

Wide-FOV and High-Gain Imaging Angle Diversity Receiver for Indoor SDM-VLC Systems

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Abstract—We propose an imaging receiver (ImR) using angle diversity detectors for indoor space division multiplexing-based visible light communication (SDM-VLC) systems. Compared with a conventional ImR which utilizes vertically oriented detectors, the proposed imaging angle diversity receiver (ImADR) enjoys two main advantages, including a wider field-of-view (FOV) and higher optical gain. Both theoretical analysis and Monte Carlo simulations are carried out to evaluate the performance of the proposed ImADR in an indoor four-channel SDM-VLC system. Analytical results show that, for a target bit error rate of 10^{-3} , the proposed ImADR-based SDM-VLC system achieves 44% reduction in the transmit optical power and 130% coverage improvement than the system using a conventional ImR.

Index Terms—Visible light communication, space division multiplexing, imaging receiver, angle diversity, spatial diversity.

I. INTRODUCTION

VISIBLE light communication (VLC) using light-emitting diodes (LEDs) has attracted tremendous attention in recent years, due to its many inherent advantages such as license-free spectrum, low-cost front-ends, high security and immunity to electromagnetic interference [1]. White LEDs based VLC has many practical applications such as high-speed optical wireless communications [2], object ranging and detecting [3], and visible light networking and sensing [4]. However, the further development of high-speed VLC systems is limited by the small modulation bandwidth of white LEDs [5]. So far, many techniques have been reported to address this limitation, such as high spectral efficiency modulation schemes like orthogonal frequency division multiplexing (OFDM) [5], multiple input multiple output (MIMO) transmission [6], and so on.

In practical indoor environments, multiple white LEDs are commonly mounted in the ceiling for sufficient illumination. Therefore, it is natural to employ MIMO techniques in indoor VLC systems by exploiting the existing LEDs based lighting

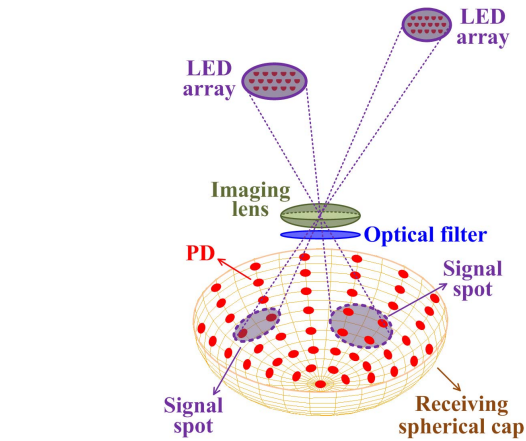


Fig. 1. Schematic diagram of the proposed ImADR.

fixtures. Since intensity modulation/direct detection (IM/DD) is used, channel matrix coefficients of MIMO-VLC systems are highly correlated, resulting in a limited multiplexing gain [7].

Recently, non-imaging angle diversity receivers (NImADRs) have been proposed to reduce the channel correlation, including an angular-segmented receiver [8], a receiver using inclined photodetectors (PDs) [9] and a pyramid or hemispherical shaped receiver [10]. Nevertheless, NImADRs can only reduce the channel correlation to a certain extent and the capacity improvement is still limited, which largely depends on the performance of the NImADR applied. As reported in [11] and [12], imaging receivers (ImRs) have the potential to fully exploit the capacity of indoor MIMO-VLC systems, since they can effectively decorrelate the multiplexed channels. Due to the negligible inter-channel interference, ImRs based MIMO is also referred to as space division multiplexing (SDM) [13]. A Gigabit/s MIMO-VLC system using a convex lens based ImR was demonstrated in [12]. However, the coverage of such a system is limited due to the small field-of-view (FOV) of the ImR. The FOV of a conventional ImR is mainly determined by the imaging lens and the size of the planar PD array [11]. In order to improve the FOV of an ImR, two advanced imaging lenses have been adopted to replace the common convex lens, including a fisheye lens [13] and a hemispherical lens [14].

In this letter, for the first time, we propose an imaging angle diversity receiver (ImADR), which is shown in Fig.1 for indoor SDM-VLC systems. By utilizing angle diversity PDs instead of vertically oriented PDs, the proposed ImADR

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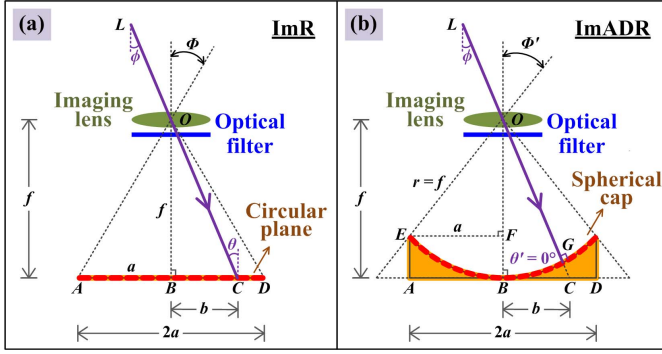


Fig. 2. Side views of: (a) a conventional ImR with vertically oriented PDs, and (b) the proposed ImADR with angle diversity PDs.

has a wider FOV and achieves higher optical gain than the conventional ImR. We evaluate the performance of the proposed ImADR in an indoor four-channel SDM-VLC system. It is revealed that, for a target bit error rate (BER) of 10^{-3} , the system using an ImADR achieves 44% reduction in the average transmit optical power and 130% improvement in the communication coverage in comparison to the system using a conventional ImR.

II. THE PROPOSED ImADR FOR INDOOR SDM-VLC SYSTEMS

The schematic diagram of the proposed ImADR is illustrated in Fig. 1. The ImADR consists of an imaging lens, an optical filter and an array of angle diversity PDs. The imaging lens is used to project the incident light from the LED arrays onto the PD array. The optical filter is used to attenuate the unwanted ambient light. Differing from the conventional ImR which has a two-dimensional circular PD array consisting of vertically oriented PDs, as shown in Fig. 2, the proposed ImADR has a three-dimensional spherical-cap-shaped PD array consisting of angle diversity PDs. Note that either a common convex lens or an advanced imaging lens such as a fisheye lens can be adopted in the proposed ImADR. In this work, a convex lens based ImADR is considered for analysis. As can be seen from Fig. 1, each of the signal spots might cover multiple adjacent PDs. To generate a final output signal from one signal spot, the optical gain between an LED chip in the LED array and a PD in the PD array can be individually calculated. Those PDs that are not illuminated by the signal light can be excluded by setting an adequate threshold level [6]. The resultant signals from the PDs that are illuminated by the signal light can be further processed to obtain a final output signal via diversity combining [15].

A. Field of View

Figs. 2(a) and (b) show the side views of a conventional ImR with vertically oriented PDs and the proposed ImADR with angle diversity PDs, respectively. In the conventional ImR, f is the focal length of the convex lens, a is the radius of the circular PD array and Φ is the half-angle FOV of the ImR.

Using the right triangle OAB , Φ is given by

$$\Phi = \tan^{-1}(AB/OB) = \tan^{-1}(a/f). \quad (1)$$

As can be seen from Fig. 2(a), the horizontal size of an ImR is determined by the diameter of the two-dimensional circular PD array. For an ImADR with the same horizontal size, as shown in Fig. 2(b), the radius of the base of the three-dimensional spherical-cap-shaped PD array in the ImADR is equal to the radius a of the circular PD array in the ImR. It is assumed that the spherical-cap-shaped PD array is centered at O and the radius of the spherical cap is $r = f$. Using the right triangle $OE'F$, the half-angle FOV of the ImADR is obtained by

$$\Phi' = \sin^{-1}(EF/OE) = \sin^{-1}(a/f). \quad (2)$$

B. Optical Gain

In typical indoor environments with LEDs lighting fixtures, the receiver can detect both the line-of-sight (LOS) and diffuse components. Here we only consider the LOS component in the analysis, because the light intensity of the LOS path is much higher than that of the diffuse paths [6]. The LOS irradiance of an LED can be modeled by a generalized Lambertian radiation pattern and the optical channel gain between the i^{th} LED array and the r^{th} PD in the PD array can be calculated by [6], [16]

$$h_{rt} = \sum_{i=1}^n \frac{(m+1)A}{2\pi d_{rti}^2} \mu \eta \cos^m(\phi_{rti}) \cos(\theta_{rti}), \quad (3)$$

where n is the number of LED chips in each LED array, $m = -\ln 2 / \ln(\cos(\Psi_{1/2}))$ is the Lambertian emission order, $\Psi_{1/2}$ is the transmitter semi-angle at half power, A is the active area of the PD, d_{rti} is the distance between the i^{th} LED chip in the t^{th} LED array and the r^{th} PD, μ and η are the gains of the optical filter and the imaging lens, respectively, ϕ_{rti} is the emission angle, and θ_{rti} is the incident angle. If θ_{rti} is outside the FOV of the receiver, the optical gain becomes zero. For both the conventional ImR and the proposed ImADR, all the parameters in (3) are the same except for d_{rti} and θ_{rti} . As shown in Fig. 2(b), the difference in the distance is denoted by CG , which is negligible in comparison to the distance between the LED array and the imaging lens. Thus, the difference in the optical gains between the ImR and the ImADR is primarily caused by different incident angles. Assuming that both the ImR and the ImADR are vertically oriented, see Fig. 2(a), the incident angle θ of the ImR is equal to the emission angle ϕ , which is given by using the right triangle OBC

$$\theta = \tan^{-1}(BC/OB) = \tan^{-1}(b/f), \quad (4)$$

where b ($0 \leq b \leq a$) is the distance between the center of the focal plane and the image of the LED chip on the focal plane. In the ImADR, as in Fig. 2(b), the incident angle $\theta' = 0^\circ$ since the spherical-cap-shaped PD array is centered at O . Substituting θ and θ' into (3) yields the optical gain of the ImR h_{ImR} and that of the ImADR h_{ImADR} , respectively. The ratio between h_{ImADR} and h_{ImR} (i.e., the optical gain improvement) is given by

$$\frac{h_{\text{ImADR}}}{h_{\text{ImR}}} = \frac{\cos(\theta')}{\cos(\theta)} = \frac{1}{\cos(\tan^{-1}(b/f))} \quad (5)$$

From the practical point of view, (5) indicates the improvement in the received optical and electrical power levels.

III. BER ANALYSIS

In this section, we derive the analytical BER expression for an indoor SDM-VLC system using the proposed ImADR. Since OFDM is a spectral efficient modulation scheme, it is a very promising option for bandwidth-limited VLC systems [5], [12]. We consider that N independent OFDM signals are modulated onto N LED arrays, respectively, which are transmitted in the free space and received by a PD array. It is assumed that there are N signal spots on the PD array, corresponding to N LED arrays [11]–[13]. Moreover, the j^{th} ($1 \leq j \leq N$) spot covers k adjacent PDs. Following [15], the signal-to-noise ratio (SNR) at the output of the i^{th} PD in the j^{th} spot can be calculated by

$$SNR_{ij} = \frac{(R\gamma P_{rx,ij})^2}{\sigma_{tot,ij}^2}, \quad 1 \leq i \leq k, \quad (6)$$

where R is the responsivity of the PD and γ is the modulation index. $P_{rx,ij} = h_{ij} P_{tx}$ is the average received optical power, where h_{ij} is the optical gain between the i^{th} PD and the j^{th} LED array, and P_{tx} is the average transmit optical power of the j^{th} LED array. $\sigma_{tot,ij}^2$ is the total additive noise including both shot and thermal noises, i.e., $\sigma_{tot,ij}^2 = \sigma_{shot,ij}^2 + \sigma_{thermal,ij}^2$ [16].

Since k output signals can be obtained from the k adjacent PDs in the j^{th} signal spot, diversity combining techniques can be adopted to re-generate the final output signal. Here two diversity combining techniques are considered, which are the select-best combining (SBC) and the maximal-ratio combining (MRC) [15]. In SBC, a PD in the PD array with the highest SNR is selected with the SNR given by

$$SNR_{SBC,j} = \max_i \left\{ \frac{(R\gamma P_{rx,ij})^2}{\sigma_{tot,ij}^2} \right\} = \max_i \{SNR_{ij}\}. \quad (7)$$

In contrast, in MRC, all the k output signals are used by setting the weight $w_{ij} = R^2 \gamma^2 P_{rx,ij}^2 / \sigma_{tot,ij}^2$ [15], thereby maximizing the SNR, which is obtained by

$$\begin{aligned} SNR_{MRC,j} &= \frac{\left(\sum_{i=1}^k w_{ij} R\gamma P_{rx,ij} \right)^2}{\sum_{i=1}^k w_{ij}^2 \sigma_{tot,ij}^2} \\ &= \sum_{i=1}^k \frac{(R\gamma P_{rx,ij})^2}{\sigma_{tot,ij}^2} = \sum_{i=1}^k SNR_{ij}. \end{aligned} \quad (8)$$

The BER expression for the j^{th} channel OFDM signal using $I \times J$ rectangular QAM mapping can be approximated by [17]

$$\begin{aligned} BER_j &= \frac{2}{\log_2(I \times J)} \left(\frac{I-1}{I} + \frac{J-1}{J} \right) \\ &\quad \times Q \left(\sqrt{\frac{6 \times SNR_j}{I^2 + J^2 - 2}} \right), \end{aligned} \quad (9)$$

where $Q(\cdot)$ is the Q-function. Substituting (7) and (8) into (9) yields the BER of the j^{th} channel OFDM signal using SBC and MRC, respectively. Therefore, for the N -channel

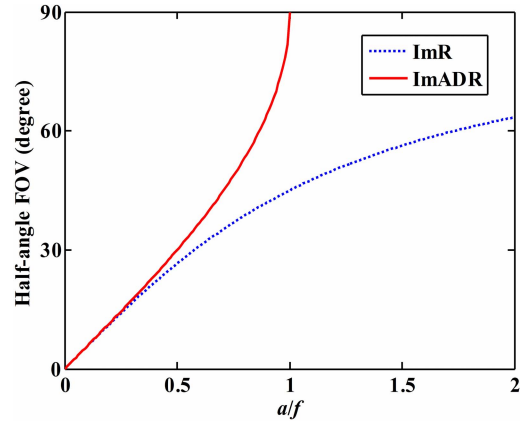


Fig. 3. Half-angle FOV versus a/f for ImR and ImADR.

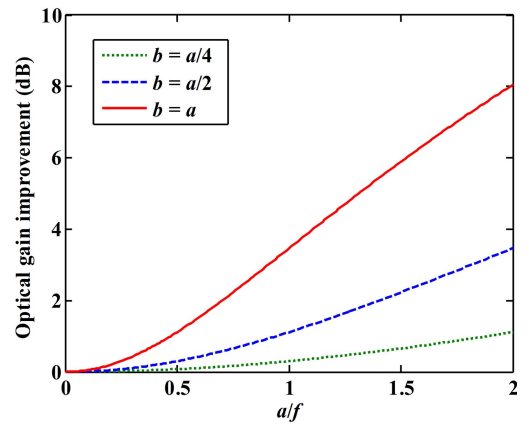


Fig. 4. Optical gain improvement in dB versus a/f for a range of b .

SDM-VLC system, the average BER is given by $BER_{av} = \frac{1}{N} \sum_{j=1}^N BER_j$.

IV. RESULTS AND DISCUSSIONS

We consider a four-channel SDM-VLC system in an indoor environment with a dimension of $5\text{m} \times 5\text{m} \times 3\text{m}$, where four LED arrays, each with two LED chips, are mounted in the ceiling. We assume each signal spot covers two PDs and each PD has an active area of 1cm^2 . The other parameters are the same as given in [16, Table 1]. Four independent 16-QAM ($I = J = 4$) OFDM signals each with a 50 MHz bandwidth are transmitted and the total data rate of the system is 800Mb/s.

Fig. 3 shows the relationship between the half-angle FOV and the ratio a/f for both ImR and ImADR, with the latter achieving a much larger FOV than the former. For example, at $a/f = 1$, the half-angle FOVs are 45° and 90° for the ImR and the ImADR, respectively. Moreover, to achieve the same FOV of 60° , the required values for a/f are 1.73 and 0.87 for the ImR and ImADR, respectively. Hence, $\sim 75\%$ reduction in the horizontal area of the receiver is achieved by using ImADR in comparison to ImR. Fig. 4 displays the relationship between the optical gain improvement and a/f . It can be seen that the optical gain improvement increases with a/f . For $b = a/2$, a 3 dB improvement is achieved when a/f is 1.8.

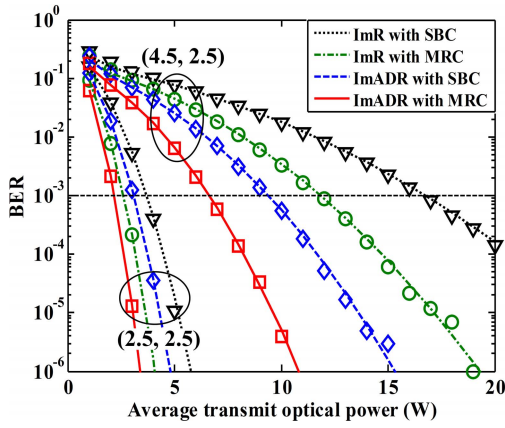


Fig. 5. BER versus average transmit optical power. Markers and lines show the simulation and analytical results, respectively.

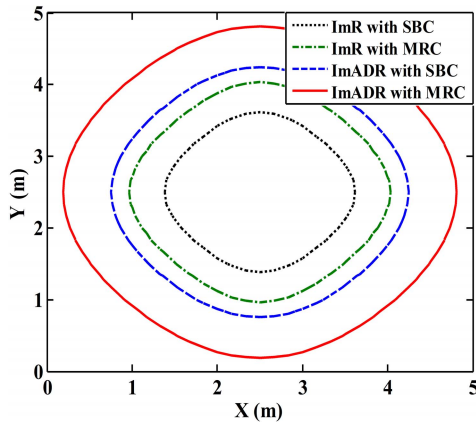


Fig. 6. Communication coverage comparison for a target BER of 10^{-3} with an average transmit optical power of 8 W.

Moreover, the optical gain improvement also increases with b . An optical gain improvement of 8 dB is achieved for $a/f = 2$ when $b = a$.

Based on the analytical formulae obtained in Section III, we evaluate the BER performance of the four-channel SDM-VLC system. Monte Carlo simulations are performed to verify the analytical results. Fig. 5 depicts the relationship between the BER and the average transmit optical power, showing a good agreement between predicted and simulated results. For a receiver location (2.5, 2.5), i.e., the center of the receiving plane, the MRC based system requires lower optical power than the SBC based system. With the receiver moved to the location (4.5, 2.5), the required optical powers for MRC based ImR and ImADR are 11.8 W and 6.6 W, respectively. Hence, a power reduction of about 44% is achieved by using the ImADR.

Fig. 6 compares the communication coverage (contours) over the receiving plane for a target BER of 10^{-3} with an average transmit optical power of 8 W. The coverage contours can be approximated as circles and the coverages are estimated by the areas of the circles. It can be seen that MRC outperforms SBC, and ImADR with MRC achieves the largest coverage. ImR with MRC attains a coverage diameter

of 3.1 m whereas ImADR with MRC attains a coverage diameter of 4.7 m, thus resulting in a coverage improvement of about 130%.

V. CONCLUSION

We have proposed a novel wide-FOV and high-gain ImADR for indoor SDM-VLC systems. Either a common convex lens or an advanced imaging lens such as a fisheye lens can be adopted in the ImADR. Our analytical and simulation results showed that for a target BER of 10^{-3} , a four-channel SDM-VLC system using the proposed ImADR achieved 44% reduction in the transmit optical power and 130% improvement in the communication coverage than the system using a conventional ImR. Therefore, the proposed ImADR is a promising candidate for high-speed indoor SDM-VLC systems.

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