable position at the receiver. Analysis of the channel matrix and system performance in a general MDR model will be our next project.

Finally, we also note that our proposed MDR can be applied to various scenarios although we consider only an indoor VLC scenario in this paper. For instance, the proposed MDR might improve the system performance of a multi-user detector in multiple access (MAC) free space optical MIMO channels and underwater wireless optical MIMO channels. To achieve better performance, our proposed MDR can be easily combined with the other previous receivers without modification.

APPENDIX A PROOF OF THEOREM 1

We first consider the case for $0 \leq x < x_0$. In this case, we prove that (15) with $\tilde{d}_1 = d_p$ and $\tilde{d}_2 = d_p$, i.e., $h_M \geq \frac{d_p}{\tan \beta_1}$ is always larger than that with the other case of $\tilde{d}_j$ on $h_M < \frac{d_p}{\tan \beta_1}$. The determinant in (14) for $h_M \geq \frac{d_p}{\tan \beta_1}$ defined as $D(\tilde{d}_1, \tilde{d}_2) = \det \left[I + \rho \tilde{\mathbf{H}} \tilde{\mathbf{H}}^T \right]$ can be computed as

$$D(d_p, d_p) = (1 + 4\rho A^2 \xi_1^2)(1 + 4\rho A^2 \xi_2^2). \quad (23)$$

For $\frac{d_p}{\tan \beta_2} \leq h_M < \frac{d_p}{\tan \beta_1}$, the following inequality of the determinant holds:

$$\begin{aligned} D(h_M \tan \beta_1, d_p) &= (1 + 2\rho A^2(1 + a^2)\xi_1^2)(1 + 4\rho A^2 \xi_2^2) \\ &\quad - (2\rho A^2 \xi_1 \xi_2(1 - a))^2 \\ &< \left(1 + 4\rho A^2 \xi_1^2 \frac{1 + a^2}{2}\right)(1 + 4\rho A^2 \xi_2^2) \\ &< D(d_p, d_p), \end{aligned} \quad (24)$$

where we define $a = \frac{h_M \tan \beta_1}{d_p}$ for $\frac{\tan \beta_1}{\tan \beta_2} \leq a < 1$ in this range. Similarly, for $0 \leq h_M < \frac{d_p}{\tan \beta_2}$, we can see the following inequality holding:

$$\begin{aligned} D(h_M \tan \beta_1, h_M \tan \beta_2) &= \left(1 + 4\rho A^2 \xi_1^2 \frac{1 + a^2}{2}\right) \left(1 + 4\rho A^2 \xi_2^2 \frac{1 + b^2}{2}\right) \\ &\quad - (2\rho A^2 \xi_1 \xi_2(1 - ab))^2 \\ &< D(d_p, d_p), \end{aligned} \quad (25)$$

where we define $b = \frac{h_M \tan \beta_2}{d_p}$ for $0 \leq a \leq b < 1$ in this range. Therefore, to maximize the capacity, the optimal h_M is set to $h_M^* \geq \max\left(\frac{d_p}{\tan \beta_1}, \frac{d_p}{\tan \beta_2}\right) = \frac{d_p}{\tan \beta_1}$ so that $\tilde{d}_1 = d_p$ and $\tilde{d}_2 = d_p$.

We now consider the case for $x \geq x_0$. For $h_M \geq \frac{d_p}{\tan \beta_1}$, the determinant can be calculated as $D(d_p, d_p) = 1 + 4\rho A^2(\xi_1^2 + \xi_2^2)$. For $\frac{d_p}{\tan \beta_2} \leq h_M < \frac{d_p}{\tan \beta_1}$, the determinant is given by

$$\begin{aligned} D(h_M \tan \beta_1, d_p) &= 1 + 2\rho A^2(1 + a^2)\xi_1^2 + 4\rho A^2 \xi_2^2 \\ &\quad + (2\rho A^2 \xi_1 \xi_2(1 - a))^2. \end{aligned} \quad (26)$$

We note that $D(h_M \tan \beta_1, d_p) = D(d_p, d_p)$ for $a = 1$. (26) is a convex quadratic function of variable a . Therefore, the determinant in (26) is maximized at the end of range, i.e., $\max_a D(h_M \tan \beta_1, d_p) = \max(D(h_M \tan \beta_1, d_p)|_{a=\frac{\tan \beta_1}{\tan \beta_2}}, D(h_M \tan \beta_1, d_p)|_{a=1})$. The a -coordinate of the vertex in this function is $a_v = \frac{2\rho A^2 \xi_2^2}{1 + 2\rho A^2 \xi_2^2}$ which ranges in $(0, 1)$. (26) becomes larger as the variable a is further away from the a -coordinate of the vertex. Therefore, the following inequality holds: if $a_v \geq \frac{1}{2}\left(1 + \frac{\tan \beta_1}{\tan \beta_2}\right)$,

$$D(h_M \tan \beta_1, d_p)|_{a=\frac{\tan \beta_1}{\tan \beta_2}} \geq D(d_p, d_p),$$

while $D(h_M \tan \beta_1, d_p)|_{a=\frac{\tan \beta_1}{\tan \beta_2}} < D(d_p, d_p)$, otherwise.

For $0 \leq h_M < \frac{d_p}{\tan \beta_2}$, the determinant in this range is bounded by

$$\begin{aligned} D(h_M \tan \beta_1, h_M \tan \beta_2) &= 1 + 2\rho A^2(1 + a^2)\xi_1^2 + 2\rho A^2(1 + b^2)\xi_2^2 \\ &\quad + (2\rho A^2 \xi_1 \xi_2(b - a))^2 \\ &< 1 + 2\rho A^2(1 + a^2)\xi_1^2 + 4\rho A^2 \xi_2^2 + (2\rho A^2 \xi_1 \xi_2(1 - a))^2 \\ &< D(h_M \tan \beta_1, d_p)|_{a=\frac{\tan \beta_1}{\tan \beta_2}}. \end{aligned} \quad (27)$$

Finally, we can see the optimal $h_M^* = \frac{d_p}{\tan \beta_2}$ or $h_M^* \geq \frac{d_p}{\tan \beta_1}$ under the condition on the vertex described above.

APPENDIX B PROOF OF THEOREM 2

Here, we focus only on the derivation of $\tilde{A}_{12}$, the effective active area of the first PD shaded by the mirror for the light emitted in the second LED. Note that we can derive the other effective active areas, $\tilde{A}_{ji}$, in the same way. As shown in Fig. 2, we can see that the first PD is shaded as much as the intersection with the shade of the mirror, which is the area ACDE. Therefore, $\tilde{A}_{12}$ is calculated by subtracting the area ACDE from the area of the PD. The area ACDE is computed as

$$\begin{aligned} A_{ACDE} &= A_{ABDE} - A_{ABC} \\ &= d_p \tilde{d}_2 \cos \beta_r - \frac{1}{2} \tilde{d}_2^2 \cos \beta_r \sin \beta_r, \end{aligned} \quad (28)$$

where $\tilde{d}_2$ is the same as the line AC, which is given by

$$\tilde{d}_2 = \begin{cases} \min \left(h_M \tan \beta_2, \frac{d_p}{\cos \beta_r} \right), & \text{if } 0 \leq \beta_r \leq \frac{\pi}{4} \\ \min \left(h_M \tan \beta_2, \frac{d_p}{\sin \beta_r} \right), & \text{if } \frac{\pi}{4} < \beta_r \leq \frac{\pi}{2} \end{cases}. \quad (29)$$

Therefore, we can calculate $\tilde{A}_{12} = A - A_{ACDE}$. In the same way, we can generally calculate the effective active area as

$$\tilde{A}_{ji} = \begin{cases} A + (-1)^{i+j} \eta_M^{\delta_{j-i}} \left(d_p \tilde{d}_i \cos \beta_r - \frac{\tilde{d}_i^2}{2} \cos \beta_r \sin \beta_r \right), & \text{if } 0 \leq x \leq x_0 \\ A + (-1)^j \eta_M^{\delta_{j-2}} \left(d_p \tilde{d}_i \cos \beta_r - \frac{\tilde{d}_i^2}{2} \cos \beta_r \sin \beta_r \right), & \text{if } x \geq x_0 \end{cases} \quad (30)$$

where η_M reflects the efficiency of the mirror, which does not affect the area size but the channel gain. Finally, we can obtain the channel gain multiplied by ξ_i .

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