A Numerical Study on Optical Concentrators for Visible Light Communications

Pituk Panthong[1,2], Paramin Sangwongngam[2], Jutaphet Wetcharungsri[2], Keattisak Sripimanwat[2], Adisorn Kaewpukdee[3], Piya Kovintavewat[3], Lunchakorn Wuttisittikulkij[4]

[1]Department of Physics, Faculty of Science, Kasetsart University, Bangkok, Thailand

[2]National Electronics and Computer Technology Center, NSTDA, Pathum Thani, Thailand

[3]Telecommunications Engineering Program, Faculty of Science and Technology, Nakhon Pathom Rajabhat University, Nakhon Pathom, Thailand

[4]Department of electrical Engineering, Chulalongkom University, Bangkok Thailand

pituk.panthong@gmail.com

Abstract

Optical design has played a key role in the optical wireless communications since it can enhance the gains and the fields of view (FOVs) of the receivers without power consumption. In this paper, we propose an optical front end which is comprised of a multiple-radius concave mirror, lens, and a detector so as to enlarge coverage areas of the optical wireless access point for an indoor scenario. The numerical investigation into performance of the proposed and the conventional optical concentrators has been conducted and presented. From the numerical studies, it is clear that although the proposed concentrator offers a smaller gain, it provides a significantly larger FOV in the indoor environment, resulting the substantially large coverage areas. As the proposed optical front end facilitates the ease of the manufacture and the broad coverage, its deployment at the uplink could reduce the installation cost.

Keywords: optical antenna, concentrator, concave mirror, optical wireless communications, visible light communications, LED.

1. Introduction

In optical wireless communications, the major components encompass a sender is mainly an LED bulb connected with electronics circuit and a receiver principally includes a photodetector of a considerable photosensitive value and a wide FOV. Generally, their design is rather impractical to implement due to its cost and weight.

Last one is holographic mirror that was propose in 2001 [1] and 2002 [2]. It was compounded from concave mirror to gather light signal together with holographic plate as filter, consequently it is filter and antenna simultaneously, and small size. However, its efficiency to amplify signal is less, when light approach on near field of view boundary, where field of view is narrow (about 10 degree).

Another one is optical pyramidal fly-eye diversity receiver was proposed in 2003 [3] for indoor wireless communication, which plan for receive signal in wide field, whereas it has few amplification, otherwise using lens to enhance that has large size.

In [4] and [5], to obtain a large FOV, In [4] introduced an imaging receiver based on a hemispherical lens and showed that the receiver can distinguish the light coming from various directions in a MIMO system. In [5] introduced a receiver based on many prisms arranged circularly around a common center directions in a MIMO system. Both in systems where need to use multiple photodetector.

In this work, we present the impact of signal reflections on the performance of an optical receiver module in a room indoor environment. In addition, we propose the optical gain and power under several receivers. Two types of the receivers are analyzed and compare for communication. The optical receiver consists of a group of lens and a group with concave mirrors.

The remainder of this paper is organized as follows. Section 2 describes an analog front-end part of the indoor visible light communication link and revisits some principles of illumination that are related to this study. In Section 3, important issues of practical optic system are studied and discussed. Section 4 solves simulation results. Conclusions are drawn in Section 5.

2. Background

The background of the VLC system and theory of concentrator are described in details.

A. System description

To design the VLC system, we consider a typical of a small room. A room is assumed for the objective of these analyzed, the room size is 5m × 5m × 3m with four LED lighting. A distance from the ceiling to the work area is 2.15 m. The four LED arrays are equally installed on the ceiling at (1.25, 1.25), (1.25, 3.75), (3.75, 1.25), (3.75, 3.75). The order of Lambertian emission (m) defied

$$m = -\ln 2 / \ln(\cos(\Phi)) \quad (1)$$

where Φ is the semiangle at half illuminance of an LED.

In this model, we consider the LOS component directly from an LED sources to the receiver. The ray entering are detected only in the FOV of the receiver. The rays of light hit the walls are reflected to the receiver. This modeling scheme which considered only the LOS and the first reflections from the wall, as shown in Fig. 1.

Each LED is a source with a Lambertian radiation pattern. The channel DC gain on directed path is given as

$$H_{\mathrm{d}}(0)= \begin{cases} \frac{A_{\mathrm{r}}(m+1)}{2\pi d^2}\cos^m(\emptyset)T_S(\Psi)g(\Psi)\cos(\Psi)\,; & 0\leq\Psi\leq\Psi_{\mathrm{c}} \\ 0; & \text{elsewhere} \quad \Psi>\Psi_{\mathrm{c}} \end{cases} \quad (2)$$

where A_{r} is the area of an optical detector, d is a distance between LED and a detector, m is the Lambertian index of the LED, $\emptyset$ is the irradiance angle, Ψ is the incidence angle, Ψ_{c} is the FOV, $T_{\mathrm{S}}(\Psi)$ is the gain of optical filter, $g(\Psi)$ is the optical concentrator gain.

The DC channel gain of the first reflection is given by

$$H_{\mathrm{ref}}(0)= \begin{cases} \frac{A_{\mathrm{r}}(m+1)}{2(\pi d_1 d_2)^2}\rho\, dA_{\mathrm{wall}}\cos^m(\emptyset_{\mathrm{r}})\cos(\alpha_{\mathrm{r}}) \\ \times\cos(\beta_{\mathrm{r}})\,T_{\mathrm{S}}(\Psi)g(\Psi)\cos(\Psi)\,; & 0\leq\Psi\leq\Psi_{\mathrm{c}} \\ 0; & \text{elsewhere} \quad \Psi>\Psi_{\mathrm{c}} \end{cases} \quad (3)$$

where d_1 is distance between LED and a reflective point, d_2 is distance between a reflective point and a receiver. ρ is the reflectivity, dA_{wall} is a reflective area of a small region, $\emptyset_{\mathrm{r}}$ is the irradiance angle to a reflective area, α_{r} is the incidence angle to a reflective point, β_{r} is the irradiance angle to the receiver, Ψ is the incidence angle of the reflective surface, Ψ_{c} is the FOV, $T_{\mathrm{S}}(\Psi)$ is the gain of optical filter, $g(\Psi)$ is the optical concentrator gain.

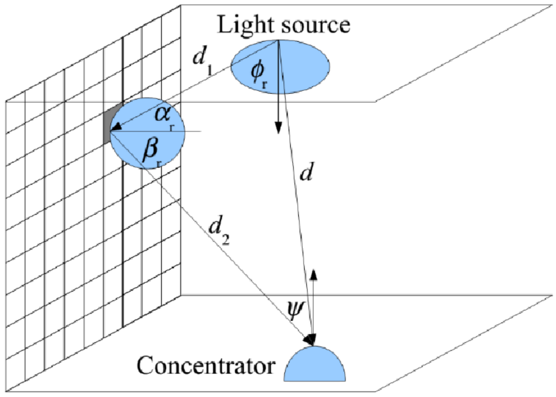


Fig. 1. Model of diffused link.

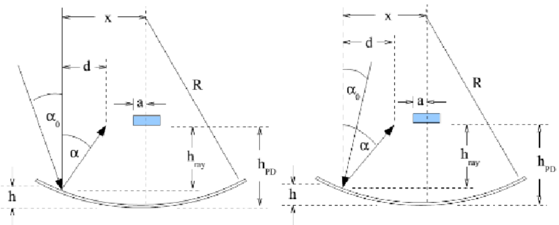
We can calculate the total optical power P_{R} received by the photodetector by integrating over all the points for which the light rays pass through all optical component and fall into the surface of the photodetector. The received optical power at the receiver therefore becomes

$$P_R = \sum_{\mathrm{LEDs}}\{(H_{\mathrm{d}}(0) + H_{\mathrm{ref}}(0))P_{\mathrm{t}}\} \quad (4)$$

where P_{t} is optical transmit power.

B. Conventional optical antenna: concave mirror

The concave mirror antenna consists of the concave mirror and the photodetector, as shown in Fig. 2.



(a) (b)

Fig. 2. (a) the light incident approached on the photodiode (b) the light incident out from PD but reflected to the PD.

When the reflection ray in Fig. 2 is considered, the horizontal distance d between the incident point and the point where the ray reaches the height of the photodiode (PD) can be calculated by

$$\tan\alpha = \frac{d}{h_{\mathrm{ray}}}$$
$$d = \left(h_{\mathrm{PD}} - R + \sqrt{R^2 + x^2}\right)\tan(\alpha_0 + 2x/R) \quad (5)$$

where α_0 denotes the angle of incidence, α is the angle of reflection, h_{ray} is the vertical distance from the incident point to the PD, R is the radius of the mirror curvature, and x is the horizontal distance from the incident point to the PD.

The ambient light radiant flux at the receiver is

$$\Phi_s(\phi) = \int_{r=0}^{r} \int_{\psi=0}^{2\pi} E_s \frac{r}{\sqrt{1-(r/R)^2}} \cos\phi \, d\psi dr$$

$$\Phi_s(\phi) = E_s A_{\text{eff}}(\phi) \quad (6)$$

where E_s is the signal irradiance, A_{eff} is effective area, $\emptyset$ is the irradiance angle, r is a mirror radius.

3. The proposed optical concentrator

The problem of the concave mirror system is that the photodetector cannot receive the sufficient ray of the light incident. Therefore, we propose the modified passive optical module for the indoor VLC receiver into which an optical concave mirror with multiple curvature radii and the lens are incorporated as shown in Fig. 3. For sake of simplicity, the proposed optical module can be also cited within this article as the concentrator.

The proposed concentrator consists of six lens, posing in a horizontal plane to narrow the incident rays. The light was incident to the concave mirror after been refracted by lens. The concave mirror has a three cases radius of curvature and tilt. In the first case, the light is incident in the vertical to the concave mirror, we will align the light incident to the radius curved R2 (Mirror2). In the second case, the light is incident to the center of the concave mirror, we will align the light incident to the flat mirror (Mirror1). In the last case, the light is incident out from the center of the concave mirror, we will align the light incident to the radius curved R3 (Mirror3). The optical concentrator has six Mirror3. The inclination angle of the Mirror3 is α into the center of this device. The radius of Mirror1 Mirror2 and Mirror3 is r1 r2 and r3 respectively.

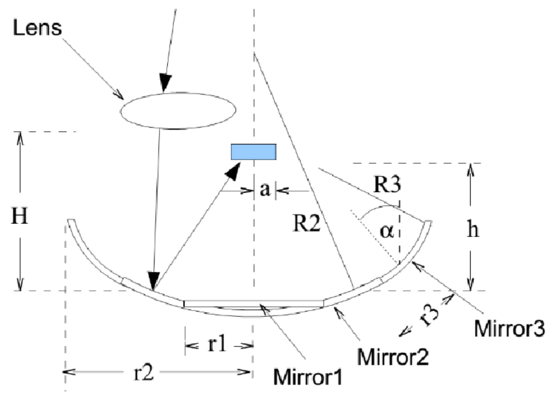


Fig.3. Side view of the proposed optical concentrator.

The signal radiant flux of the proposed optical concentrator is

$$\Phi_s(\phi) = \int_{r=0}^{r_1}\int_{\psi=0}^{2\pi}\int_{S_0} E_s T(\phi)\cos\theta \, dS \frac{r}{\sqrt{1-(r/R)^2}} d\psi dr + \int_{r_1}^{r_2}\int_{\psi=0}^{2\pi}\int_{S_0} E_s T(\phi)\cos\theta \, dS \frac{r}{\sqrt{1-(r/R)^2}} d\psi dr + \int_{r=0}^{r_3}\int_{\psi=0}^{2\pi}\int_{S_0} E_s T(\phi)\cos\theta \, dS \frac{r}{\sqrt{1-(r/R)^2}} d\psi dr \quad (7)$$

where ϕ is the irradiance angle to the lens, θ is the irradiance angle from the lens to a mirror, $T(\phi)$ is the transmission coefficient of lens, S_0 is a surface area of the lens.

The gain of the optical concentrator at the receiver is defied by

$$Gain(\phi) = A_{\text{eff}}(\phi)/A\cos(\phi) \quad (8)$$

where A is photodiode area, ϕ is the angle of incidence

4. Simulation results and Discussion

In this section, the comparative performance results in terms of the gain and the received power between the traditional and the proposed concentrators, in the indoor environment, was provided and discussed accordingly. The room walls have been divided into equal square reflection elements with a dA_{wall} of 25 cm × 25 cm. The optical transmit power per LED module is 72 W, the area of an optical detector is 1×10^{-4} m^2, the reflectivity of the wall is 0.8, the semi-angle at half illuminance of an LED is 70.

Fig. 4 shows the optical gain from simulations for the concave mirror and the optical concentrator versus angle of incidence is given in (8). It can be observed that the maximum optical gain is the result from the concave mirror but the gain decreased rapidly (for the mirror used in the simulation the FOV was 10). The result show that FOV of optical concentrator is 42.

Fig. 5 shows the power for the concave mirror receiver on the room floor in term of dB is given in (4). The power receiver from the receiver is very narrow. It is not suitable for use.

Fig. 6 shows the power for the proposed optical concentrator on the room floor is given in (4). The power distribution of the optical concentrator in the room is widely more than the concave mirror.

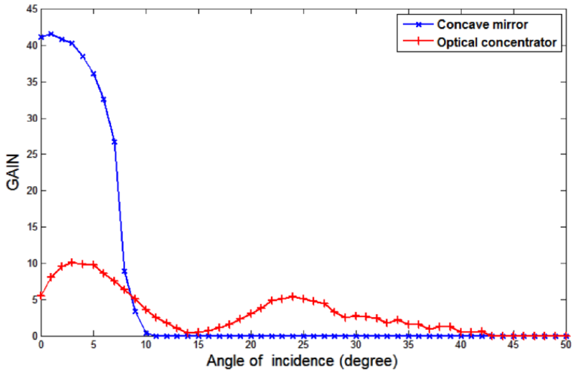


Fig. 4. Gain for the concave mirror receiver and the optical concentrator.

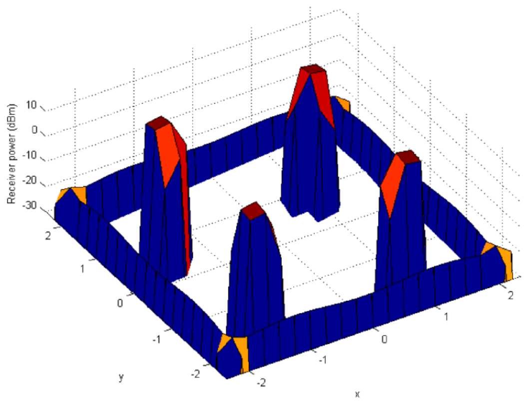


Fig. 5. Power for the concave mirror receiver on the work area.

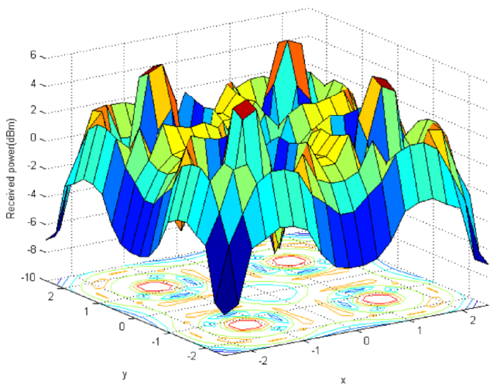


Fig. 6. Power for the optical concentrator on the on the work area.

5. Conclusion

Overall, this paper presents the numerical study of our modified optical concentrator, aiming at indoor VLC applications. Based on the numerical results, the proposed optical concentrator is superior to the conventional single concave mirror system in terms of the field of view (FOV) and the coverage area because of employing the multiple mirrors with different radii for adjusting the direction of the incoming light in order to reach the small-area photodetector.

Acknowledgment

This work was supported under a National Research Council of Thailand (NRCT) (project number 159523).

References

[1] S. Jivkova, and M. Kavehrad. "Holographic optical receiver front end for wireless infrared indoor communications." Applied optics 40, no. 17, pp. 2828-2835, 2001.

[2] S. T.Jivkova, S. Shurulinkov, and M. Kavehrad. "Holographic parabolic mirror as a receiver optical front end for wireless infrared communications: experimental study." Applied optics 41, no. 28, pp. 5860-5865, 2002.

[3] A. G. Al-Ghamdi, and J. M. H. Elmirghani. "Performance evaluation of a triangular pyramidal fly-eye diversity detector for optical wireless communications." Communications Magazine, IEEE 41, no. 3, pp. 80-86, 2003.

[4] T. Q. Wang, Y. A. Sekercioglu, and J. Armstrong, "Analysis of an optical wireless receiver using a hemispherical lens with application in MIMO visible light communications," IEEE/OSA J. Lightw. Technol., vol. 31, pp. 1744-1754, June 2013.

[5] T. Q. Wang, & J. Armstrong. "Performance of indoor MIMO optical wireless system using linear receiver with prism array." In Communications Theory Workshop (AusCTW), 2014 Australian, pp. 51-56, IEEE, 2014.