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Effects of Incident Angle and Distance on Visible Light Communication

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***Abstract*—**Visible Light Communication (VLC) provides wireless communication features in illumination systems. One of the key applications is to recognize the user location by indoor illuminators such as light emitting diodes. For localization of individual receivers in these systems, we usually assume that receivers and transmitters are placed in parallel. However, it is difficult to satisfy this assumption because the receivers move randomly in real case. It is necessary to analyze the case when transmitter is not placed perfectly parallel to receiver. It is also important to identify changes on optical gain by the tilted angles and distances of them against the illuminators. In this paper, we simulate optical gain for various cases where the tilt of the receiver and the distance change. Then, we identified changing patterns of optical gains according to tilted angles of a receiver and distance. These results can help many VLC applications understand the extent of the location errors with regard to optical gains of the receivers and identify the root cause.

***Keywords*—**Visible light communication, optical channel, indoor positioning, Lambertian radiation.

I. INTRODUCTION

THE IoT is the internetworking of devices, building, vehicle and other things, which embedded with electronics, software, sensors, actuators, and network connectivity that enable these objects to collect and exchange data [1]. It has rapidly evolved from the convergence of wireless communication technologies, including VLC. For this reason, VLC has been actively researched along with advantages of Light Emitting Diode (LED). LED have been widely used because of lifetime, eco-friendliness, and lighting efficiency. Furthermore, LEDs can also be easily modulated by current drivers. This is advantageous when configuring communication systems using LEDs. Because of that, LED can be used for both lighting and wireless communication at the same time [2]. Recently, many promising applications based on VLC have been studied. In particular, some applications to note are location-based services via indoor positioning [3].

Indoor location-based services become more important as increasing indoor activities. Because Global Positioning System (GPS) cannot be used inside a building, over the past few decades, indoor positioning techniques rely on radio frequencies like RF-ID, infrared, ultrasound, etc. However, these techniques have limitations such as additional infrastructure, low accuracy, electromagnetic interference, low security, and long response time [4]. For such reasons, indoor positioning though VLC has recently studied as competitive alternatives. Especially, it needs no extra equipment for deployment.

In the case of VLC, trilateration and angulation are typically used as indoor positioning methods. The trilateration method estimates the target location by getting distances between target and multiple reference nodes with known coordinates [5]. On the other hand, the angulation method estimates the target location by getting angle between target and multiple reference nodes [6]. Generally, the distance and angle can be measured via Received Signal Strength (RSS) [5]-[8].

Many VLC studies have applied RSS to optical channels. These optical channels have been well studied and modeled for various cases [7]. Of these various channel models, most VLC applications mainly use the channel model in the case when the illuminance of LED follows the Lambertian radiation pattern at Line of Sight (LoS) condition. In this case, some of studies assumed that a transmitter, especially LED, is placed in parallel to a receiver [2], [3]. However, this assumption is not valid for real-world applications where the receivers should be consistently movable in uncontrolled ways. If this assumption is not valid, the accuracy and reliability of indoor positioning decrease obviously. To compensate this error, the effects of tilting should be studied in the case that transmitter is not placed perfectly parallel to receiver. Furthermore, characteristic of received optical gains is affected by distance from transmitter to receiver. Thus, it is necessary to analyze many cases including a variety of the incident angle and distance.

In this paper, we conducted simulations of optical gain depending on incident angle, distance and both based on mathematical analysis. The optical channel is modeled in the case when the illuminance of LED follows the Lambertian radiation pattern on the Line of Sight (LoS) condition. We identify patterns of optical gains by several tilted angles of a receiver. Then, we compared them to the optical gain assuming that the transmitter is placed in parallel to a receiver.

II. OPTICAL CHANNEL MODEL

Almost VLC applications which are used for indoor positioning generally apply RSS method to optical channel, especially optical DC gain. This optical DC gain relates the transmitted and received average powers, and it can be obtained from the frequency responses of optical channels [7]. Fig. 1 describes the optical channel model on the LoS condition. In this optical channel model, the channel dc gain $H(0)$ can be calculated as [7]

$$H(0) = \frac{(m+1)A}{2\pi d^2}\cos^m\phi\cos\psi\, T_s(\psi)g(\psi)rect(\frac{\phi}{FOV}) \quad (1)$$

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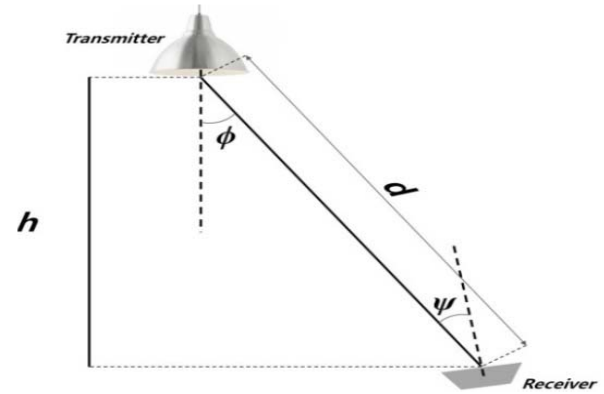

Fig. 1 Optical channel model on the LoS

where A is the detector physical area, ϕ and ψ are radiation angle and incidence angle with respect to the transmitter and receiver, respectively. The order m is related to $\phi_{1/2}$, which is the transmitter half angle, defined by $m = -\ln 2 / \ln(\cos \phi_{1/2})$. $rect(x)$ is the rectangular function defined by $rect(x) = 1$ for $|x| \leq 1$, otherwise $rect(x) = 0$. If the Field of View (FOV) of receiver is large enough so that $0 \leq \phi \leq$ FOV always satisfied, then $rect(\frac{\phi}{FOV})$ is always 1 at (1). Lastly, $T_s(\psi)$ is the optical gain of the filter, $g(\psi)$ is the concentrator gain. $T_s(\psi)g(\psi)$ is modeled together by using Lambertian property and expressed as [8]

$$T_s(\psi)g(\psi) = \cos^n \psi \tag{2}$$

where the order n is given by $n = -\ln 2 / \ln(\cos \psi_{1/2})$. $\psi_{1/2}$ is the half angle of the receiver. By substituting (2), (1) can be expressed as

$$H(0) = \frac{(m+1)A}{2\pi d^2} \cos^m \phi \cos^{n+1} \psi \tag{3}$$

In this model, some studies assume the axes of transmitter and receiver to be perpendicular to the ceiling, which gives [3]

$$cos\, \phi = \cos \psi = h / d \tag{4}$$

It means incidence angle only depends on height and distance. Then, (3) can be simplified into (5) by substituting (4).

$$H(0) = \frac{(m+1)Ah^{m+n+1}}{2\pi d^{m+n+3}} \tag{5}$$

From (5), the distance d between the transmitter and the receiver can be expressed as

$$d = \sqrt[m+n+3]{\frac{(m+1)Ah^{m+n+1}}{2\pi H(0)}} \tag{6}$$

In (6), the variables except $H(0)$ are determined by characteristics of transmitter and receiver. Accordingly, we can estimate distance via getting $H(0)$. This $H(0)$ can be calculated by considering the ratio of the received power to the transmitted power. However, the distance calculated from (6) is far different from real distance when the transmitter is not placed in parallel to the receiver. That is because (4) is not satisfied. The more receiver tilts, the larger error would be expected.

III. Results and Discussion

To compensate the errors caused by tilting, the effect of tilting should be studied for various cases by using simulation and experiment. Simulations are conducted in both cases whether the assumption is valid or not.

A. Effect of Incidence Angle

In order to simulate the effect of incidence angle, let the transmitter and the receiver to be on a straight line. Then we can eliminate incidence angle transition caused by horizontal distance. The received optical gains are calculated while rotating the receiver. The simulation result is shown in Fig. 2. In the simulation, the half angle of transmitter $\phi_{1/2}$ is set to 45°, the half angle of receiver $\psi_{1/2}$ is set to 30°, and FOV of receiver is set to 60°.

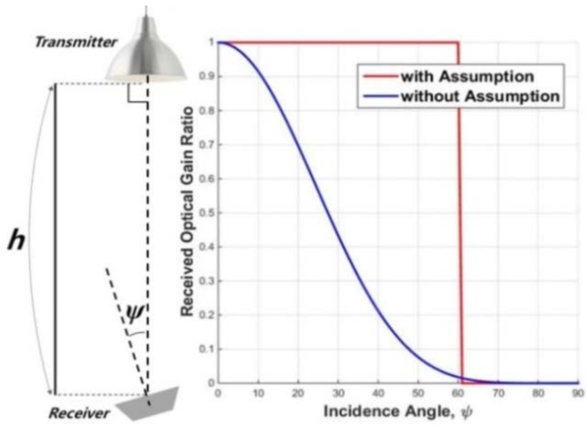

Fig. 2 Received optical gain according to incidence angle

In Fig. 2, the received optical gain in real case decreases significantly from when the receiver tilts over more than 10°, even if the receiver tilts not over the half angle of receiver. On the other hand, without considering the tilting of receiver, the gain is always same until it reaches FOV of the receiver. That is because incidence angle is not considered. Those studies, which assume that a transmitter is placed in parallel to a receiver, replace all expressions of incidence angle with expressions of height and distance like as (6). However, during the conversion some characteristics are missing. Particularly in this simulation situation, the optical gain of the filter $T_s(\psi)$ and the concentrator gain $g(\psi)$ are missing. As we can see in (2), if incidence angle is fixed, $T_s(\psi)g(\psi)$ is a constant value. These missing characteristics make the difference seriously. It can deteriorate reliability and accuracy of the VLC applications which use RSS.

B. Effect of Distance

After checking the effect of incidence angle, the effect of distance between a transmitter and a receiver should also be identified. If the receiver is not tilted and only the distance is changed, the existing assumption could be considered valid. Of course, as we said before, there should be no missing characteristic. In this condition, radiation angle is same as incidence angle. If the height is fixed, the incident angle increases as the distance increases. So when distance is gradually changed, this transition of distance can be expressed by the transition of incidence angle. The simulation result is shown in Fig. 3 where the constants of simulation are same as before simulation. In this simulation, we assume the axes of transmitter and receiver to be perpendicular to the ceiling. A simulation regarding the case when the assumption is not valid is presented in the next section.

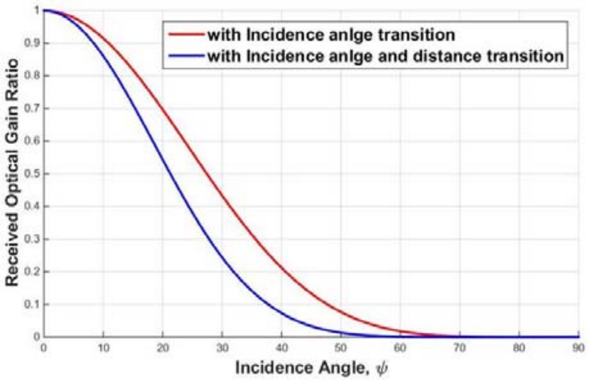

Fig. 3 Received optical gain according to distance

In Fig. 3, we compared the case when distance varies and the case when incidence angle varies. By comparing these two graphs, the effect of distance transition can be identified. Differences between two cases exist in radiation angle and distance. When distance increases, radiation angle also increases, but it reduces $H(0)$. Because, in (3), an increase of radiation angle ϕ makes $\cos^m \phi$ smaller. Of course, an increase of distance also makes $H(0)$ smaller. However, the effect of the angle of incidence seems to be more dominant in Fig. 3. The reduction of $H(0)$ due to the increase of the incidence angle is larger than the reduction of $H(0)$ due to the increase of the distance and the increase of the radiation angle. It is mainly because half angle of receiver $\psi_{1/2}$ is generally smaller than half angle of transmitter $\phi_{1/2}$. The order m is 2 and the order n is 4.888 when $\phi_{1/2}$ is set to 45° and $\psi_{1/2}$ is set to 30°. So the amount of decrease due to the incident angle is dominant in (3). Conversely, if we use the transmitter which has smaller half angle than the half angle of receiver, the effect of distance transition is more dominant.

C. Effect of Both Incidence Angle and Distance

In this section, we conduct simulation regarding the case for tilted receiver when the receiver and the transmitter are not positioned in a straight line. Fig. 4 describes the simple simulation model. In this model, the height is fixed to 1 m.

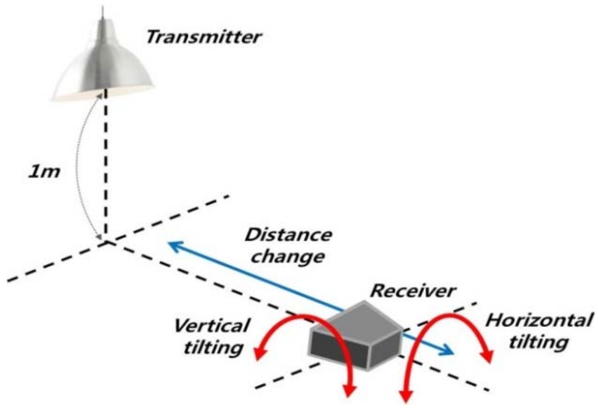

Fig. 4 Simulation model of transition

To investigate the effect of each characteristic, we conducted simulations of three cases. First, we checked the case when the receiver tilts only vertically at various distances. Second, the case when the receiver tilts only horizontally at various distances is also considered. Last, we conduct simulation of the case when the receiver tilts horizontally and vertically.

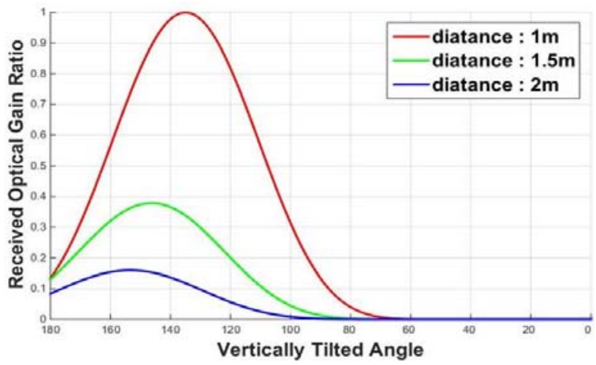

Fig. 5 Received optical gain according to vertical tilting

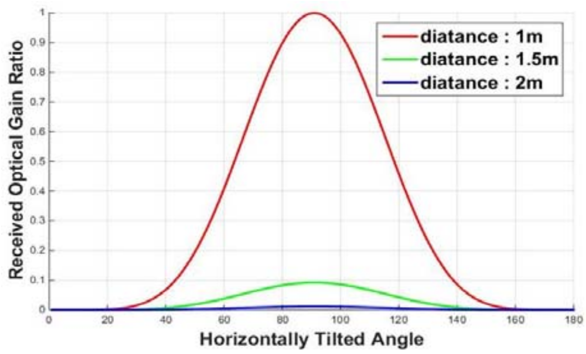

Fig. 6 Received optical gain according to horizontal tilting

Fig. 5 shows the received optical gain according to vertical tilting. When vertically tilted angle of receiver is 90°, the receiver is placed in parallel to the transmitter. Regardless of distance, when the receiver looks at the opposite side of the transmitter, the value decreases. It is caused by incidence angle increasing, which makes the gain decrease in (3). Conversely, if the receiver is tilted toward the transmitter, the incident angle decreases, and it makes the gain increase. As the distance increases, the gain decreases and it reaches faster the angle that makes the gain nearly zero.

Received optical gain according to horizontal tilting is shown in Fig. 6. As same as above case, the receiver is placed in parallel to the transmitter when horizontally tilted angle of receiver is 90°. In this simulation, the gain is symmetric with 90° as the center. The farther the tilted angle is from 90 degrees, the smaller the incidence angle, and it causes a decrease in gain regardless of direction. This pattern appears regardless of distance. Of course, as like the above simulation, the gain decreases as the distance increases.

Lastly, we conduct simulation of the case when the receiver tilts horizontally and vertically. In this case, the distance is set to 1m and not changed. The simulation result is shown in Fig. 7. X-axis is vertically tilted angle and Y-axis is horizontally tilted angle. This graph is the same as the merged graph of the above two cases. Consequently, if the gain characteristics for the previous two cases are identified, we can predict the approximate gain by using these characteristics, regardless of tilted angles.

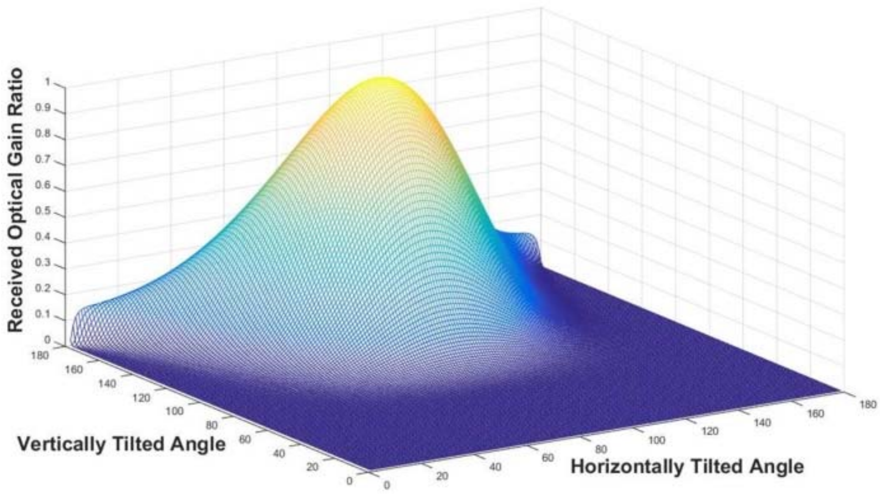

Fig. 7 Received optical gain according to horizontal and vertical tilting

IV. Conclusion

This paper researched the effects of incident angle and distance on optical gain by conducting simulation based on mathematical analysis. The simulations are divided into five major cases. By using simulation result, the effects of incidence angle transition and distance transition are studied. And the change pattern of the optical gain can be checked. These patterns are generally applied in various cases including above five major cases. Therefore they can be used as an index when determining the error range of actual specification in many applications using VLC.

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